NASA CONTRACTOR REPORT

NASA CR-1334

NASA CR-1334

A STUDY OF ASTRONAUTS' EXTRAVEHICULAR WORK CAPABILITIES IN WEIGHTLESS CONDITIONS

by E. C. Wortz, W. Schreck, W. Robertson, G. Lamb, and L. Browne

Prepared by
GARRETT CORPORATION
Los Angeles, Calif.
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1969

NASA CR-1334

A STUDY OF ASTRONAUTS' EXTRAVEHICULAR WORK CAPABILITIES IN WEIGHTLESS CONDITIONS

By E. C. Wortz, W. Schreck, W. Robertson,
G. Lamb, and L. Browne

Prepared under Contract No. NAS 1-7571 by
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

Exploratory experiments were conducted on methods of erection and assembly of large modules, transportation of cargo modules, and crew rescue during weightless simulation by neutral buoyancy techniques. A formal experiment was conducted on four typical restraint systems during the performance of various tasks with varying work envelopes. Data were collected on energy expenditures, reactive loads, and performance times. Conclusions are drawn about various aspects of extravehicular activity work and the efficacy of restraint systems.

Preceding Page Blank

FOREWORD

This report was prepared by the Department of Life Sciences, AiResearch Manufacturing Company, Los Angeles, California. The technical assistance of Dr. D. Busby, R. A. Diaz, G. Raynes, N. J. Belton, Mrs. M. Peters, Miss L.J. Miller, and S. Saltzberg is gratefully acknowledged.

Preceding Page Blank

CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

A STUDY OF ASTRONAUTS' EXTRAVEHICULAR WORK CAPABILITIES IN WEIGHTLESS CONDITIONS

CONTRACT NAS 1-7571

By E. C. Wortz, Ph. D., W. Schreck,
W. Robertson, Ph. D., G. Lamb, and L. Browne
Department of Life Sciences
AiResearch Manufacturing Company
A Division of The Garrett Corporation

SECTION I

INTRODUCTION

This final report describes a program conducted for NASA/Langley Research Center under Contract NAS 1-7571 to study astronaut's extravehicular work capabilities in weightless conditions. The program consisted of a series of experimental efforts that varied from exploratory experimentation to fully designed experiments. This report describes these experimental efforts and also the various pieces of apparatus, procedures, and experimental methods used. Conclusions are made about the various aspects of extravehicular activity (EVA) work including types of fasteners, levels of energy expenditure, reactive loads, procedures, and restraint devices.

Experience with the Gemini 12 flight program has emphasized the need to develop extravehicular hardware and procedures, to train the astronaut in the EVA tasks well in advance of the flight, and to understand the astronaut's capabilities and limitations. Exploratory work reported in NASA CR-859 Study of Astronaut Capabilities to Perform Extravehicular Maintenance and Assembly Tasks in Weightless Conditions showed that it was possible for the astronaut to perform extravehicular tasks, such as maintenance and repair, assembly of large equipment, assembly of large antenna, and assembly of rigid and inflatable modules in space. Realistic simulation by means of water immersion techniques made it possible to (1) observe the capabilities of a pressure-suited subject under simulated weightless conditions, (2) determine his energy expenditure, and (3) evaluate the suitability of the extravehicular hardware and task sequencing for accomplishing the assigned tasks. From this information, it is possible to understand the biomechanics required for performance of tasks in weightless conditions, develop procedures within the capabilities of the astronaut, provide metabolic data for the design of portable life support equipment, and make recommendations for the design of extravehicular structures, equipment, and tools.

The program reported in this document extends this previous NASA study to:

(a) Obtain precise metabolic and performance data on tasks similar to those that will be performed in space with statistical confidence.

(b) Obtain precise comparative data on performance, metabolic cost, and physiological parameters associated with the use of several restraints in maintenance work in a weightless condition with statistical confidence.

(c) Further explore the problems associated with the assembly of large modules.

(d) Explore the problems associated with rescue and transport operations.

An exploratory effort was conducted on the task of assembling large modules which evolved from the initial study under Contract NAS 1-5875. An improved task sequence and better task hardware were developed and tested on an exploratory endeavor. The goal of an exploratory test is to achieve maximum task improvement during the course of the task at the expense of data and statistical replication. Also, if during testing, a certain step cannot be performed as prescribed, the fact may be noted and the step filled in by scuba divers until the subject can again take over. The problems explored under this task involved methods of mating and securing beams, modules, and panels; locomotion aids; methods of tethering modules; methods of stopping the motion of modules; and concepts for restraining the subject so that his hands are free to work, but at the same time, so that he is free to move around and reach objects.

Exploratory studies were also conducted on the task of transporting cargo and incapacited crew members. Using manual methods to get objects from one secure position to another was emphasized.

In addition, an experiment was conducted on four restraints: a Gemini 12 foot restraint with a Gemini 12 strap restraint, a single-leg rigid restraint, a cage (or rail) restraint, and a Gemini 12 foot restraint with a single strap. To compare these restraints, tests were made with six trained subjects per cell in a two-dimensional experimental design consisting of a matrix of 12 cells (96 tests). The cells are defined by the four restraints and by the following three conditions: (1) local task with no reach or motion required outside of the subject's envelope of the stationary work position, (2) task with considerable reach and motion required outside of the subject's work position, and (3) task with intermediate reach required.

Section 2 describes the subjects, apparatus, methods, and procedures employed in these experiments.

SECTION 2

METHODS

SUBJECT TRAINING

Test subjects were selected from the AiResearch test subject panel. The selection process included, but was not limited to, the following: (1) an Air Force Type II flying physical examination with a 12-lead ECG and Harvard Step Test, (2) a psychological interview, (3) the ability to be pressurized in a suit, and (4) previous training for scuba diving. Subjects were sized by their anthropometric measurements to fit the Gemini pressure suits currently on hand. As part of the selection procedure, the entire contract effort was thoroughly discussed so that the subjects completely understood all aspects of the tests for which they volunteered.

The subjects selected for this program first received basic pressure suit training if they were unfamiliar with the suit specified. This training included familiarization with the suit, its operation and uses; suit fitting; and finally experience in the ventilated and pressurized suit. In addition, the subject received basic physiologic information about the effects of pressure change on the body; techniques of equalizing pressure in the aural cavity and sinuses were emphasized.

Each subject was trained to function in a neutrally buoyant condition while wearing a fiberglass shell and attached weights. Mockups, restraint devices, modules, and other prototype equipment used or developed for the programs were used by the subjects during the initial training to ensure familiarization with the equipment.

The subjects received additional immersion training during the pilot tests necessary for developing and finalizing the task procedures for each of the tests conducted. After the test procedures were developed and the timing points for each of the task-elements established, the subjects performed the tasks according to a checklist to establish task validity and also to ensure that subject training was complete. This provided repeated exposures of the subjects to the suit and associated hardware, the water environment, and the actual tasks for each subject until he was thoroughly oriented and his task performance was adequate.

All subjects were trained in scuba diving. Part of the program training consisted of repeated practice in rescuing a suited subject from the test tank. A standard set of procedures was developed, and each subject demonstrated his ability to follow these procedures by performing the rescue operation to the satisfaction of the test conductor.

In summary, the subject training included the following:

- Suit orientation and familiarization
- Diving safety and diving physiology lectures

- Familiarization with intent, purpose, and procedures of the study
- Shell fitting and application of weight to the shells
- Neutral-buoyancy checkout
- Training in neutrally buoyant work (task procedure development)
- Development and training in rescue of subject
- Pilot test participation
- Demonstration of task procedure knowledge (checklist validation)

APPARATUS

Underwater Test Facility

The underwater test facility was constructed to simulate weightlessness in a pressurized suit with neutral-buoyancy techniques.

Figure 2-1 shows a general view of the tank and the various features required to support the experimental activities. The tank is 30 ft in diameter, 21 ft high, and 20 ft deep. The stairway and catwalk around the top are 4 ft wide and of steel construction with a 4-in. concrete fill. 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 the instrumentation recording and control room. An 18-in. square porthole in the tank is within the control room for observation and photography. Two additional portholes are at a 5-ft, 4-in. level: one opposite the control room and one perpendicular to this room on the far side of the tank. Three clusters of five flood lights are symmetrically spaced about the upper elevation of the tank, and four 500-w underwater-pool flood lights are located symmetrically between the portholes 6 ft above ground level.

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

Figure 2-3, a photograph taken from the porthole in the control room, shows the interior of the tank. The fixed platform used for all operations is also shown. A movable lowering and raising platform (not shown) is adjacent to this porthole with the same dimensions as the fixed platform. Three ladders, one of which is shown in Figure 2-3, are symmetrically spaced.

Figure 2-4, a photograph taken from the top of the tank next to the jib boom, shows two ladders, two underwater lights, a porthole, the fixed platform, and an upper-elevation light cluster.

Underwater tests were designed to permit the main part of the test sequence to take place in the principal test area shown in Figure 2-5.

Figure 2-1. Underwater Test Facility

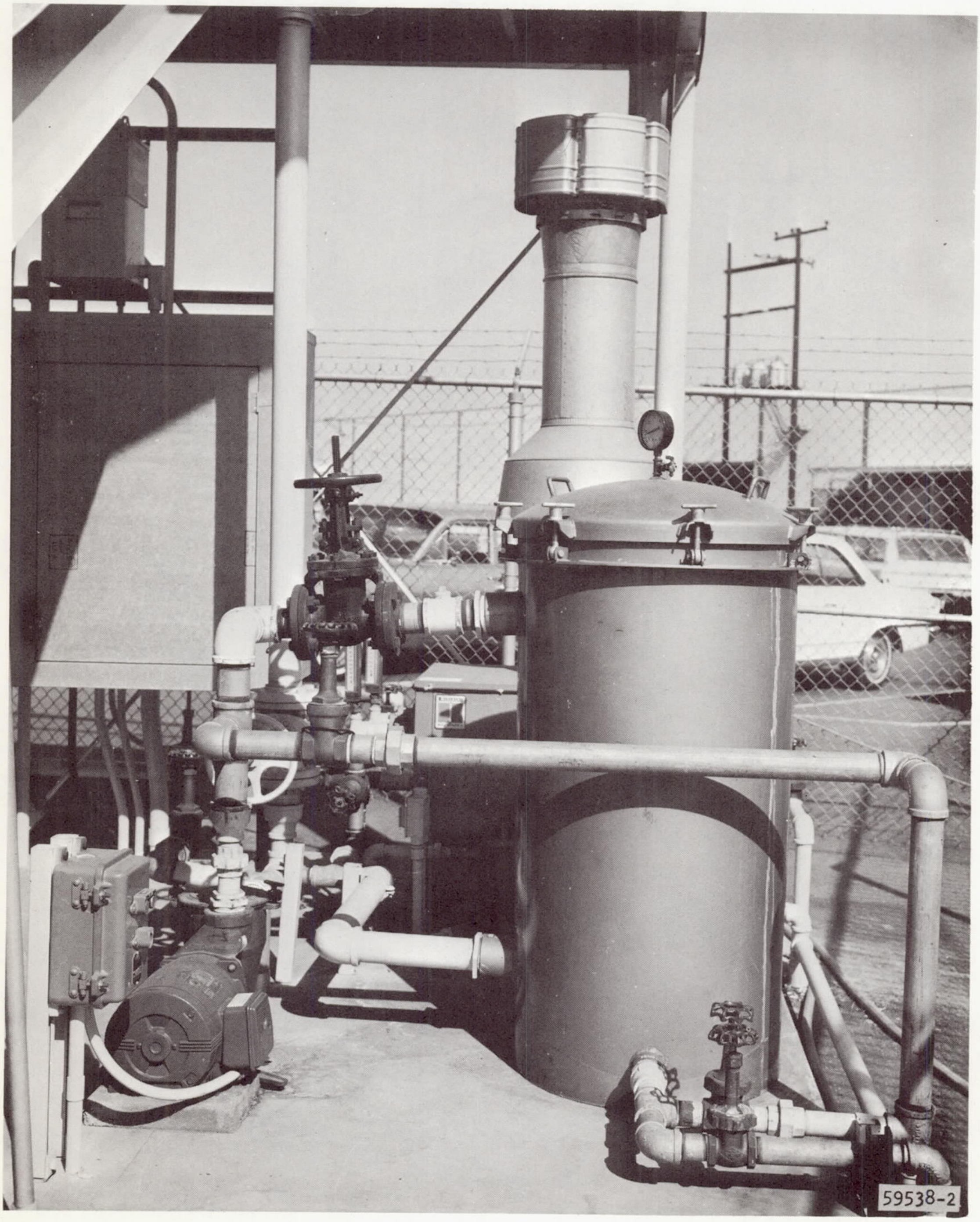


Figure 2-2. Water Conditioning Equipment

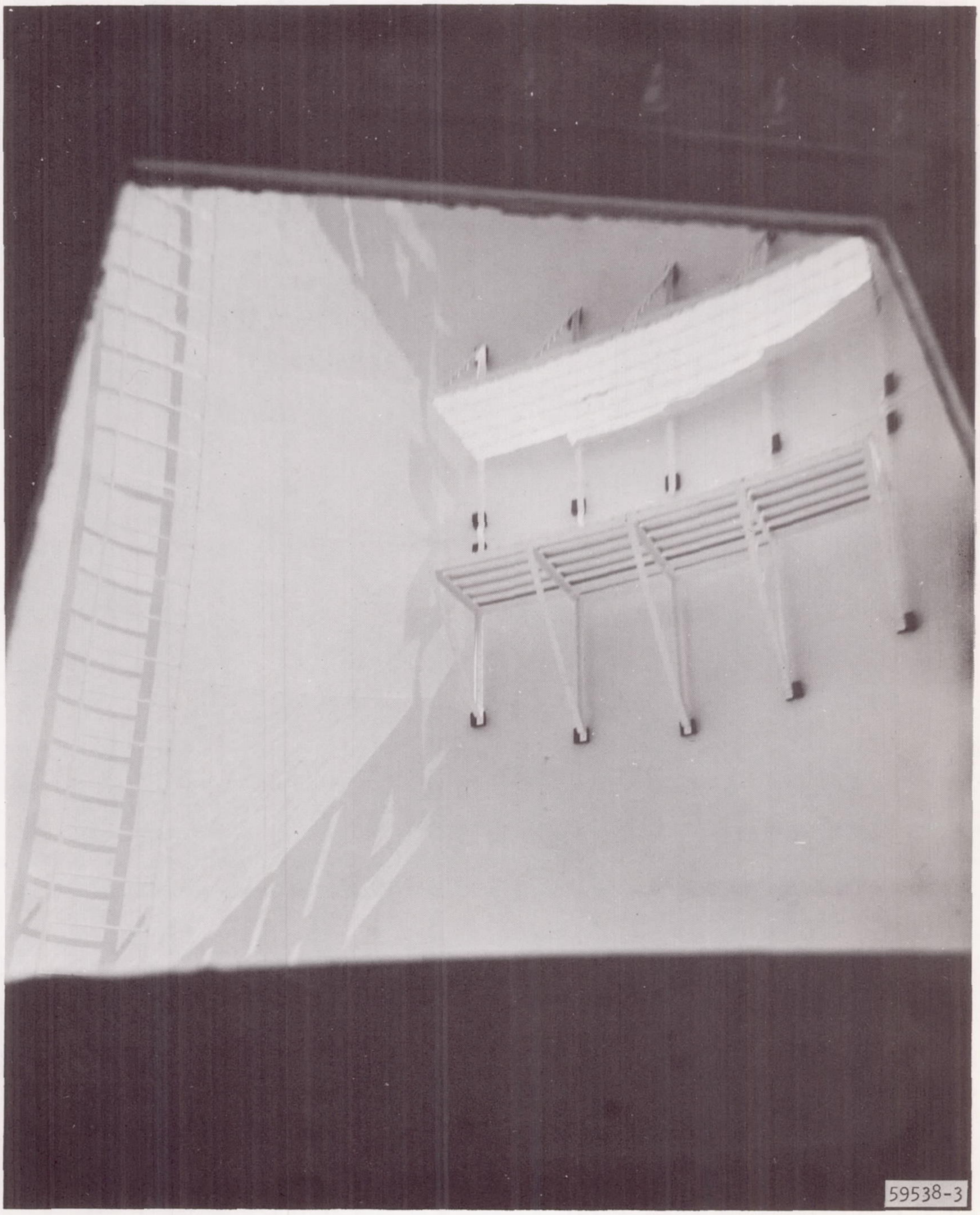


Figure 2-3. Water Tank Interior

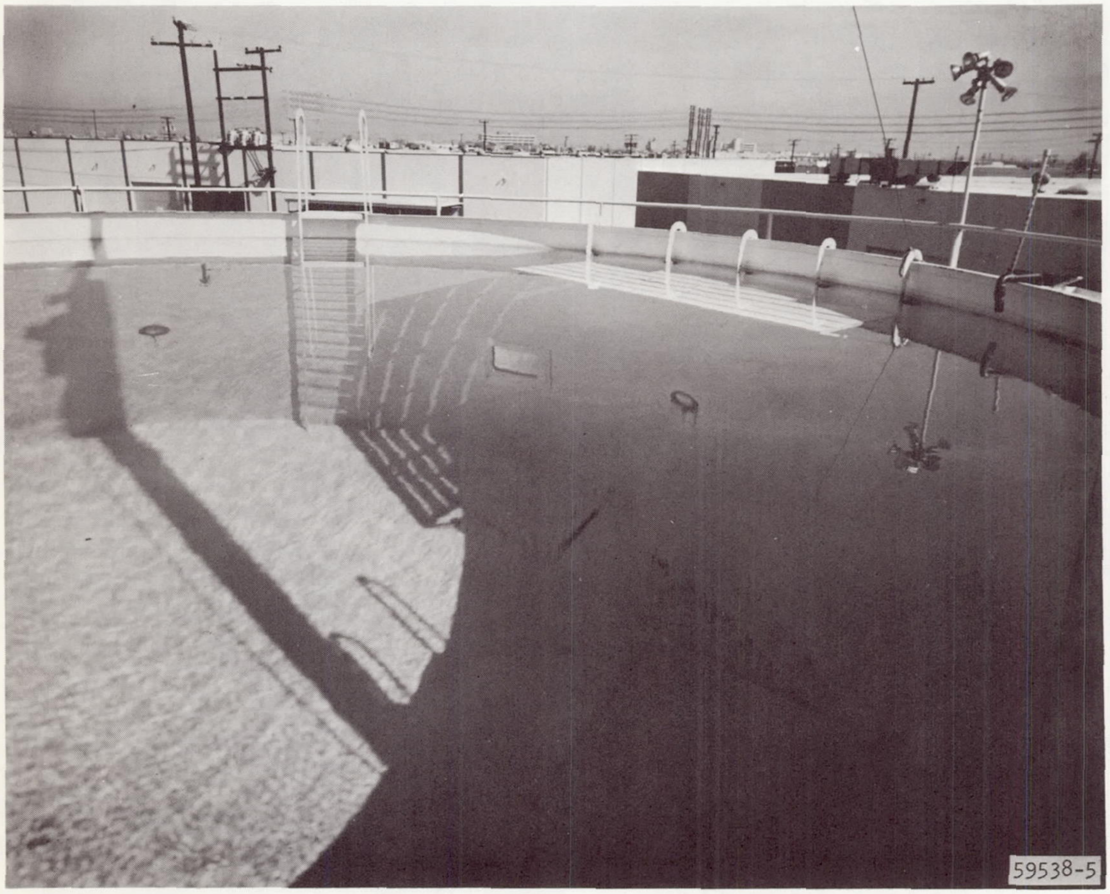


Figure 2-4. Top View of Water Tank

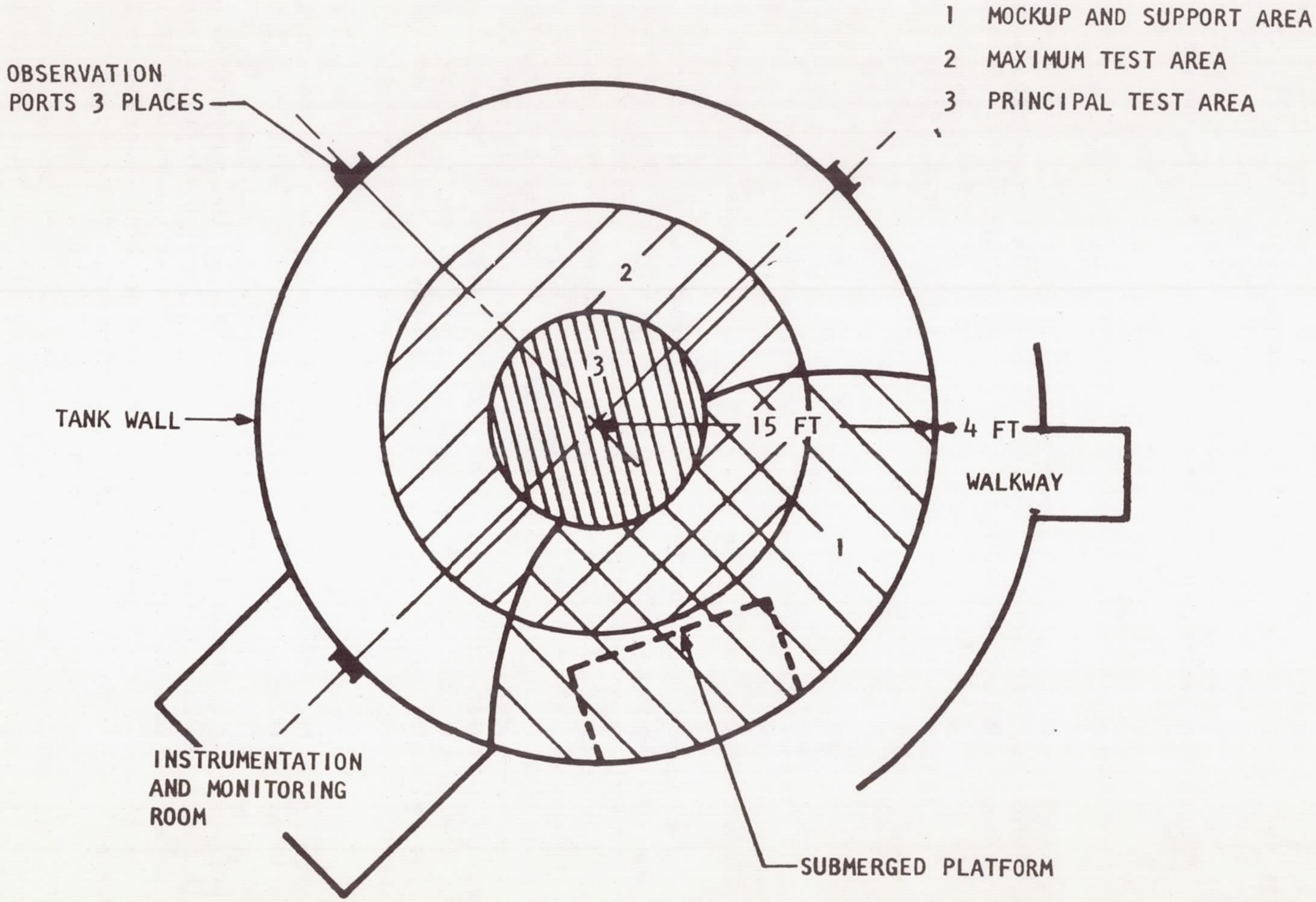


Figure 2-5. Schematic of Tank Work Area

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

Mounting Shell for Neutral Buoyancy

A fiberglass shell, which fits the torso of the pressure suit, provides the mounting structure for the lead weights required to establish neutral buoyancy. Miscellaneous equipment and restraint devices are also attached to it. Figure 2-6 illustrates the use of the shell with the lead weights attached. By the proper addition of weights on the shell and in the backpacks, good neutral buoyancy can be obtained for all body positions.

Full-Pressure Suits

Five G-2C full-pressure suits were used in this program.

Suit Environmental Control System (ECS) and Miscellaneous Equipment

Figure 2-7 is a schematic of the instrumentation and suit environmental conditioning. The ventilating gas for environmental control is supplied from a dewar of liquid air through an ambient vaporizer (heat exchanger) and then to an accumulator. The accumulator mixes the vaporized gas to minimize the fluctuation in oxygen and nitrogen vapor pressures. The vaporized air is introduced to the suit inlet. A differential pressure flow regulator on the outlet hose of the suit maintains flow rates and suit pressure. The exhaust ventilating gas is ducted back through the bulkhead ambient to reduce the bubbles in the water. Figure 2-8 shows the bulkhead placed in the tank wall in the control room. The bulkhead minimizes the length of lines required for bioinstrumentation and gas flow lines. Liquid air was used to provide the scuba divers breathing air through this bulkhead.

An AiResearch automatic pressure/flow regulator maintained suit pressure and ventilation flow. This regulator is currently designed to maintain 3.5 ±0.1 psid at 10 scfm. The subject is pressurized at the surface to 3.5 psi above ambient, and the regulator controls the flow at 10 scfm. As the subject descends to working depth, the regulator maintains the suit at 3.5-psi differential pressure above the water pressure and at the same time regulates the flow to 17 scfm. The response of this regulator compensates for any fluctuations in pressure as the subject changes depth and also minimizes this error of simulation.

An aircraft low-impedance intercommunications system with special helmet microphones enables communication with the subject. Additional instrumentation includes motion and still photographs and a special sequence timing board. An observer operates a bar mechanism that actuates three stopwatches at specific predetermined events. This actuation stops one watch, which must be started at

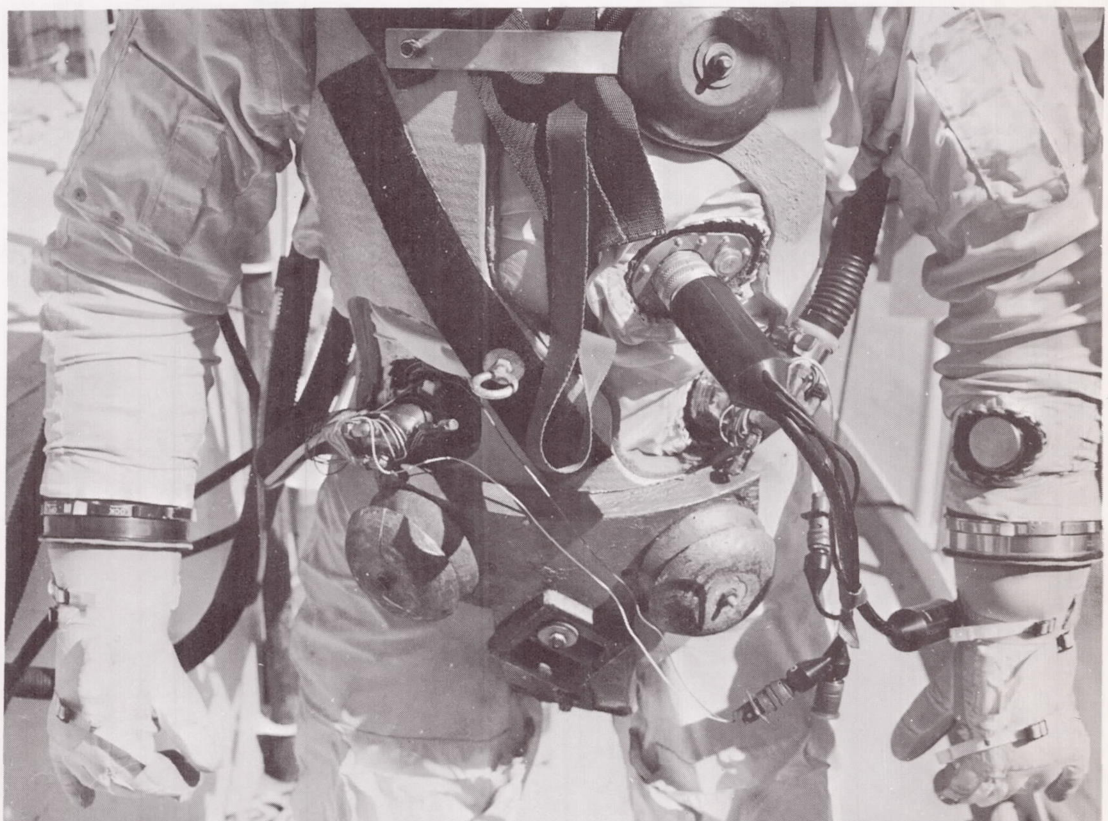
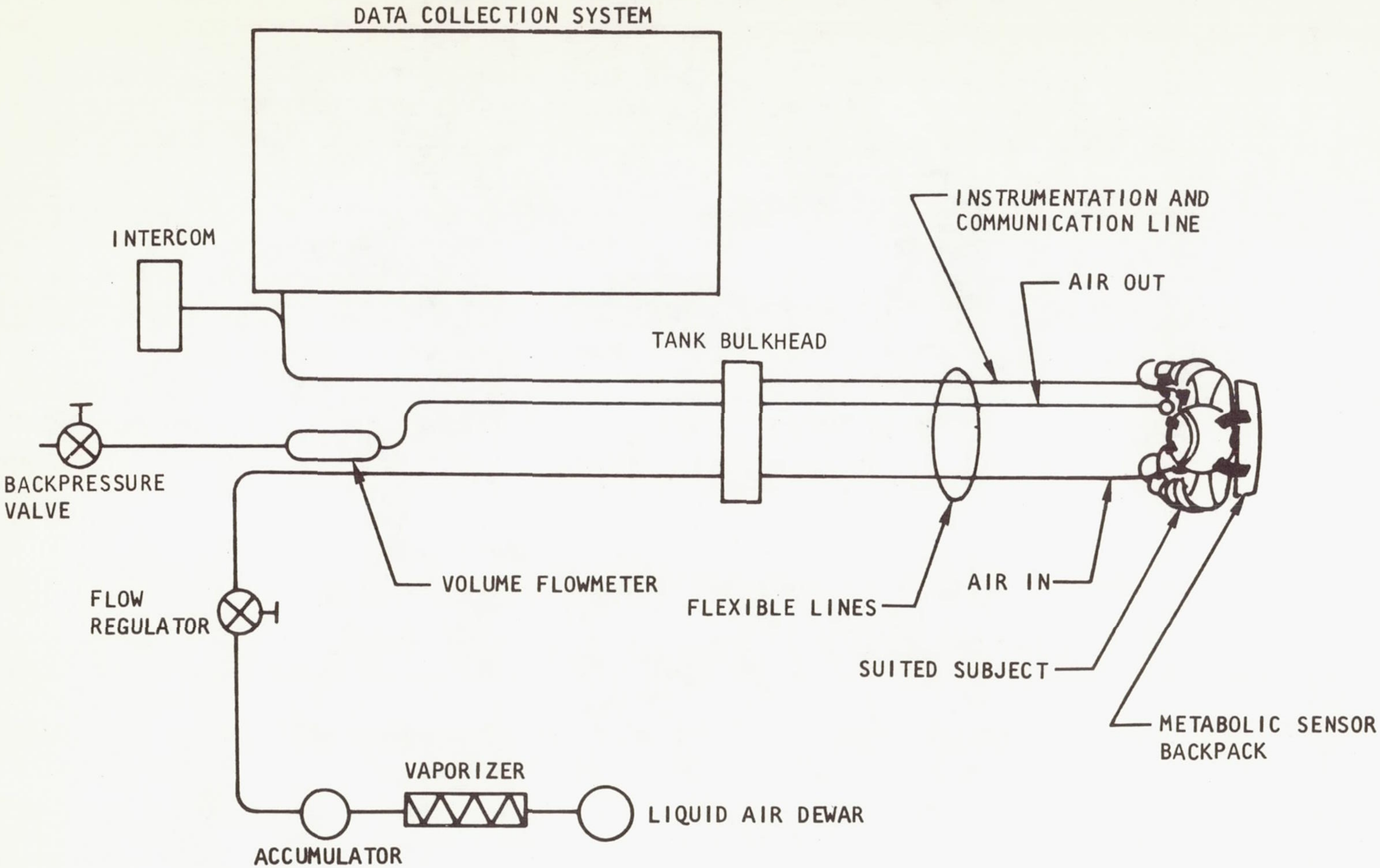


Figure 2-6. Use of Shell (with Lead Weights Attached)



A-34959

Figure 2-7. Instrumentation and Suit ECS Schematic

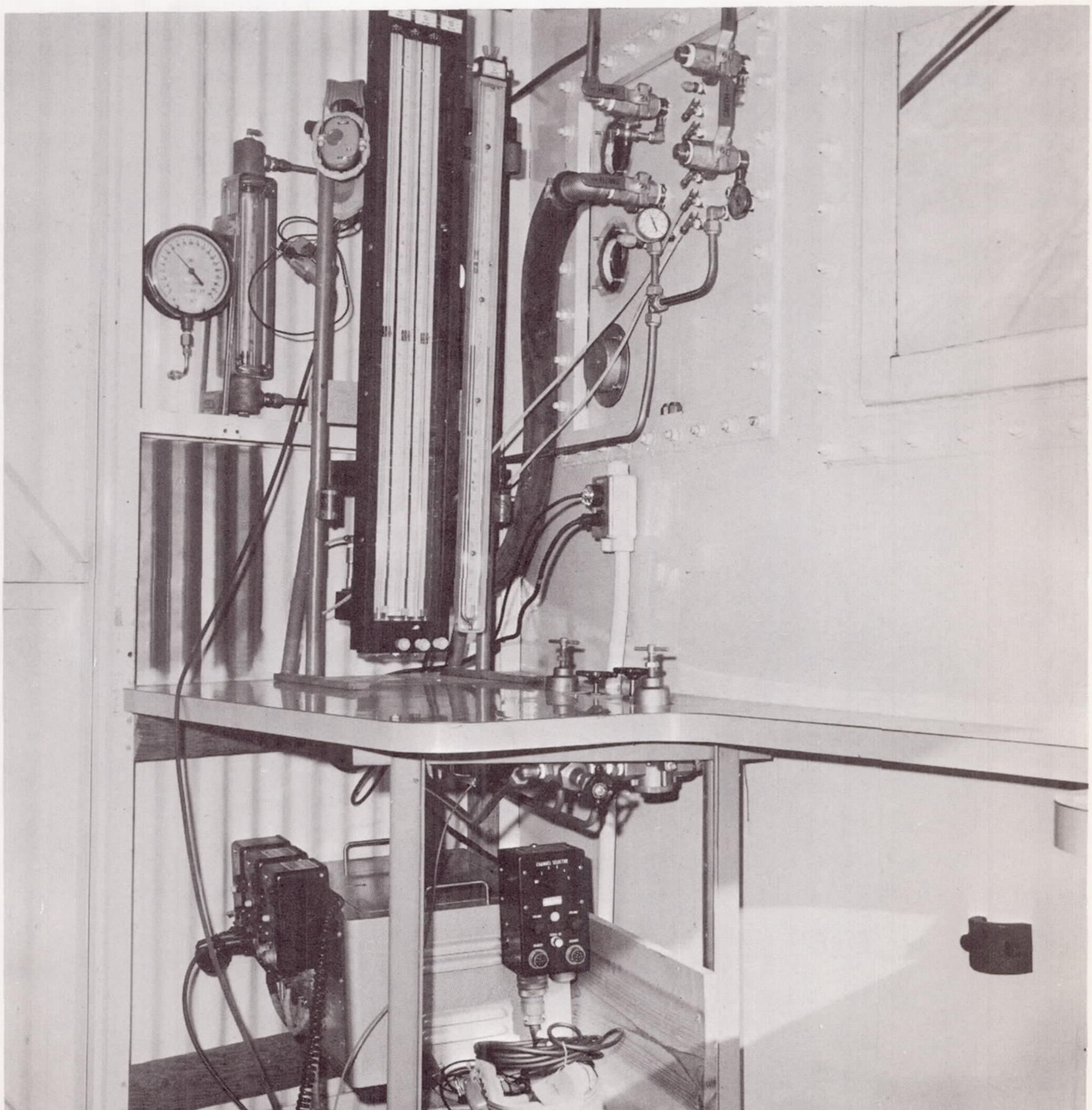


Figure 2-8. Suit Control Console and Bulkhead

the beginning of the event, and starts the next stopwatch for the beginning of the next event.

Metabolic Apparatus

Metabolic rates were measured by indirect calorimetry. This technique measures the energy cost of a given activity by calculation from the amounts of oxygen consumed and the carbon dioxide produced. The open-circuit method of indirect calorimetry was used. The subject inhaled, through a set of one-way valves, from the helmet free space and exhaled into a gas meter located in a backpack. Expired gases were analyzed for oxygen and carbon dioxide content. From these data, the oxygen consumption, carbon dioxide production, and respiratory exchange ratio can be calculated. Appropriate notations of experimental pressure, temperature, and water vapor pressure are required to reduce oxygen consumption and carbon dioxide production to the conventional standard temperature and pressure dry conditions (STPD). The basic equations for the calculations are as follows:

$$\dot{V}_{O_2} = (\dot{V}_I F_{I_{O_2}} - \dot{V}_E F_{E_{O_2}}) \times \frac{P_T - P_{H_2O}}{760} \times \frac{273}{273 + T}$$

$$\dot{V}_{CO_2} = (\dot{V}_E F_{E_{CO_2}} - \dot{V}_I F_{I_{CO_2}}) \times \frac{P_T - P_{H_2O}}{760} \times \frac{273}{273 + T}$$

$$R = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}}$$

where $\dot{V}_{O_2}$ = oxygen consumption (STPD), l per min

$\dot{V}_{CO_2}$ = carbon dioxide production (STPD), l per min

R = respiratory exchange ratio

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

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

$F_{I_{CO_2}}$ = fraction of inspired carbon dioxide

$F_{E_{CO_2}}$ = fraction of expired carbon dioxide

$\dot{V}_I$ = inspired volume per minute, l per min

$\dot{V}_E$ = expired volume per minute, l per min

P_T = observed barometric pressure, mm Hg

P_{H_2O} = water vapor pressure at temperature (T), mm Hg

T = observed temperature, ^oC

C = kcal/liter $\dot{V}_{O_2}$ at the measured R

Energy corresponding to oxygen consumption is calculated by the caloric equivalents for oxygen as related to the respiratory exchange ratio. The caloric equivalent of a liter of oxygen varies from 4.686 to 5.04 cal within the normal range of R.

Metabolic rates are measured by a unidirectional respiratory circuit made up of special one-way valves conducting tubing to a respirometer located in a backpack and return tubing, gas analyzers, pressure transducers, temperature transducers, and a recording system.

The overall instrumented system is shown in Figure 2-9. The basic components of the system, described below, are the modified pressure suit helmet, the analyzer backpack, and the recording system. Each measuring device and its use also are described.

Pressure suit helmet.--A helmet from the G-2C pressure suit used in this program was modified to accept the new AiResearch breathing system. The earphones were removed from the helmet and replaced with a speaker from a transistor radio, and two 3/4-in.-dia penetrations were made into the back of the helmet (Figure 2-10). This modification was necessary to position a set of AiResearch low-resistance, low-deadspace, one-way valves. This new valve system (Figure 2-11) operates on the wedge-leaf valve concept; it has a low profile and does not interfere with the subject's visual field. With this system, the subject inhales from the free airspace of the helmet through the one-way valves fitted with a rubber athletic type mouthpiece, and exhales through a connecting hose that runs along the side of the helmet out through the rear of the helmet. The exhaled air is ducted to the backpack by 3/4-in. convoluted tubing and returns to the rear of the helmet through a 3/4-in. convoluted hose. A deflector on the helmet return port directs the air down the back of the suit to prevent the exhaled carbon dioxide from being inhaled again.

Metabolic rate analyzer backpack.--Analyzers to determine metabolic rates were packaged in a backpack worn by the subject underwater. The pack housing is 1/4-in. stainless steel; its dimensions are 18.5 by 17.5 by 7.8 in.

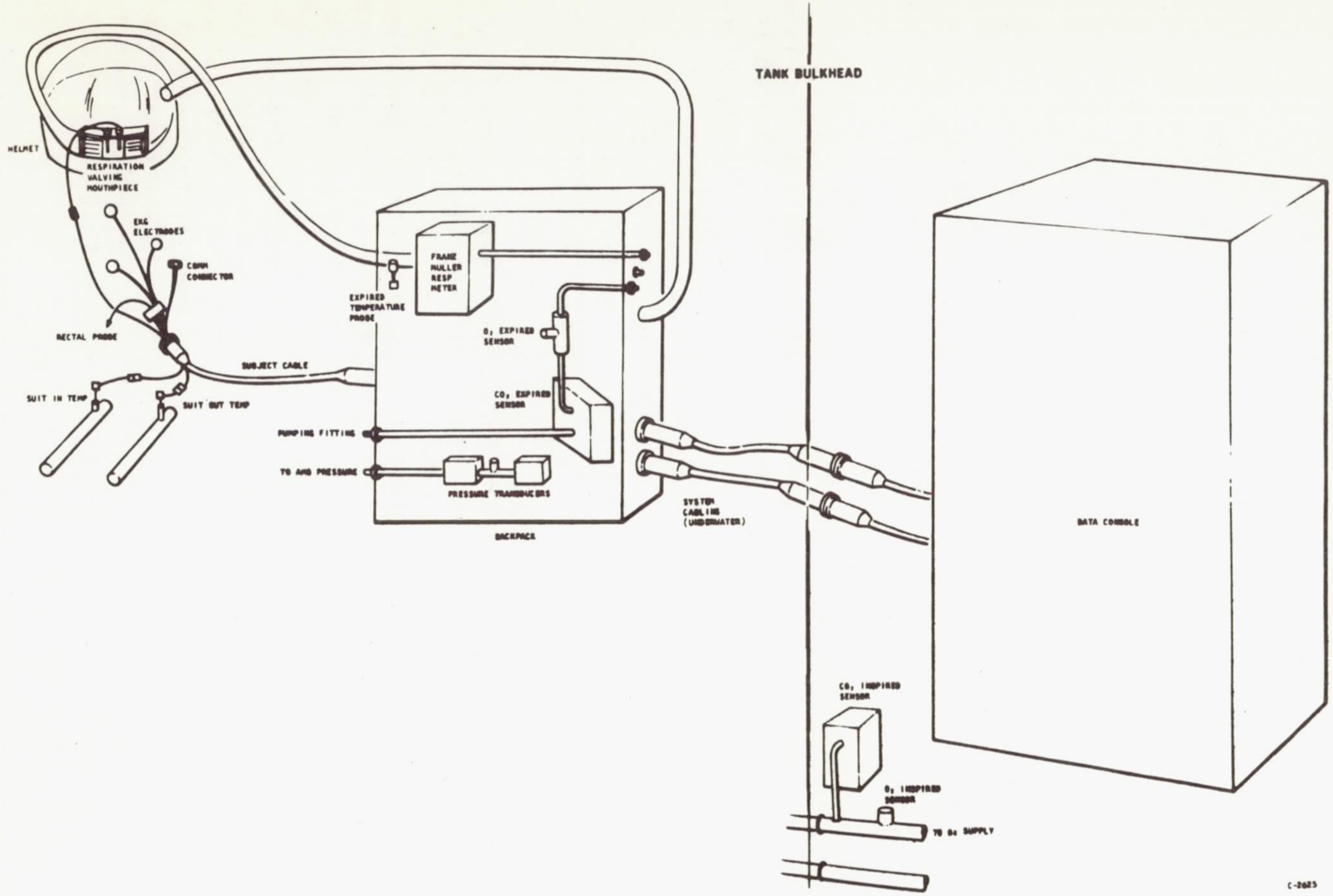
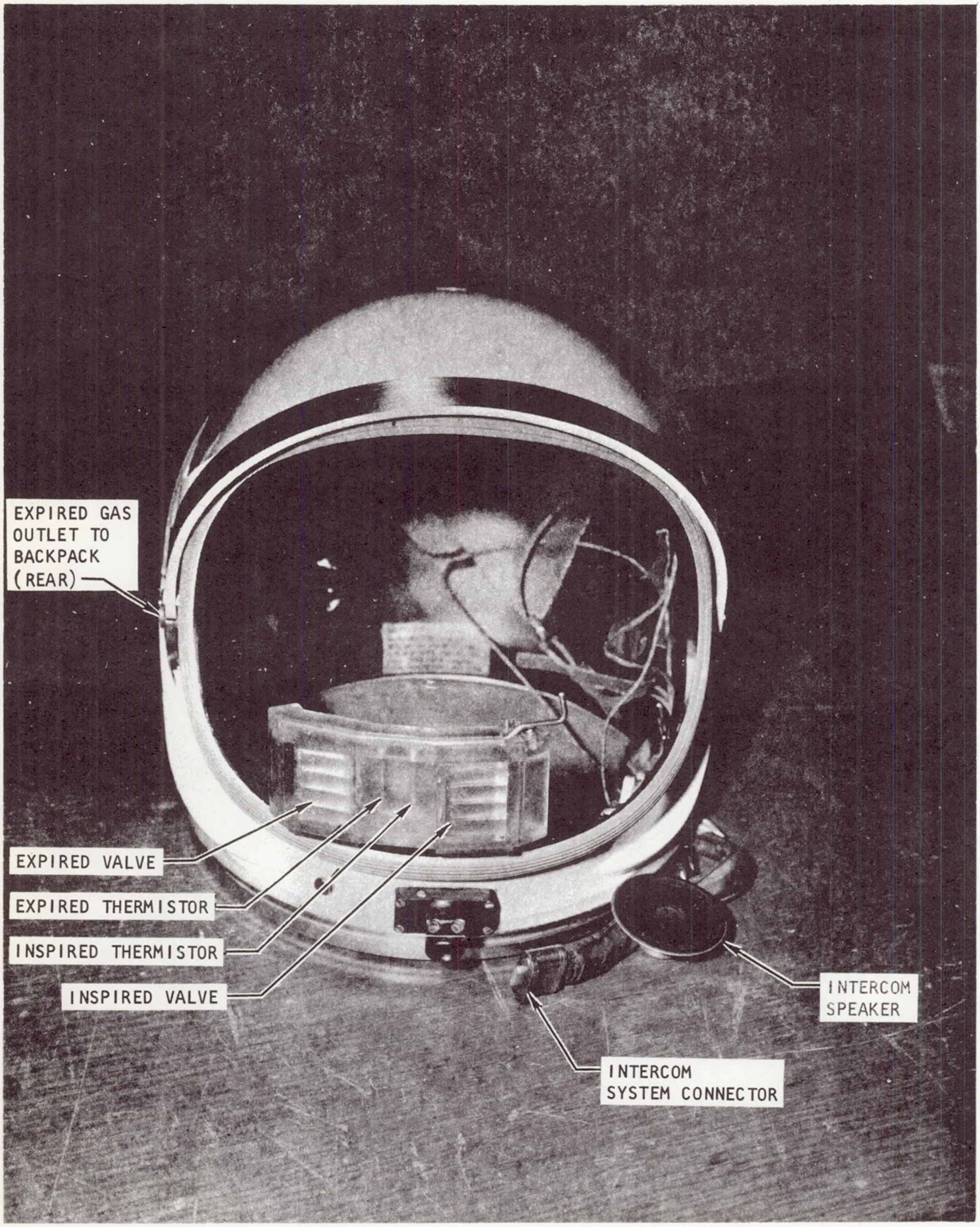


Figure 2-9. Instrumented System

Figure 2-10. Pressure Suit Helmet Modification



F-9117

Figure 2-11. Helmet Gas Valving and Intercom Hardware

When the backpack is pressurized to 3.5 psi above ambient and all the instruments are installed, its total weight is 112 lb. It has a buoyant force of 91.2 lb and thus a negative buoyancy of 20.8 lb.

Normally, about 75 lb must be added to obtain neutral buoyancy at a depth of 15 ft for a subject wearing a pressurized G-2C pressure suit. Forty-five pounds of this weight were usually added to the front of one of the formed shells worn by AiResearch subjects. This weight was positioned near the subject's center of gravity. The remaining 30 lb was added to the subject's back and extremities. The backpack accounts for 20.8 lb of the 30 lb added to the back.

The measuring system consists of a modified Franz-Mueller respirometer, a Beckman LB-1 infrared carbon dioxide sensor, a Technology Inc. polarographic oxygen sensor, and sensors to measure the temperature and pressure of the expired air. The expired air moves from the mouthpiece and tubing at the rear of the helmet into the respirometer for measurement of gas volume. The respirometer was modified to include an electronic sensor that provides a signal for volume recording. The sampling device of the respirometer samples the expired air over each breath. This device also acts as the pump to push the expired gas sample past the oxygen electrode and through the infrared carbon dioxide sensor. The gas moves into the buffer volume of the backpack and is ducted to the pressure suit through the rear of the helmet.

The data from the respirometer and from the oxygen and carbon dioxide sensors, the temperature of the gases, and the total pressure in the backpack provide all the information needed to calculate oxygen consumption, carbon dioxide production, and respiratory exchange ratio.

It should be noted that since the pressure of the backpack and that of the pressure suit are the same, all calibrations and analyses are made at that pressure.

Calibration techniques.--The various components of the analyzer system were calibrated by specialized techniques suited for each particular component. Calibrations were performed at least before every test and periodically during a test as required. Calibration of the gas analyzers was the most critical to the measurements to be made and the instruments most susceptible to electronic drift. However, the instruments used were stable for periods of 4 to 8 hr and therefore did not prove to be a problem.

The gas analyzers were calibrated by passing gases from known oxygen and carbon dioxide concentrations through the system respiratory circuit with the system at test pressure (total pressure expected with the subject in his work position). At least a 4-point calibration curve was generated for each analyzer. Calibrations were repeated after each test to ensure accuracy of the data. A schematic of the gas analyzer calibration console is shown in Figure 2-12.

Bioinstrumentation

Rectal temperature changes were measured with a thermistor probe (0.46 cm in diameter and 3.9 cm long) and recorded on an Offner Type S Dynograph. All rectal temperature probes were inserted approximately 10 cm beyond the anal sphincter.

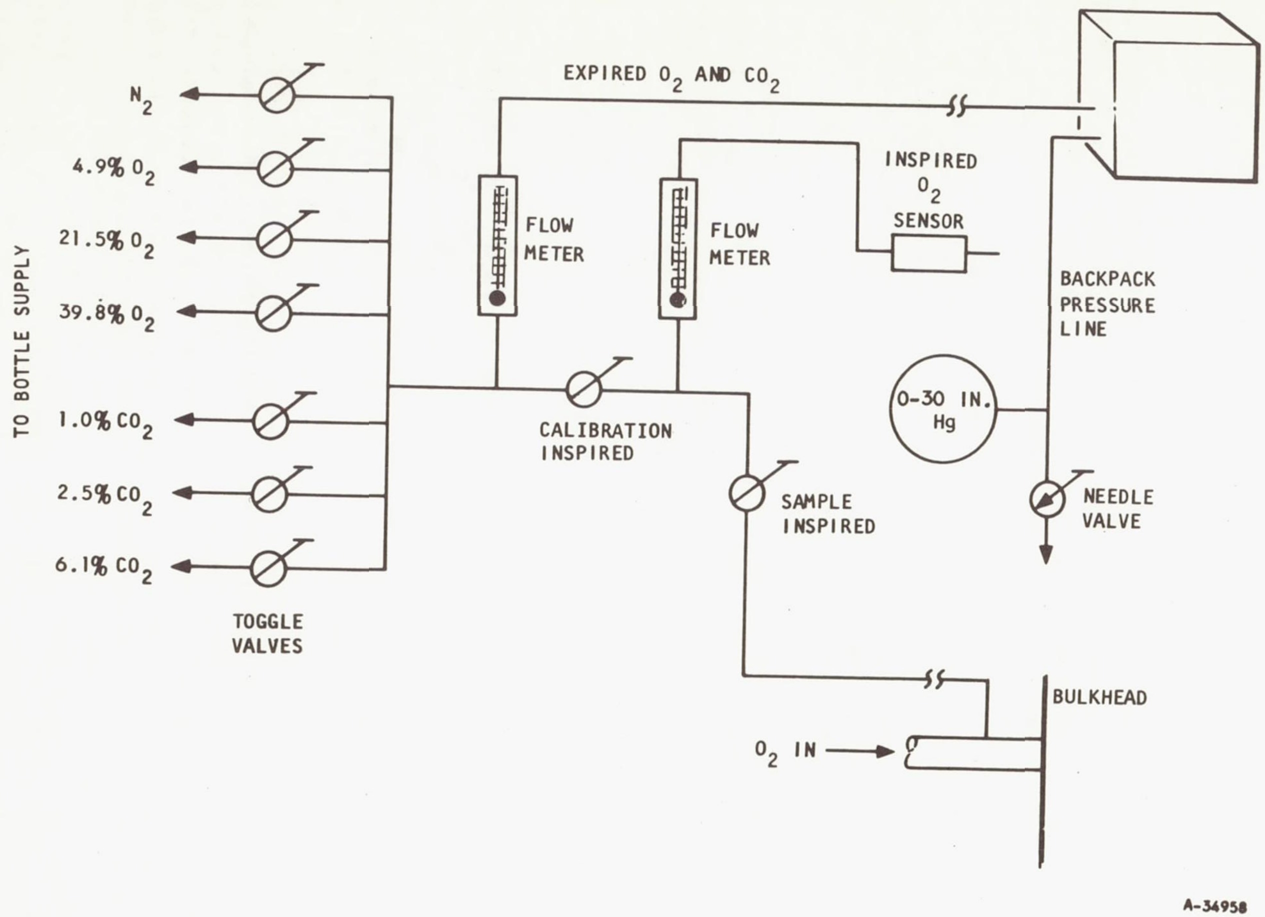


Figure 2-12. Gas Calibration Console Schematic

Continuous electrocardiograms (ECG's) were taken with a three-electrode system consisting of a bipolar modified V_4 lead and a ground. Recording and monitoring was done on the Dynograph at 2-min intervals; the speed of the recording paper was maintained at 5 mm per sec.

Respiratory rate was measured with short-time-constant thermocouples located in the vestibule of the one-way respiratory valves. Monitoring and recording of respiratory rate was done on the Dynograph.

Respiratory minute volumes were determined by passing the expired gas through a respiratory gas meter (Model 59, Max Planck Institute for Work Physiology). This instrument, developed to determine the respiratory minute volume of subjects performing various work loads, was ideally suited for this test program. Total pressure and dry-bulb temperature of the gas at the meter were monitored and accounted for in all quantitative measurements.

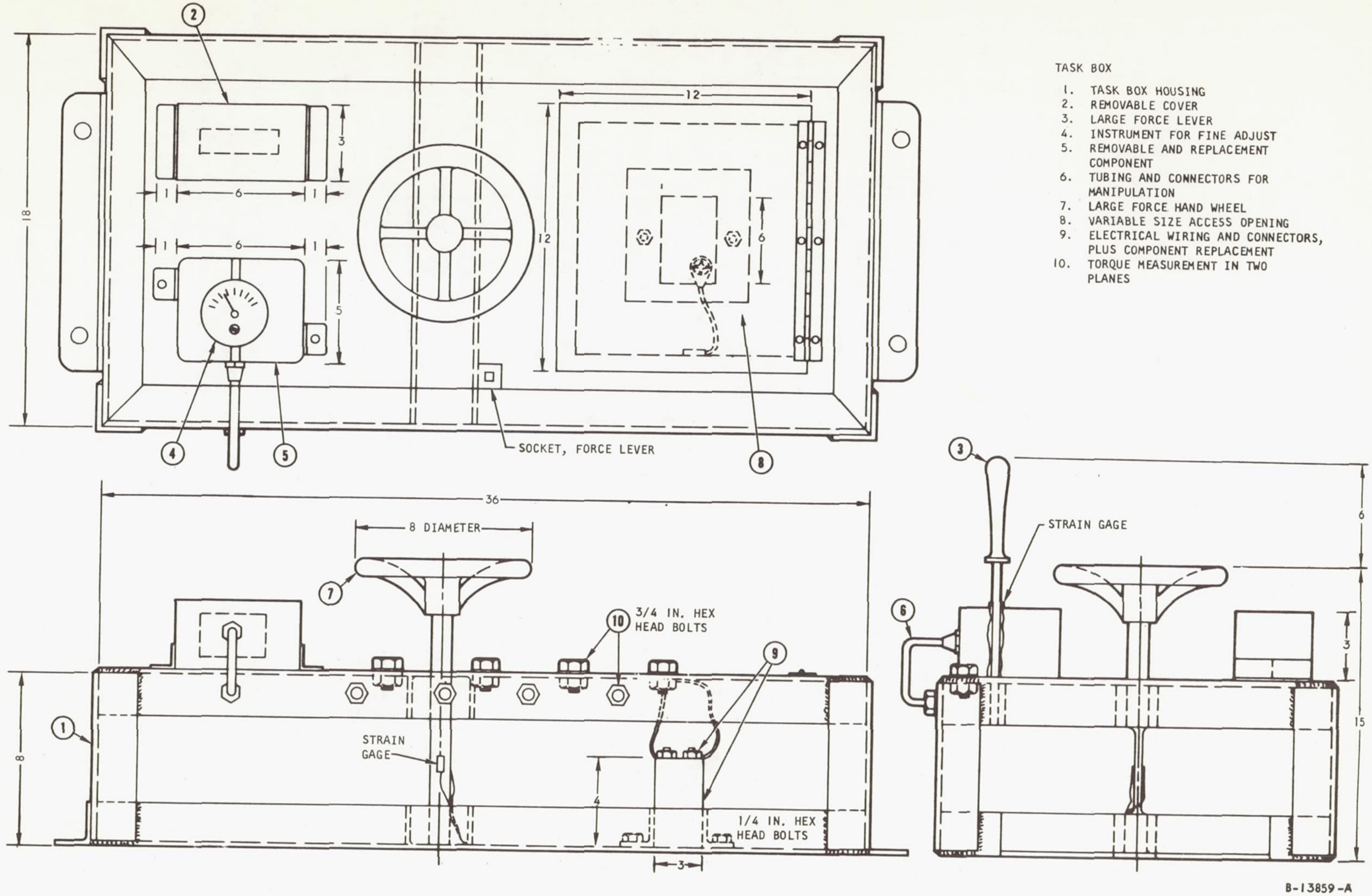
Reactive Force Measurements

One possible explanation for the increased level of energy expenditure for work in reduced or zero gravity is that a counteractive force (to accomplish work) must be supplied by muscular action. This reactive force must be developed between the astronaut and the spacecraft upon which he is working. Thus, the forces imparted to the restraint systems which are used to allow the astronaut to perform work must be determined to (1) understand the reactive force developed in performing a given task, (2) evaluate the loads imparted to the machine at the man-machine interface, and (3) provide an objective evaluation of restraint systems. The reactive forces developed are measured to provide an understanding of the normal force envelope for man working in the weightless condition and to give a time history of the actual work performed. The forces imparted to the structures on which the astronaut is working must be known to understand their potential effects on structural design.

Load cells in the load-carrying support structures (restraints) measured the loads induced in the structure from the performance of specific sequential tasks. Forces imparted in the tasks of torquing a lever similar to a valve and a pull-push device similar to tightening or loosening a bolt (Figure 2-13) were also measured. These two loads can be classified as action and reaction; that is, the supporting loads provide the reaction and the work loads of the specific task provide the action.

The task elements and primary load-carrying restraint members were designed to provide a symmetrical cross section for applying strain gages to make up the load cells. A symmetrical section reduces the complexity of data reduction and increases the sensitivity of a load cell bridge when all the gages are active. All but the thrust and flexure load cells were applied to tubular members.

The load cells used in the restraint testing and the figures that illustrate these load cells are as follows:



TASK BOX

1. TASK BOX HOUSING
2. REMOVABLE COVER
3. LARGE FORCE LEVER
4. INSTRUMENT FOR FINE ADJUST
5. REMOVABLE AND REPLACEMENT COMPONENT
6. TUBING AND CONNECTORS FOR MANIPULATION
7. LARGE FORCE HAND WHEEL
8. VARIABLE SIZE ACCESS OPENING
9. ELECTRICAL WIRING AND CONNECTORS, PLUS COMPONENT REPLACEMENT
10. TORQUE MEASUREMENT IN TWO PLANES

Figure 2-13. Task Box

No.	Load Cell	Figure Schematic	Figure Photograph
1.	Task box push-pull	2-14	2-15
2.	Task box torque tube*	2-16	2-17
3.	Strap restraints (2)	2-18	2-19
4.	Rigid-leg restraint	2-20	2-21
5.	Thrust and bending flexure	2-22	2-23
6.	Foot and cage restraint	2-24	2-25

*Two configurations were used. One was a small diameter tube with a "wheel" handle, and the other was a larger diameter tube with a "T" handle

The task box push-pull (1) called a full-bending bridge, was used in each test. The task box torque tube (2) was a torque bridge used in each test. The strap restraints (3) were ring load cells using a full-bending bridge to provide the axial tension load in the strap. The rigid-leg restraint (4), used only during the rigid-leg tests, was instrumented with full-bending, torsion, and axial bridges. The thrust and flexure (5) consisted of a full-bending bridge to measure thrust and two full-bending bridges to measure moments (bending). This load cell was used only with the rigid-leg restraint. The foot and cage restraint (6) was instrumented with full-bending, torsion, and axial bridges.

Figure 2-26 shows the strap restraint load cells mounted on the suit shell with the strap restraints. This figure also shows the Gemini 12 foot restraints mounted on the restraint platform.

Sensors and Recording Systems

Most data were recorded both in analog form and on a digital data system. This system consists of sensing equipment, signal conditioning equipment, digital data acquisition system (DDS), and the visual monitoring equipment. Figure 2-27 illustrates the DDS in block diagram.

Collecting data with digital equipment is a direct method of computer entry to improve test results by improved data accuracy and ease in computation. Data taken one day, as digital numbers, are inputted to the computer, and the results can be presented to the test conductor within 4 hr of test completion.

Sensing equipment.--The sensing equipment identified in Figure 2-28 is discussed in subsequent paragraphs.

1. Oxygen and carbon dioxide gas analysis equipment.--Inspired and expired gases were analyzed to determine the percentage of oxygen and carbon dioxide contained, and the gas percentage was converted to an electrical signal for recording purposes.

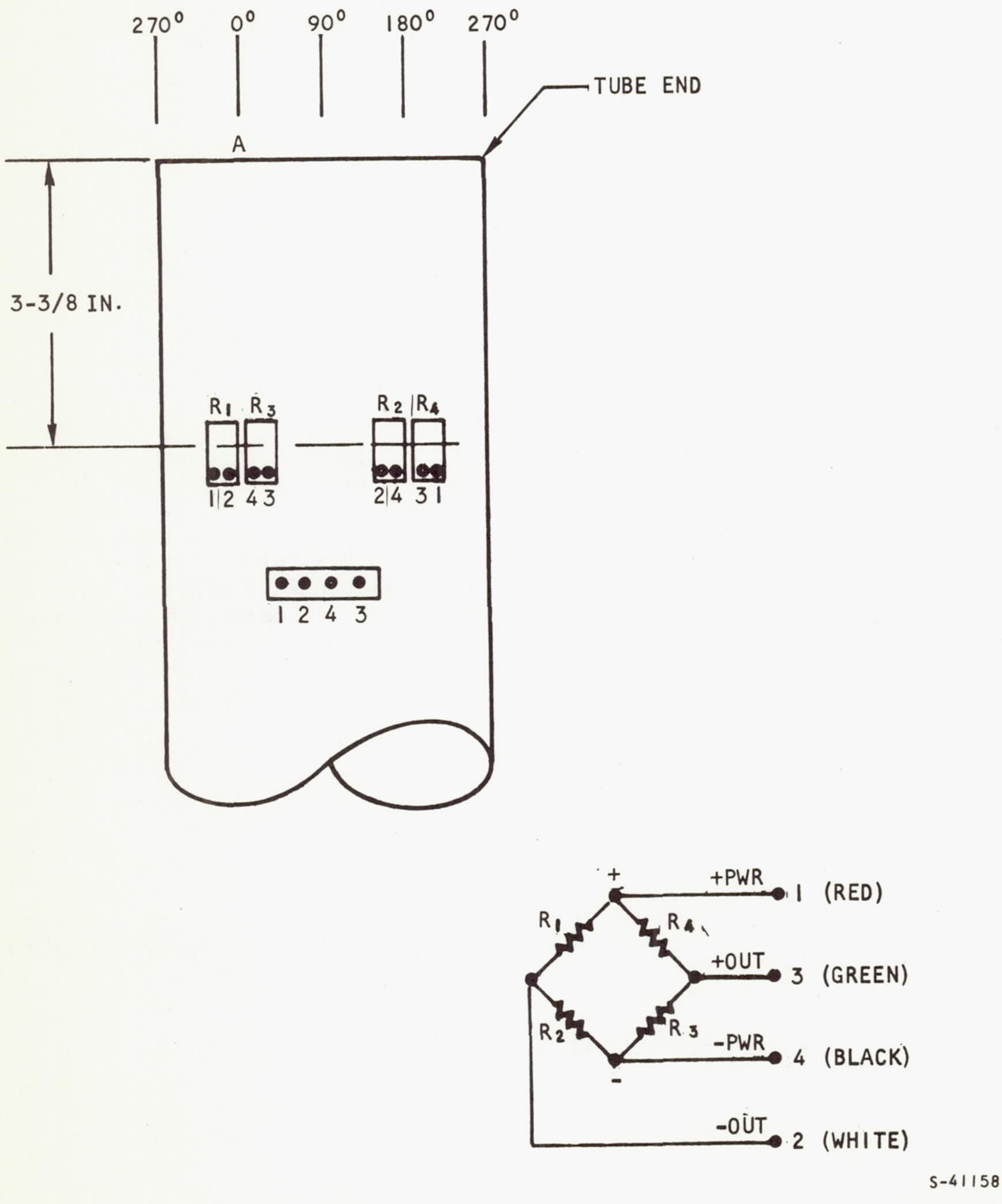


Figure 2-14. Task-Box (Push-Pull) Lever Load Cell

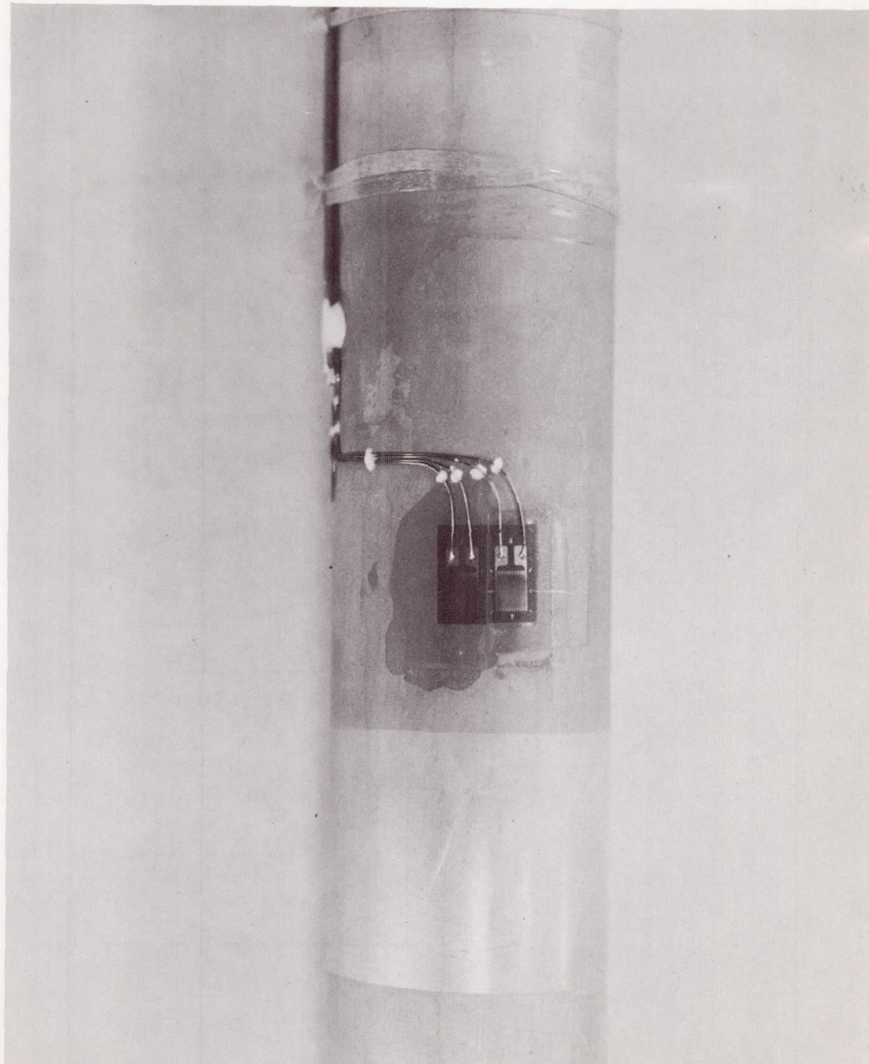


Figure 2-15. Task Box (Push-Pull) Lever Load Cell

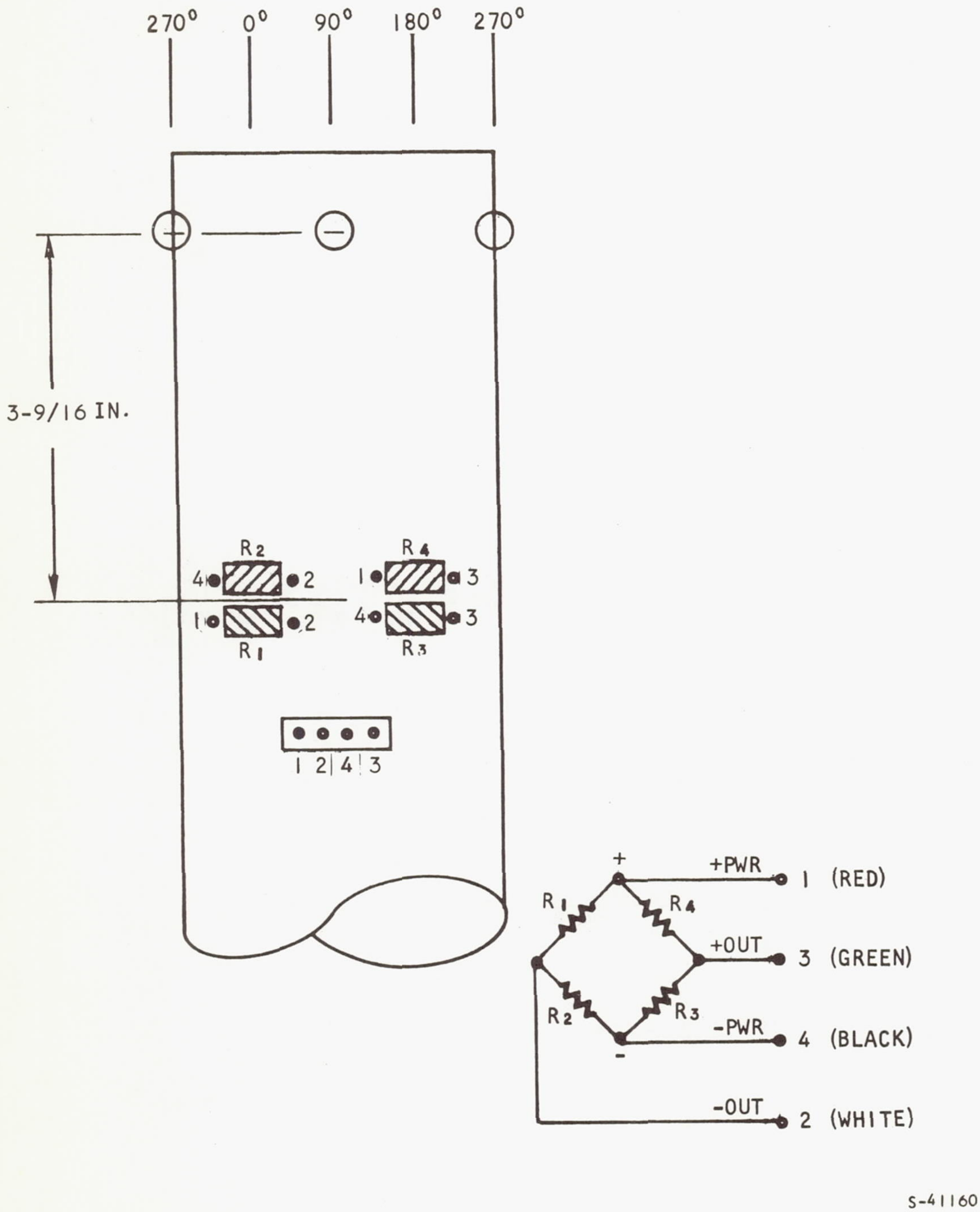


Figure 2-16. Task-Box Torque Tube Load Cell

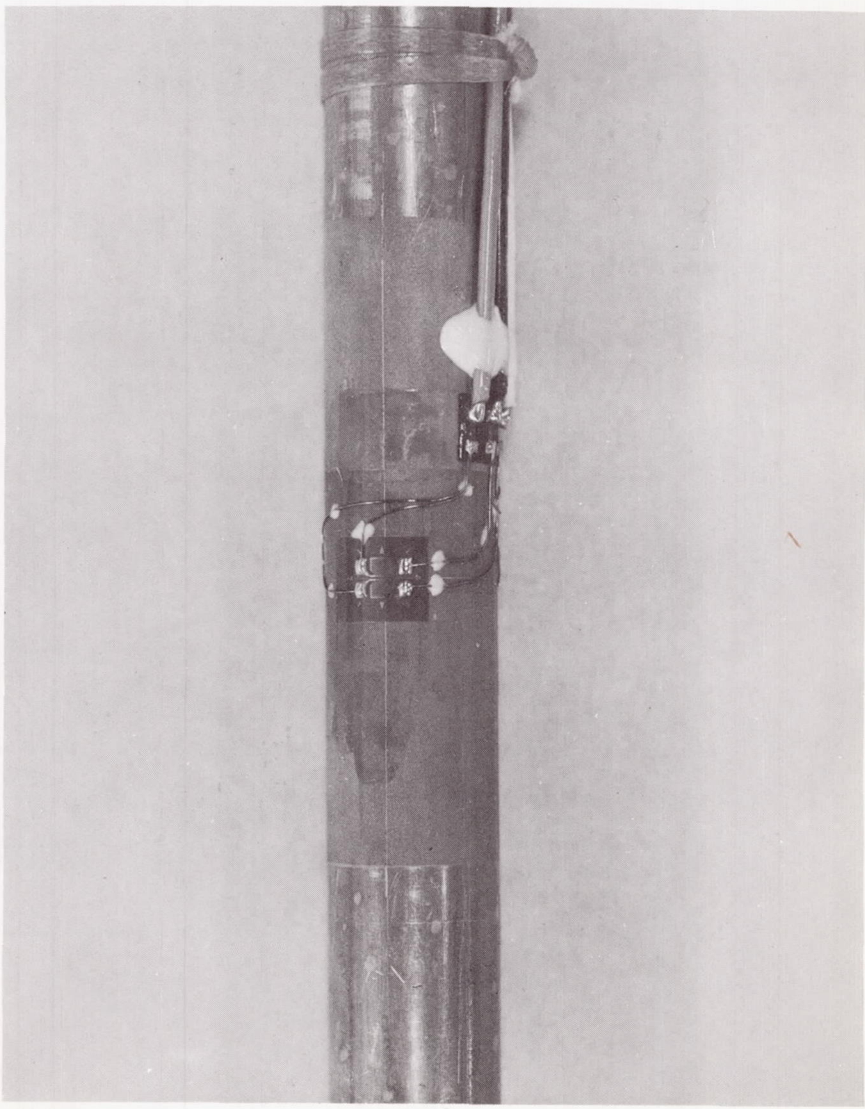
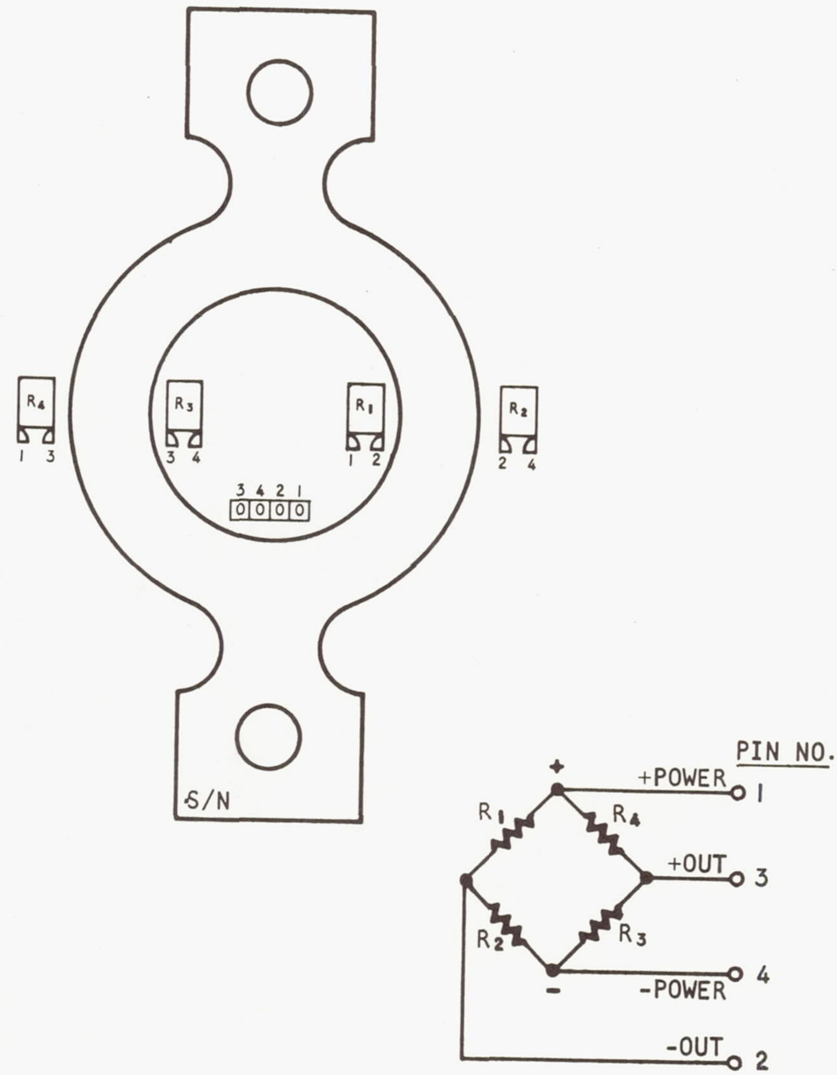


Figure 2-17. Task-Box Torque Tube Load Cell

GAGE TYPE: MA-13-250BF-350

GAGE RESISTANCE: 350.0 ±0.15%

GAGE FACTOR: 2.105 ± 0.5%



S-41061

Figure 2-18. Strap Restraints

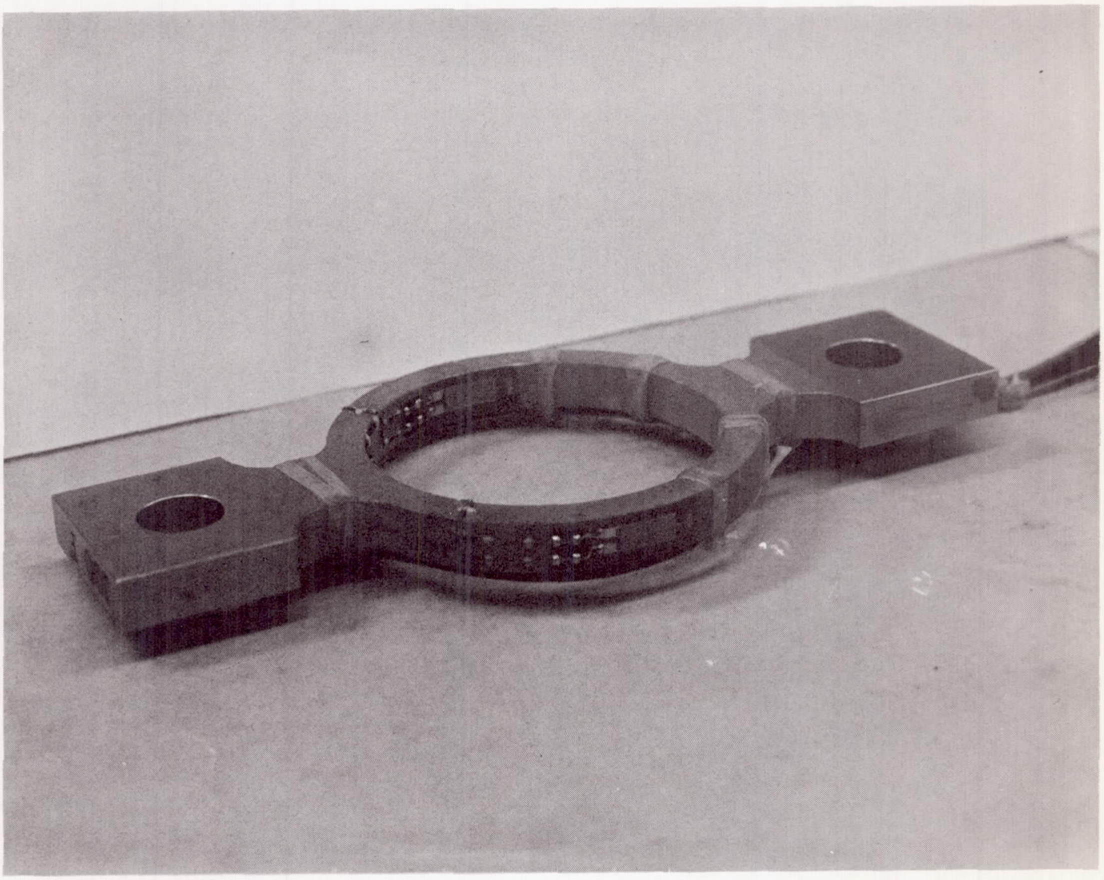


Figure 2-19. Strap Restraints Load Cell

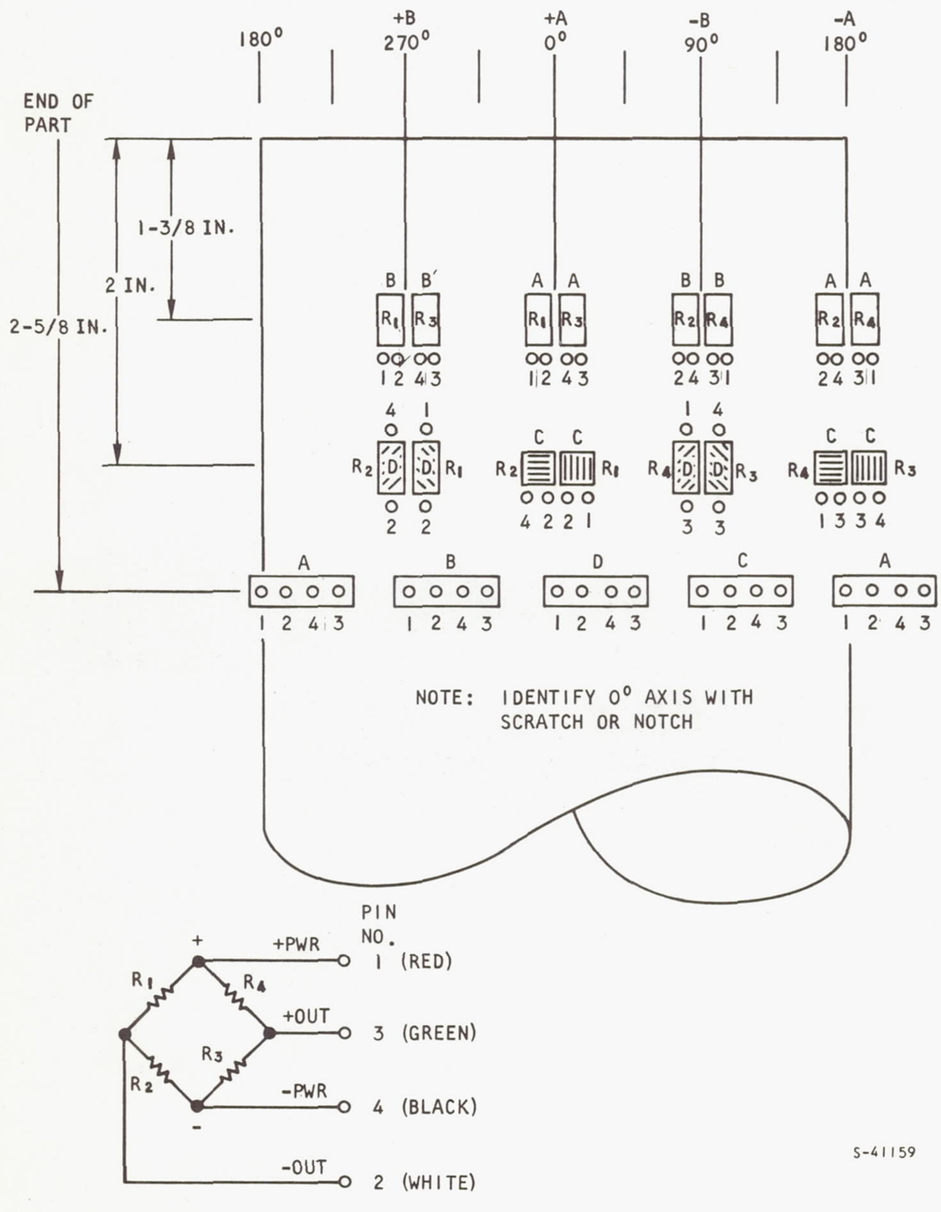


Figure 2-20. Rigid Leg Restraints Load Cell

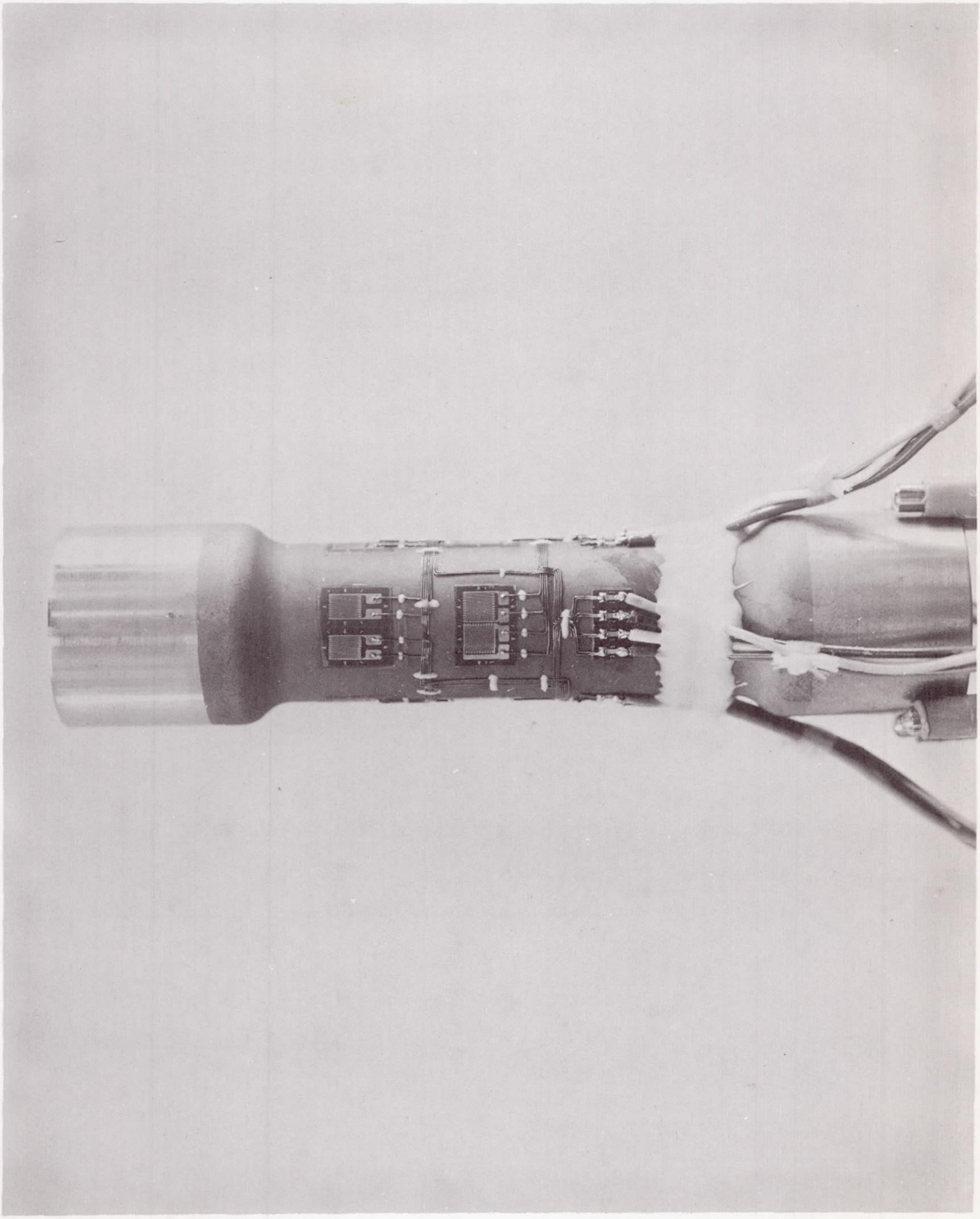


Figure 2-21. Rigid Leg Restraints Load Cell

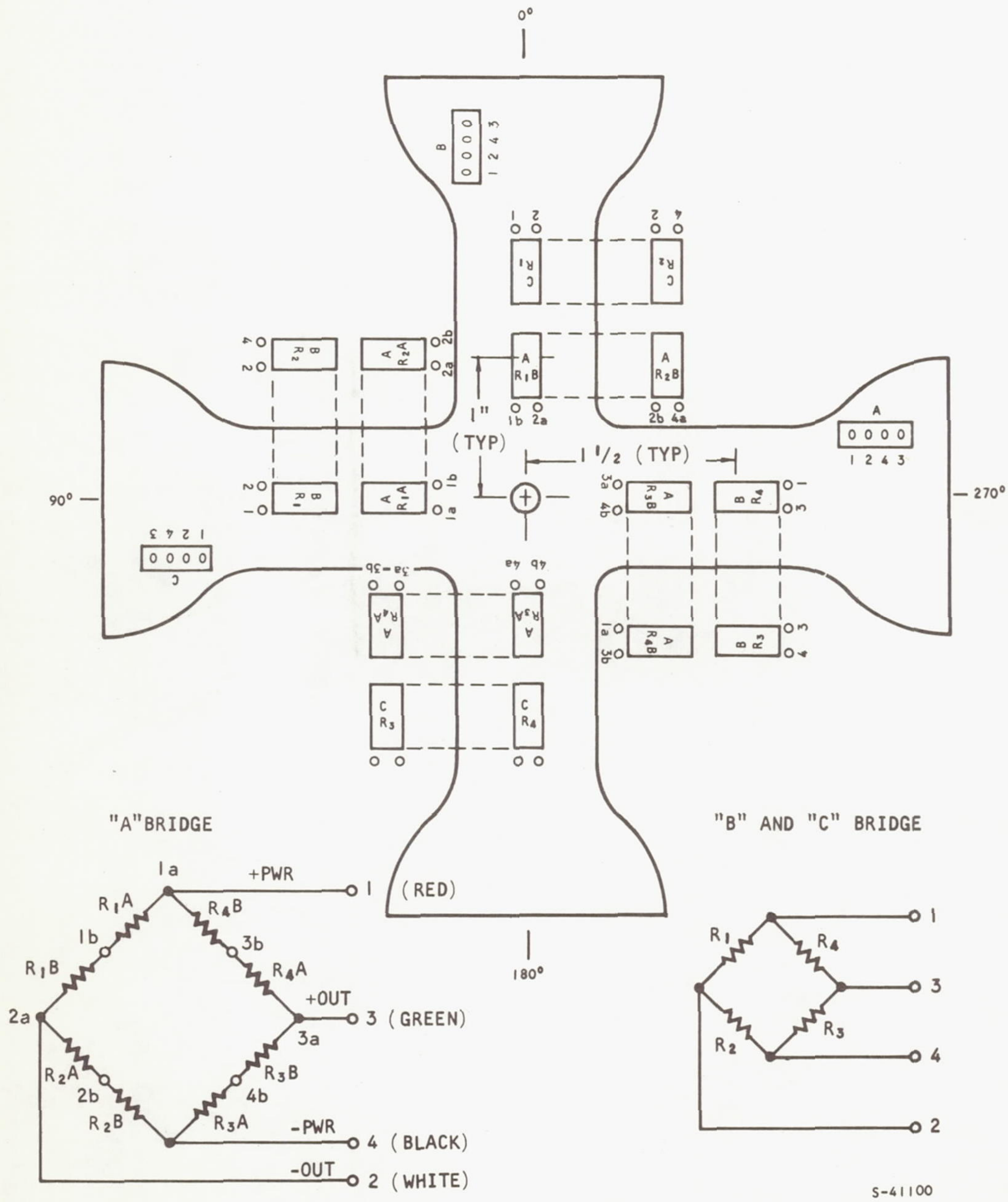


Figure 2-22. Thrust and Bending Flexure Load Cell

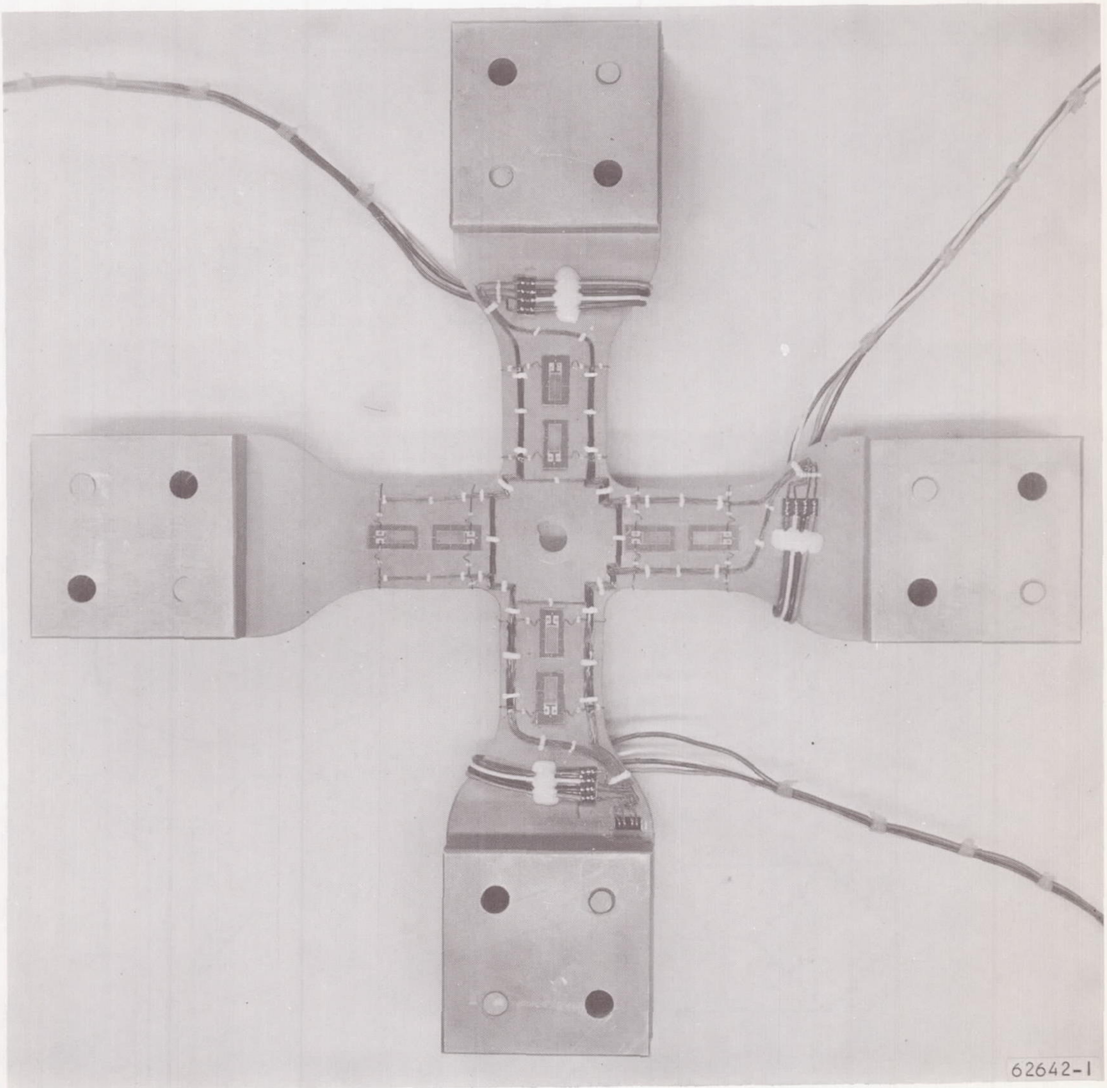


Figure 2-23. Thrust and Bending Flexure Load Cell

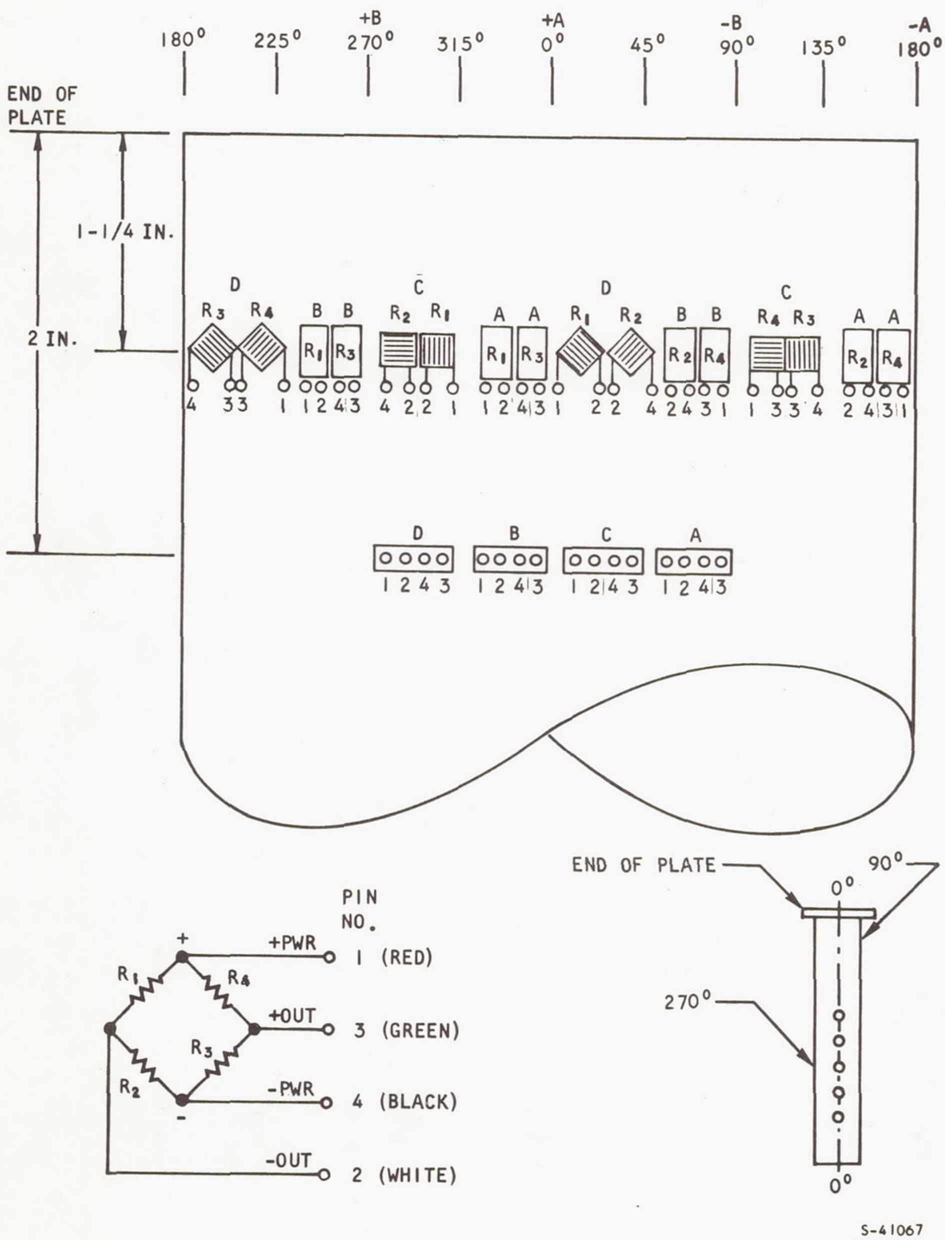


Figure 2-24. Cage and Foot Restraint Load Cell

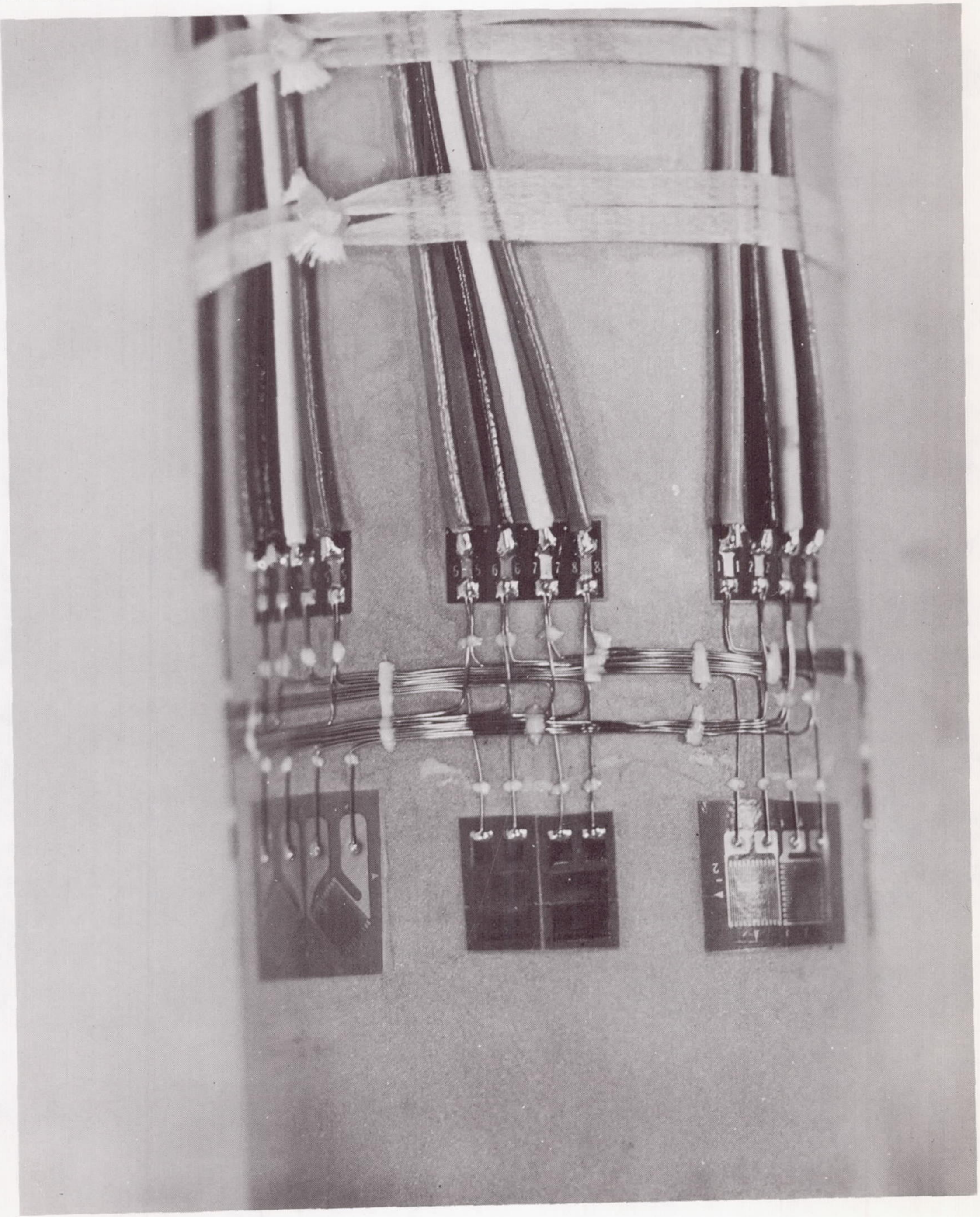
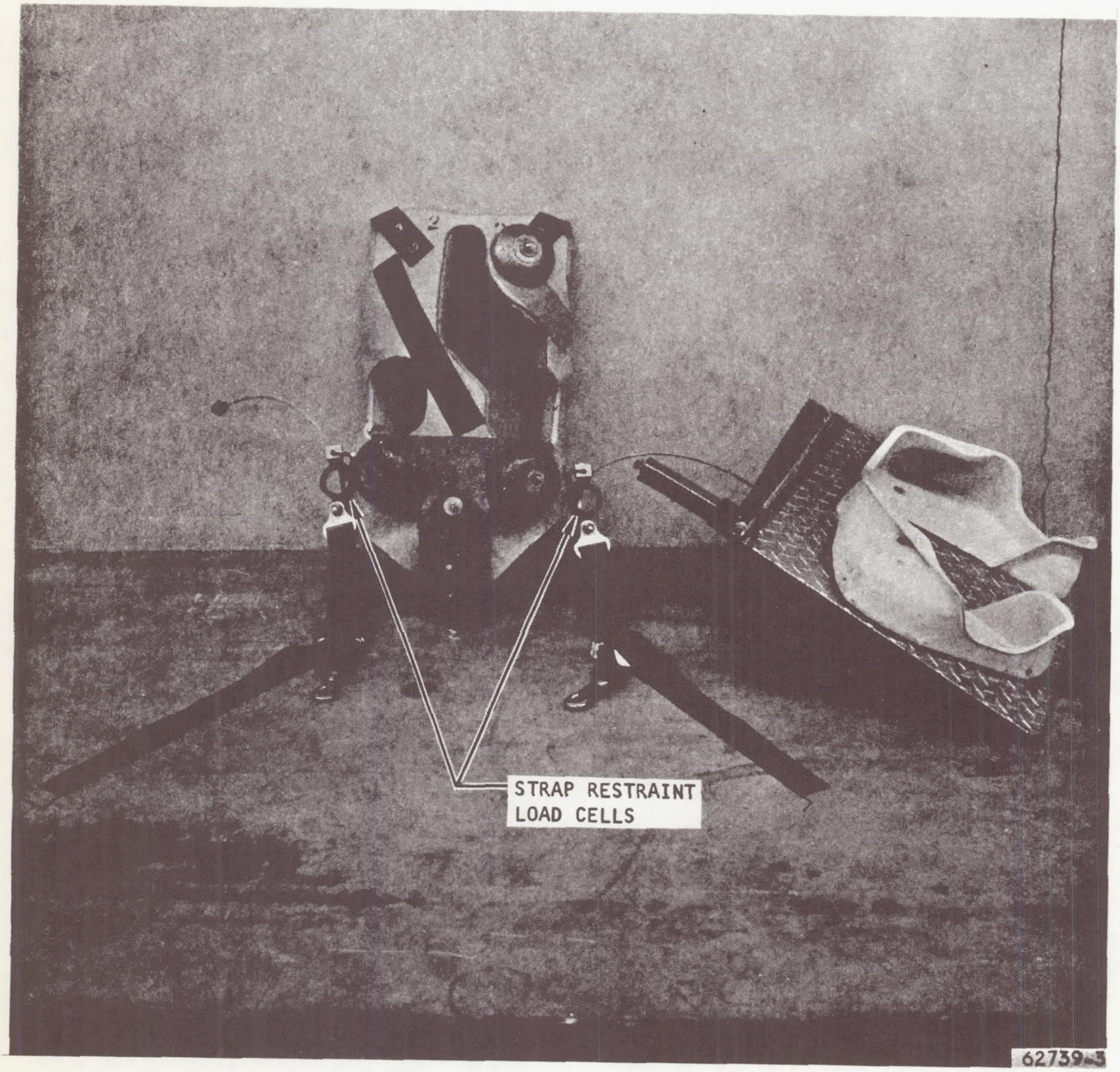


Figure 2-25. Foot and Cage Restraint Load Cell



F-9119-A

Figure 2-26. Strap Restraints with Load Cell
Gemini 12 Foot Restraints

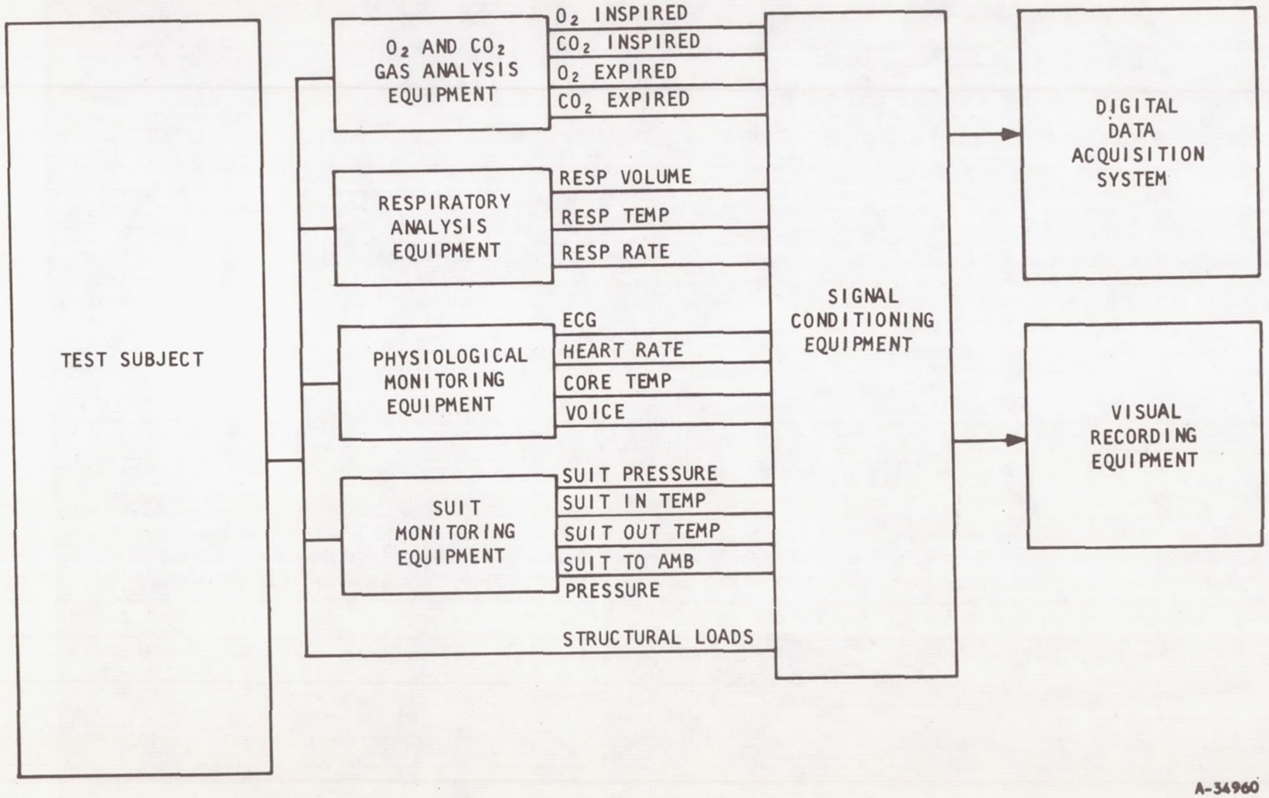
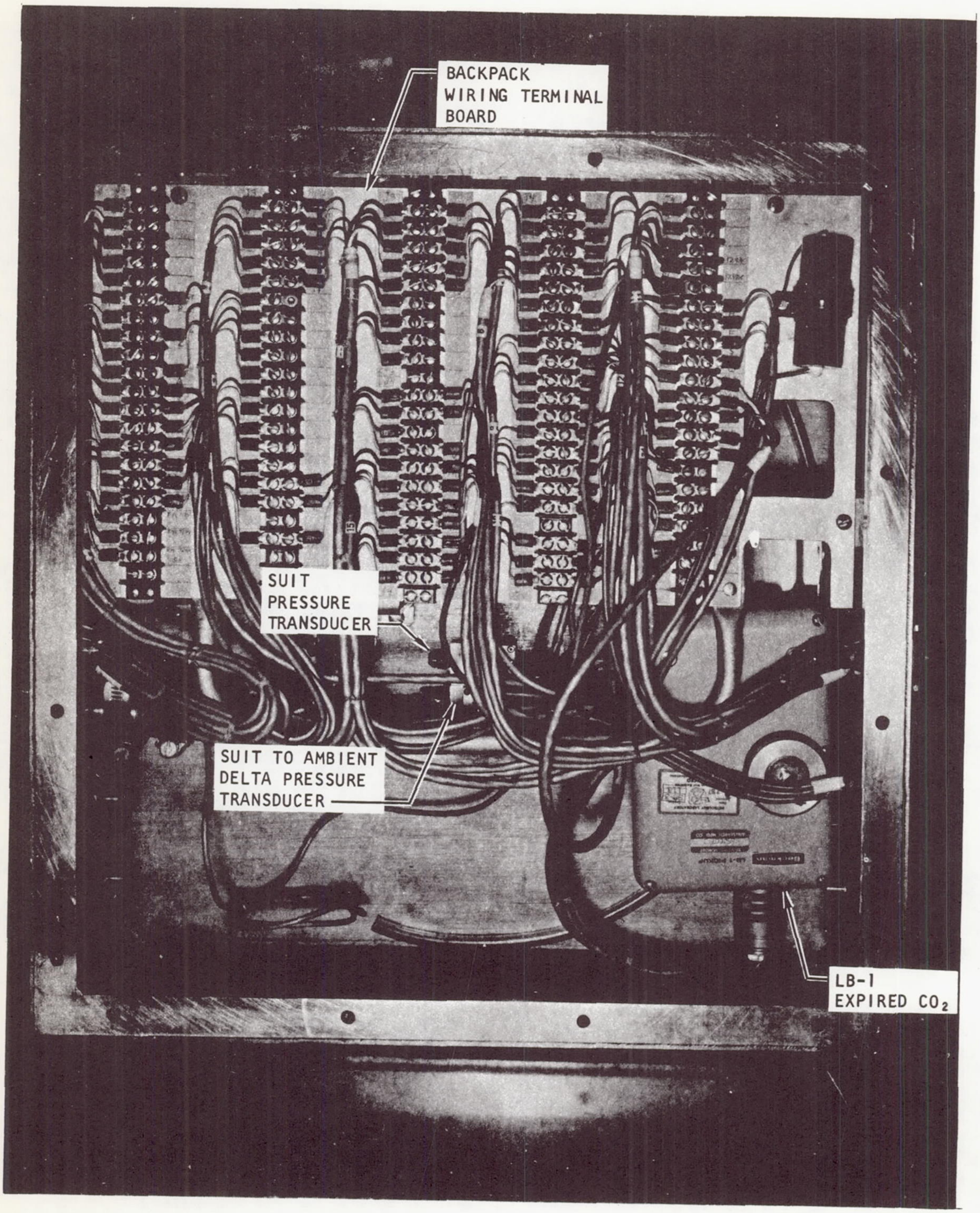


Figure 2-27. EVA Data Collection System Block Diagram



F-9120

Figure 2-28. Internal View of Backpack

The sensing equipment used to provide an electrical output proportional to the partial pressure of oxygen was the Technology Inc. Model pO 160L oxygen meter using a temperature-compensated oxygen polarographic electrode and an amplifying system with a meter readout. The sensing equipment used to provide an electrical output proportional to the percentage of carbon dioxide was the Beckman Model LB-1 medical gas analyzer using a microcatheter sample cell and an amplifier system with a meter readout. In addition to the LB-1 system, the data system uses an LB-1 linearizer to condition the data prior to entry into the DDS. The inspired gases were sensed in the subject's oxygen delivery system, and the expired gases were sensed on the expired side with the sensors mounted in the backpack unit (Figure 2-28).

2. Respiratory analysis equipment.--The respiratory expiration cycle of the subject under test was plumbed to a Franz-Mueller respiration gas meter modified to include a continuous potentiometric output proportional to the liter measurement chamber system. Each rotation of the potentiometer was the equivalent of a 2-l volumetric change. The respired gas temperature was sensed by mounting a thermistor in the gas meter plumbing. Respiration rate was sensed by two thermistors electrically connected in series and mounted in the mouthpiece (Figure 2-29). The two thermistors were mechanically isolated by valving so that one thermistor sensed the inspiration and the second thermistor sensed the expiration (Figure 2-30). The potentiometric output of the gas meter and the cyclic variation of the respiratory thermistors were connected to individual (ramp generator) counters which count and store the pulses generated.

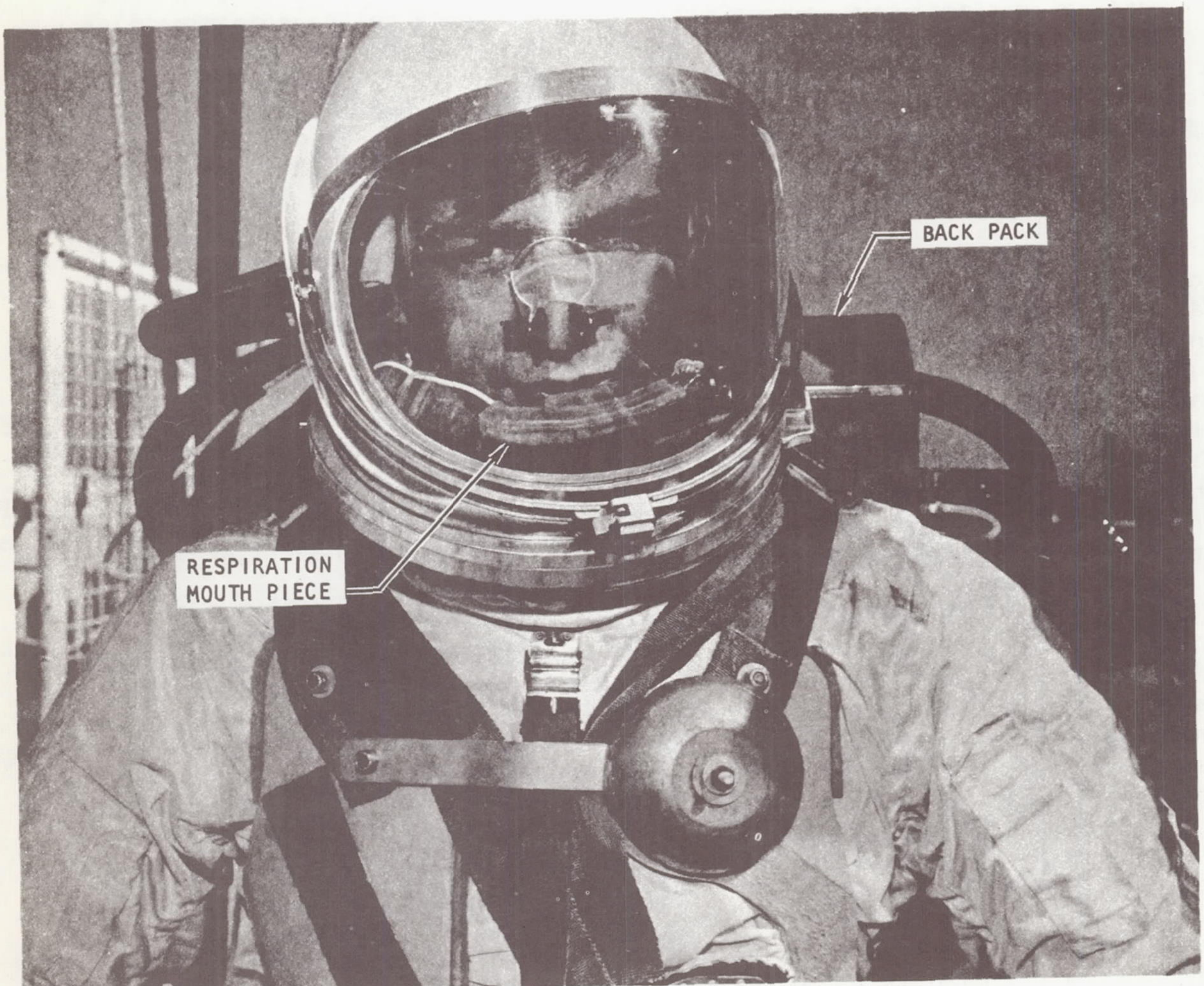
3. Physiologic monitoring equipment.--The physical well-being of the test subjects, while under test conditions, was monitored by sternal ECG electrodes and by a core (rectal) temperature probe. These sensors generated two-level electrical signals and did not require conversion prior to recording. Voice communication was maintained at all times between the test conductor and the test subject. Heart rate was determined by counting the R phase of the ECG signal on a minute-to-minute basis.

Very high heart rates are potentially dangerous. During the performance of a task, the test was immediately stopped if the subject's heart rate exceeded 180 beats per min or if the heart rate exceeded 170 beats per min for more than 3 min. These limitations are within widely recognized safety standards. High body temperature also is potentially dangerous. If the T_R exceeded 102°F, the test was ended.

The ECG and T_R were written out directly by an ink-writing recorder for immediate evaluation.

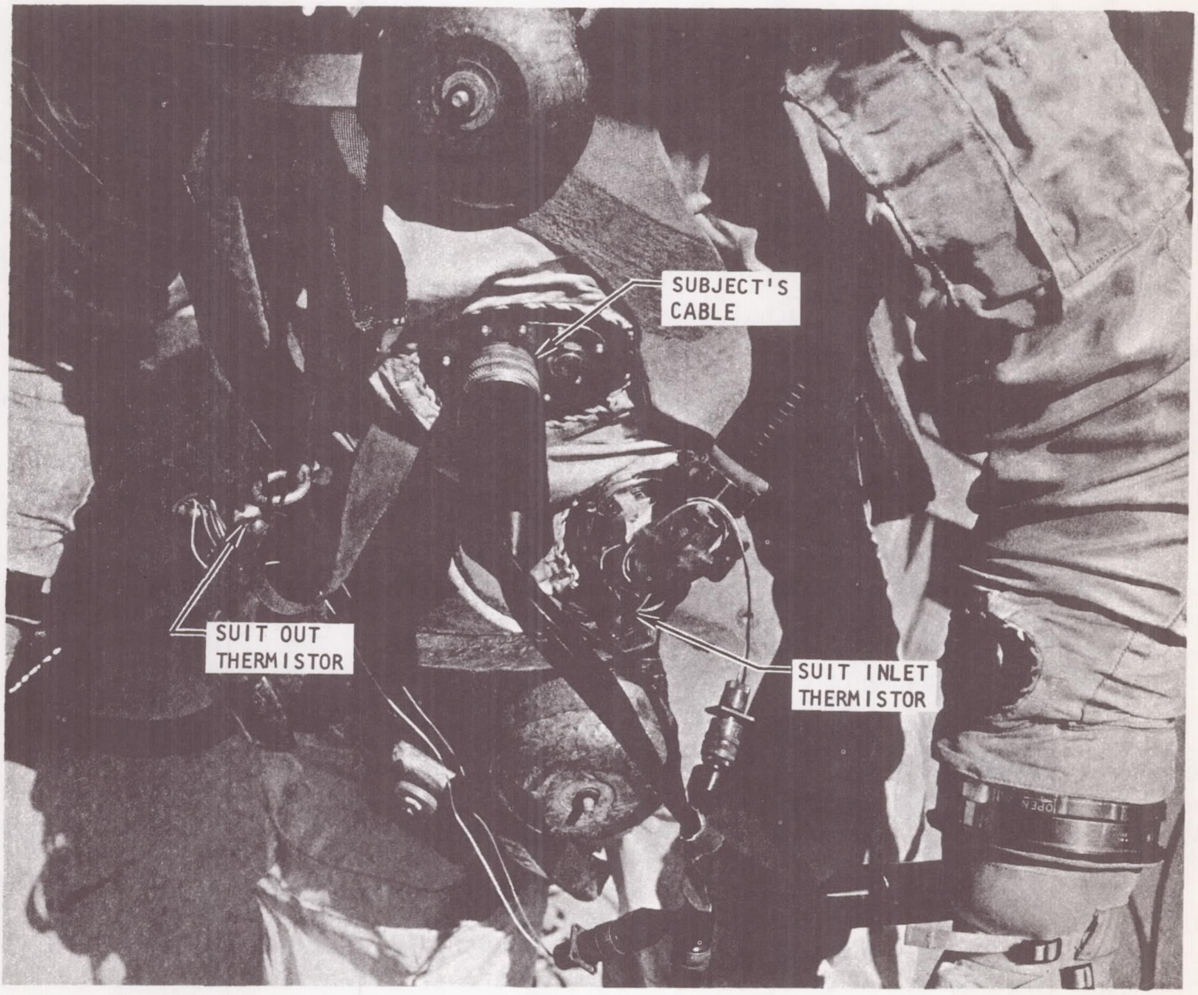
Heart rates were measured from an electrocardiogram (ECG). Although the ECG was used mainly for safety reasons, it is also a general indicator of work load.

Rectal temperature (T_R) as an indicator of body core temperature was contionously monitored. Most of the energy expended while working is dissipated as heat. If the body cannot rid itself of this heat as fast as it is produced, the core temperature will rise. As with the ECG, the T_R was mainly monitored for safety reasons.



F-9116

Figure 2-29. Suited Test Subject



F-9118

Figure 2-30. Air Supply and Subject's System Cabling

4. Suit monitoring equipment.--The suit inlet and outlet temperature, suit gases, and suit pressure parameters were measured while the suit flow was maintained at 5.19 to 5.66 l/sec, and the suit pressure was maintained at 2460.8 kg/m^2. These conditions were manually controlled, and the deviations were recorded on the data collection system for correction factor to improve the metabolic data accuracy.

The inlet and outlet temperatures were sensed using thermistors located in the inlet and outlet suit coupling fittings. The suit pressure was sensed using a Statham 0- to 25-psia strain gage pressure transducer (P/N PA 295TC-25-350). The suit-to-ambient differential pressure was sensed using a Statham 0- to 5-psid strain gage pressure transducer (P/N PL 295TC-5-350). Both pressure transducers were located in the backpack unit.

Physiologic parameters.--The physiologic parameters, ECG, rectal, voice, and respiration from the mouthpiece were cabled into the suit via the subject's cable (Figure 2-30).

Digital system.--The digital data acquisition system consists of a 20-channel multiplexing unit, an amplifier, an analog-to-digital converter, a buffer unit, and a tape perforator. Figure 2-31 illustrates this system in a block diagram. Figure 2-32 shows the digital system and the other recorders.

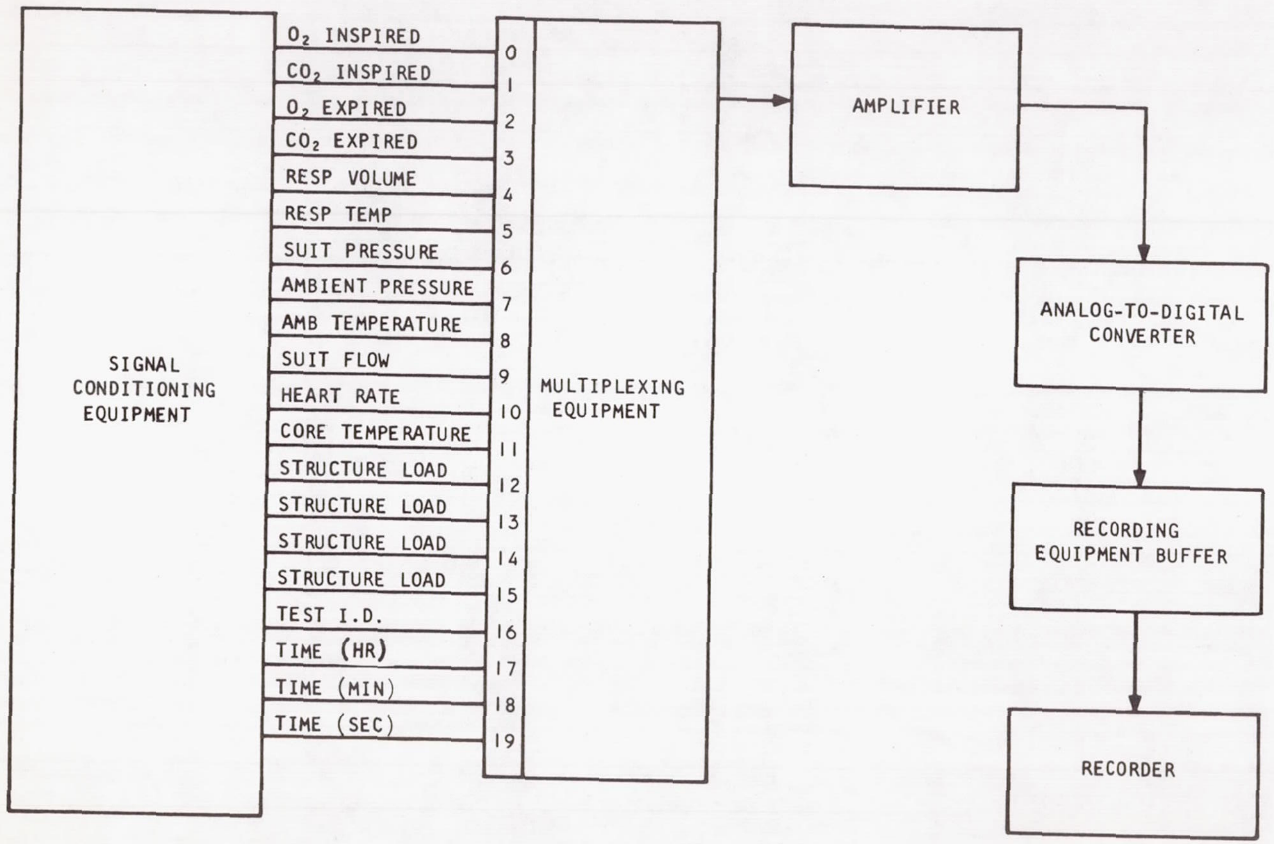
All parameters require signal conditioning prior to recording the information. Power, sensitivity, balance, and range adjustments are included in the signal conditioning equipment. All information to be recorded on the digital system are conditioned for an output of 0 to 10.0 mv dc. The digital system consists of the equipment described below.

1. 20-Channel multiplexer unit.--The multiplexer is a 3-pole relay switching unit capable of a maximum switching rate of 5 ms per channel with a cycle operating life of 10^9 cycles. The 20 channels of information are sequentially sampled every 2 min. The output (low level) is presented to the amplifier.

2. Amplifier unit.--The amplifier is a solid-state, wideband, differential, low-level dc amplifier with an integrated power supply. The amplifier is designed for use in data acquisition systems. Wide bandwidth, fast settling time, and high common-mode rejection add to the overall versatility of the amplifier.

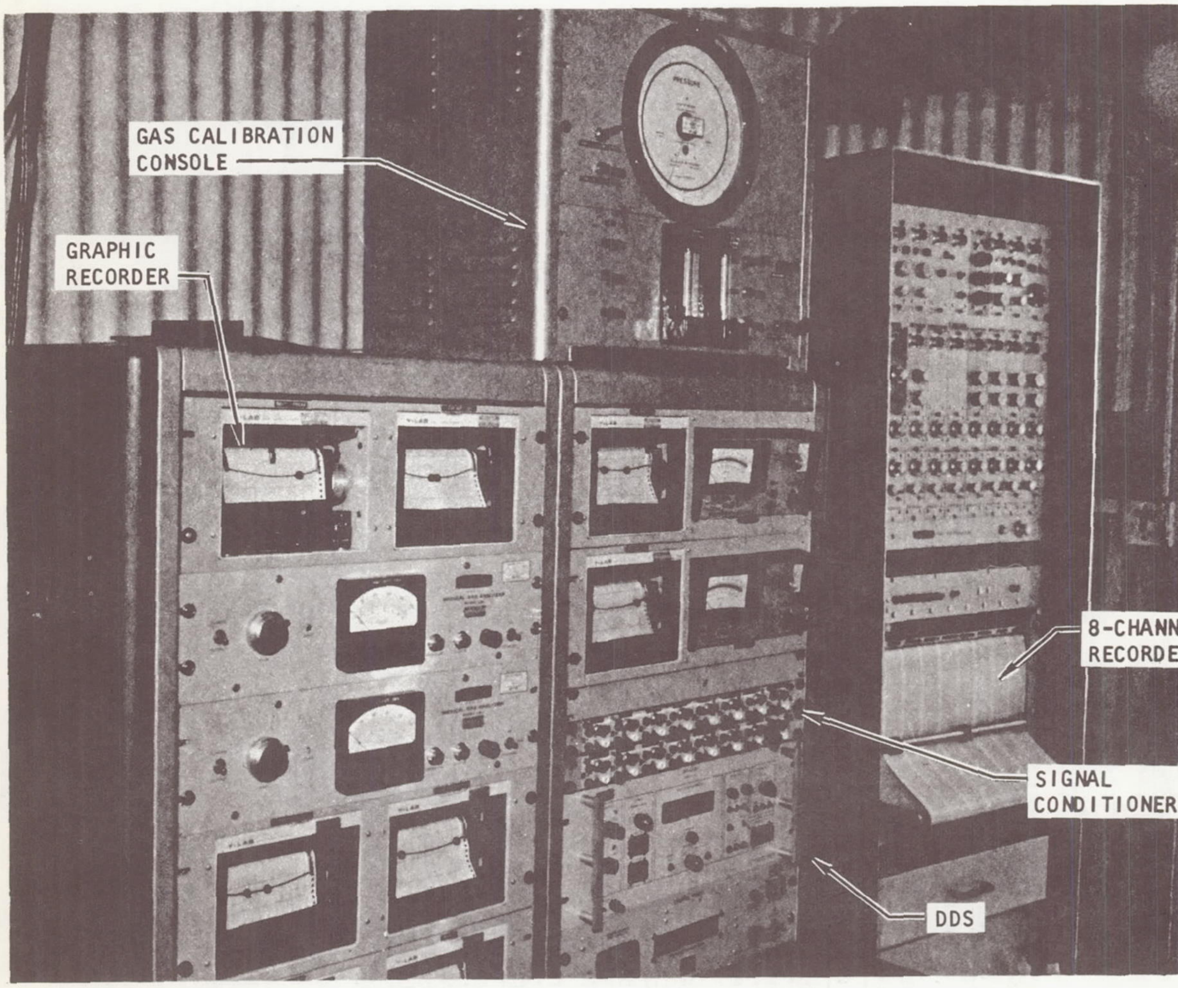
3. Analog-to-digital converter.--The analog-to-digital converter is a solid-state converter with an overall accuracy of ±0.01-percent accuracy. A conversion rate of 33 μsec per bit, producing a 12-bit binary output, contains a front panel sign and decimal presentation of the output of each channel during sampling.

4. Teletypewriter buffer unit.--The buffer unit accepts the binary output of the analog-to-digital converter and the binary output of the time of day and elapsed time digital clock and sequences the digital data to the ASC II code converter. The buffer unit programs the data to the tape punch perforator for collection of the information.



A-30151

Figure 2-31. Digital Data Acquisition System



F-9121

Figure 2-32. Data Console

5. Tape punch perforator unit.--The tape punch unit accepts the data from the buffer unit and punches the data in the ASC II code for use on the teletypewriter computer entry unit. Figure 2-33 shows a typical punched tape.

Data Collection and Analysis

The methods of data collection and analysis vary slightly for each type of test. This discussion outlines the procedures for each data type and the variations in data handling for different tests. The general plan for data collection and analysis is summarized in Table 2-1.

TABLE 2-1

DATA COLLECTION AND ANALYSIS PLAN

Data Type	Sensor	Recorder	Data Converter	Data Analyzer
Performance adequacy	Human engineering observer	Observer and note pad	Observer working rough notes	Observer making final judgments
Performance adequacy	Motion picture camera	Movies	Motion picture projector	Expert interpretation of films
Time	Observer with stop-watches	Observer with task sequence form	Human analyst	Computer and analyst
Energy expenditure	Respiration sensors	Digital data system	Computer	Computer
Physiological parameters	Heart, etc., sensors	Digital data system	Computer	Computer
Transmission preactive force	Strain gages	Analog	Hand	Hand

Performance records were made directly by a motion picture camera and by a human engineering observer. The observer updated his notes daily. This record of his observations will serve as partial data for the report. Motion picture records of tests provided backup data for the observer. The motion pictures of a test are studied along with the daily notes for data evaluation.

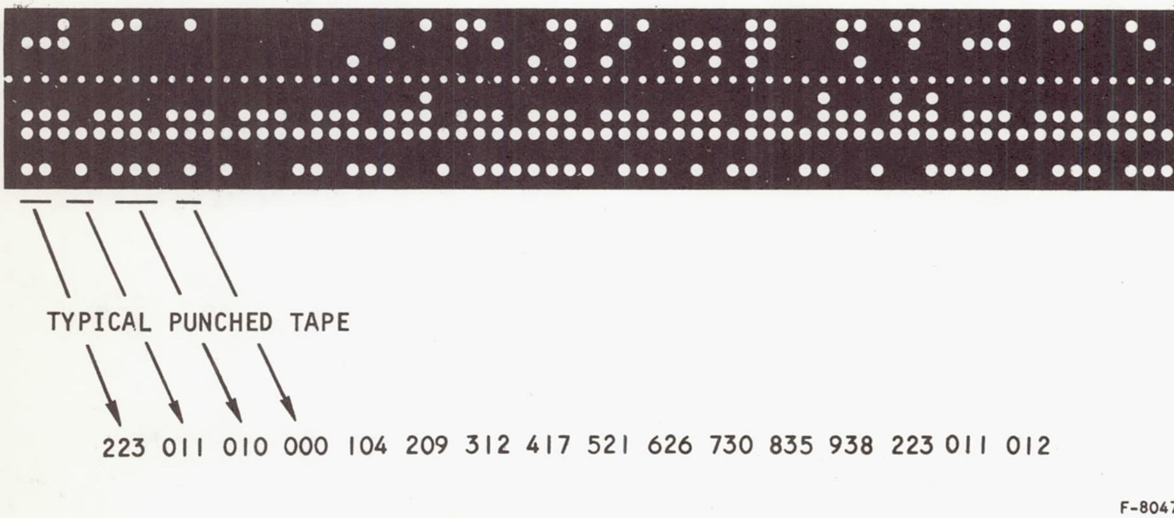


Figure 2-33. Data on Punched Tape and Printed Out

The time record of the tests was kept by a standard stopwatch board method used in similar tests. The forms on which the time was recorded were the same as those used by the observer. The forms and the timing points were developed by the observer and checked for their usability and the dependability of resultant times during subject training. Time records were used in some statistical analysis.

DAILY TEST PROTOCOL

A daily schedule was established to acquaint the subject, data collectors, and other test personnel with the sequence of events. Duties and procedures were established for each member of the test team, and all personnel were oriented and briefed for each day of testing. This information was also supplied as a daily test schedule and posted in advance of each day of testing. The checkout of the suit, subject, and support equipment were conducted simultaneously. During the subject preparation time, test personnel calibrated all gas analyzers and bioinstrumentation to ensure accuracy of data acquisition.

In-tank readiness of mockups, modules, restraints, tools, and other support equipment was performed by the scuba divers while the subject was being readied for the test. The subject entered the simulator with the appropriate harness, shell, weights, instrumentation, etc. The subject was submerged on the upper-level platform, and a final formal checkout was made for all parameters. This checkout was conducted to an established checklist and in a standardized manner. Following the checkout and prior to beginning the test, a resting metabolic measurement of the subject was taken.

After the test conductor was satisfied that all instruments were functional and calibrated and that the subject was ready, the test was started.

Each test was carried out according to the task sequence developed for the specific test condition. Task-element times were recorded for each task of the test mode. Metabolic rates, reactive loads, heart rates, respiratory rates, and core temperatures were monitored continuously over the entire test period. Physiologic data were recorded in 2-min blocks.

TEST PERSONNEL

During the immersion tests, the test team consisted of the following:

Test conductor	1
Human engineering observer	1
Time and motion observer	1
Instrumentation technician	1
Scuba divers (safety)	2
Safety observer (medical)	1
Photographer (as required)	1
Subjects	6
Suit technician	1

All the test crew assigned to carry out the tests had prior experience in neutral-buoyancy testing, in addition to being experts within their assigned field. Once selected, the personnel were permanently assigned to the program. To alleviate the difficulty of reassigning personnel in case of sickness or accident, a detailed duty sheet was prepared to provide a set of complete instructions and a daily checklist. The duty sheet was prepared for each team member.

SECTION 3

SUBJECTS

A test panel of eight healthy male subjects was chosen for these experiments. Of these eight, six actually participated in the tests. The anthropometric characteristics of the subjects participating are shown in Table 3-I. It is immediately apparent from the body surface area data that the subjects' characteristics are similar and compare favorably with the average astronaut population. The consistency in the sizes of the individuals resulted from the requirement for the subjects to fit the Gemini series pressure suits used in the tests. This consistency is advantageous because it aids in minimizing differences in metabolic rates between individuals. Also, the test subject population, with the exception of subject C.B., fits the age group of the younger astronauts.

The notes shown in Table 3-I indicate the tests each subject performed.

TABLE 3-I

SUBJECT'S ANTHROPOMETRIC CHARACTERISTICS

Subject	Age in Years	Height		Weight		Body Surface Area, m^2
		in.	cm	lb	kg	
C.B.	22	69 3/4	177.2	168	76.3	1.75
R.B.	30	70	177.8	154 1/2	70.1	1.69
D.L.*	28	68 1/4	173.4	169	76.7	1.72
L.P.**	33	70 1/2	179.1	157	71.3	1.71
A.P.***	30	69 1/2	176.5	163	74.0	1.72
R.W.**	32	70 1/2	179.1	163 1/2	74.2	1.74

Notes: All subjects performed each restraint test
All subjects participated in the cargo exploratory tests
* Participated in the rescue exploratory tests
** Participated in the large module exploratory tests

SECTION 4

TEST DESCRIPTION AND RESULTS

GENERAL

This program continues an earlier study effort performed under NASA Contract NAS 1-5875 to investigate extravehicular maintenance tasks and the assembly of large components in a weightless condition of neutral-bouyancy underwater simulation. Since little was known about the capability of a pressure-suited man to perform work in a 0-g environment, much of the work of this study was broad in scope and exploratory in nature. The following problem areas were considered critical to projected EVA work and were designated for exploratory investigative study:

(a) Problems in the assembly of large modules

(b) Problems in astronaut rescue from EVA

(c) Problems in cargo transport and manipulation for EVA

(d) Problems in restraint devices. Four astronaut restraint devices were compared under experimental conditions during a maintenance task involving six subjects. This experiment was oriented toward obtaining precise and statistically significant comparative data on performance, metabolic cost, and physiologic parameters for different restraints in maintenance work in a weightless condition.

Due to the exploratory nature of these studies, test data are presented for individual tests, and no means, standard deviation, or other statistical treatment of these data can be made. Because of the limited number of observations made during these tests, great care must be taken in forming generalizations from these data.

The human engineering procedures during this study were based on the knowledge that much of the meaningful information relative to the man/machine interface must be gained by directly observing the tasks performed. In this respect, notes of the tasks were entered on the checklist during the test situation. The primary source of data for the checklist is the task-performance time measured by manually manipulated stopwatches. An additional source of data, relative to the man/machine interface, is the motion picture films taken to furnish an unchanging data source that could be reused for analytical purposes. Experience has demonstrated that, as the analysis of the man/machine interface progresses, reexamination of the film helps to clarify data and substantiate observations.

Many observations relative to the man-machine interaction are subjective. However, information about the numerous simultaneous interactions of the test variables occurring in weightless simulation is needed. Only obvious conclusions are drawn from the subjective observations.

The physiologic data obtained were evaluated by two techniques. Such treatment was governed by the two types of experiments performed.

Data of tests that were exploratory in nature were plotted along a performance time line because the subjects were always in a dynamic state rather than in a steady state. Physiologic data from this type of testing represent the changes that occurred and cannot be compared with data derived under other conditions. Since the subjects were allowed to set their own work pace and to modify tasks to ensure their completion, the physiologic data can only be used as a comparison between resting values and peak values for each type of test and as a correlation to the human factors observations.

The restraint studies were designed to evaluate four restraint systems. In developing the tasks for these tests, a complex task with 11 subtasks was developed. The various subtasks, which differed in nature, required from short to long periods to perform and ranged from very light work to the imparting of high impulsive loads for short periods. Thus, during the performance of these tests, as in the exploratory tests, the subjects were never in a steady state. A common denominator in these tests, however, permitted an objective evaluation of the metabolic rate data. Each of the six subjects was required to perform the same amount of work on the task box with each restraint system. Thus, the total energy required to perform the total task was determined for each restraint system, and statistical comparisons were made by multiple analysis of variance and by student's "t" test. The data used for analysis were derived in the following manner. Each test was carried out so that, after neutral-bouyancy balancing, the subject was moved to his work position and rested while a final instrumentation checkout was performed. After a 4- to 6-min interval of resting, physiologic data were recorded, and the subject commenced work. The total work period was determined by the subject's dexterity to perform the various tasks. After the work period, data were recorded for another 4 to 6 min. Computer techniques reduced these raw data to meaningful data. The resting metabolic data for each subject were subtracted from the total energy expenditure for the work and postwork recording intervals. The increase above the resting metabolic rates value was then summed over the entire period and is noted as the total energy required to perform the 11 subtasks.

Table 4-I shows the general environmental conditions for the neutral-buoyancy tests. Determining the suit inlet ventilating gas temperature by the ambient water temperature is one obvious characteristic of the environment and a major difference between this type of simulation and those carried out in an air environment. Due to the large heat sink provided by the water mass, conductive cooling becomes a prime method of heat transfer of this environment. The effect of heat transfer on the physiologic data obtained during this type of simulation is not understood. The high total pressure and the drag forces of the water are also complicating environmental conditions.

TABLE 4-I

TABLE OF TEST CONDITIONS

Parameter	Average Range
Suit/water ambient ΔP, psi	3.5 ±0.1
Suit inlet ventilating gas temperature, ^{o}F	79 ±1°
Suit outlet ventilating gas temperature, ^{o}F	84 ±2°
Suit ventilation flow rate, scfm	17 ±1
Suit total pressure, psig	24.3 ±1
Water temperature, ^{o}F	79 ±1°
Water depth (at approximate c.g. of man), ft	14 ±1
Water pressure, psig	20.8 ±0.4
Staytime in the suit, hr	3 ±0.5
G field	1 g but neutrally buoyant

EXPLORATORY ASSEMBLY OF LARGE MODULES

This series of tests was structured around a module previously assembled in tests under NASA Contract No. NAS 1-5875. The basic modular hardware for this erection is illustrated in Figure 4-1. The test purpose was to examine the problem areas associated with:

- Mating and securing beams
- Mating and securing modules and panels
- Using locomotion aids
- Tethering modules
- Stopping the motion of modules

Procedures and Test Apparatus

The task selected to evaluate these problems was the assembly and mating of two cylindrical sections each 4 ft high and 10 ft in diameter.

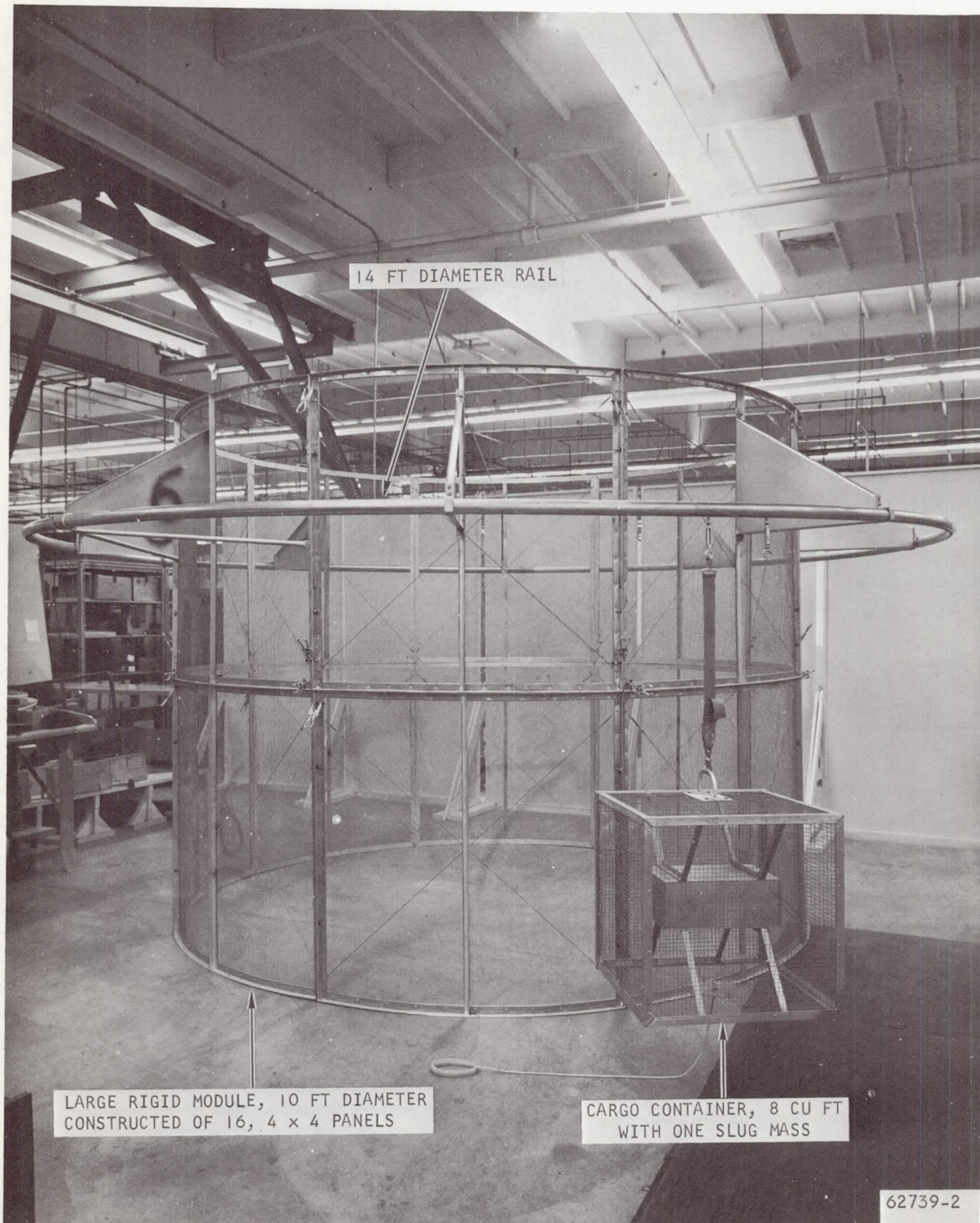


Figure 4-1. Rail Structure on Large Rigid Module

As a direct result of prior AiResearch work (NAS CR-859), it was decided to present the hardware to the subject while he remained in a stationary work spot. In the prior study, the subject had been mobile and the module stationary. To assist in the erection, a manually operated panel holder was designed. The subject assembled and attached this panel jig (Figures 4-2 and 4-3) to the mockup. The horizontal panels were modified with a panel containing channels that would hold the panel firmly in an upright position and allow the subject to mate a second panel to it. The connected panels were then pushed in this vertical position to the edge of the holder for the positioning and installation of the third panel. In this manner, the subject assembled the module from a stationary position. Each panel was aligned, fastened, and moved through the holding jig until the first panels returned to the worker and allowed fastening of the last panel to complete the circle.

The panel-holding apparatus was assembled first and attached to the mockup. Its configuration was used to observe the problem associated with mating and securing beams. The emphasis of this phase of testing was exploratory to examine the problems that arose during assembly. Exploratory in this frame of reference means taking corrective steps in the procedures to successfully perform the test. From this orientation, the test was used to examine the problems of mating and securing beams and panels cited in the statement of work.

The definitive task procedures used for the panel-holding jig erection are presented in Figure 4-4. The procedures for panel modules are shown in Figure 4-5.

Observations on Assembly of the Panel-Holding Jig

The joints and connections of the apparatus were loose. Although this arrangement may have assisted in making any individual connection, it made the total unit unstable during assembly. The subject was hampered since the unit also had to be used for his manipulation and support.

The apparatus also proved operational in the cargo transport tests and later as a panel-holding jig. Also, the assembly was accomplished on a one-trial basis with little assistance from the skin divers. Total assembly time was 23 min. Since there were 10 individual items to manipulate and 18 connectionsand reconnections to make, the overall time was acceptable. With proper sizing of the fittings and in-tank-procedure development, this time could possibly be cut by 50 percent.

The observations noted during the test are similar to those noted for the previous tests. If exceptions exist, they are those of degree and not of kind.

Using strap restraints effectively depends on (1) the subject's ability to keep the restraint taut or with a minimum amount of free-play in them and (2) correct positioning of them at the work spot so that the worker is presented to the work in a manner that he can perform the task. This is elementary and all the subjects verbalized their understanding of the concept.

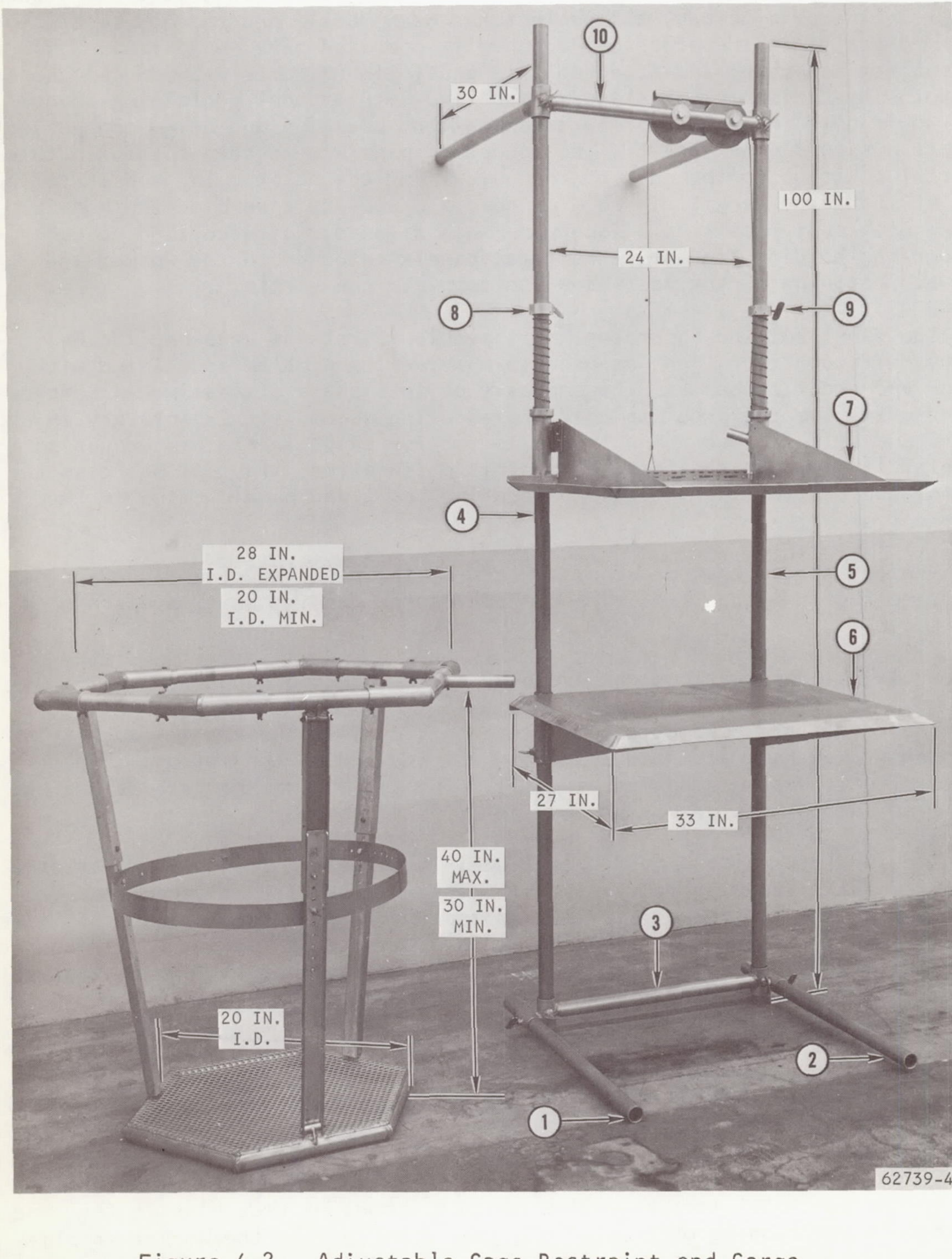


Figure 4-2. Adjustable Cage Restraint and Cargo Module/Panel Holding Jig

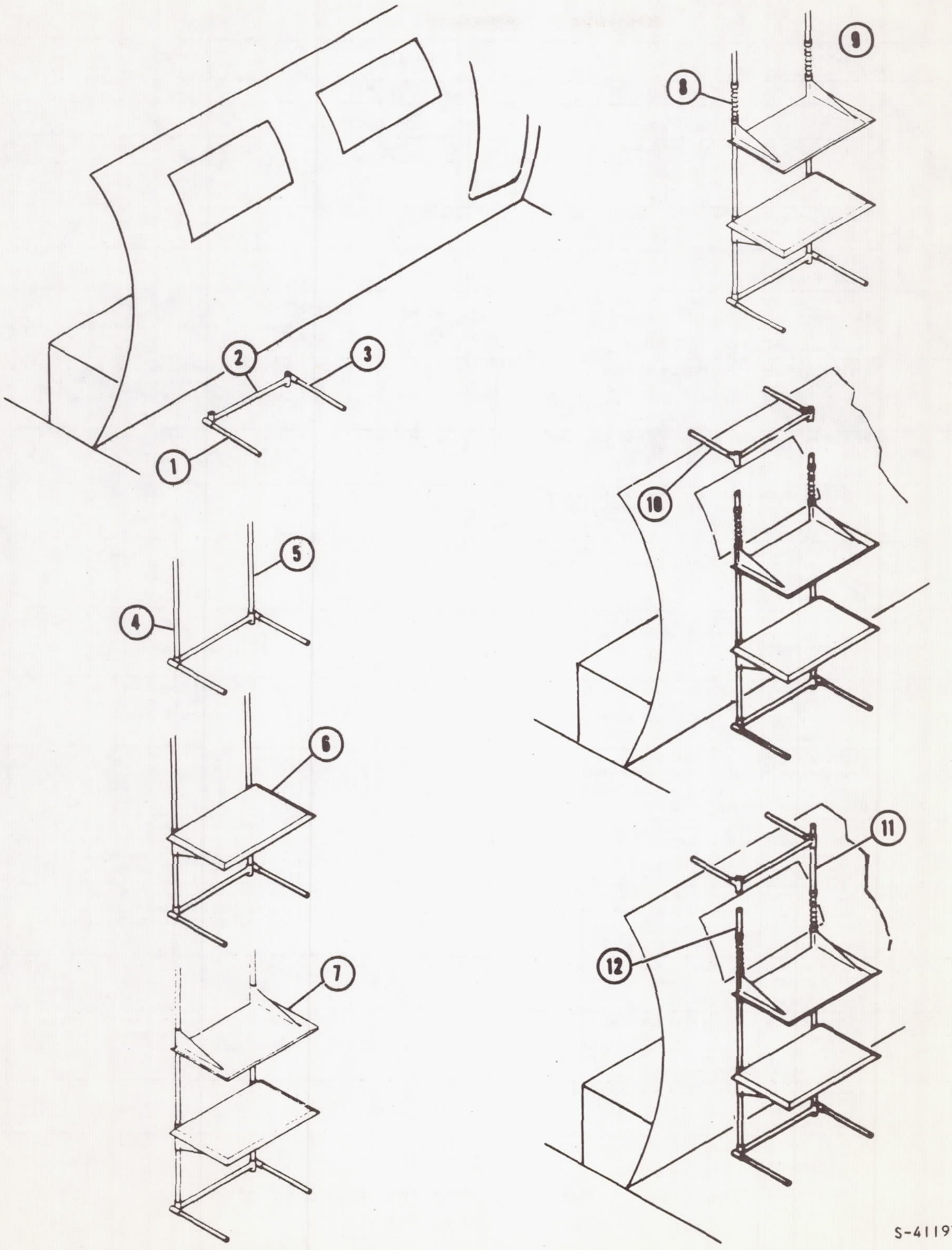


Figure 4-3. Assembly of the Panel Jig

TEST NO. PANEL HOLDING JIG	DATE	SUBJECT	OBSERVER

TASK NO.	TASK TIME		TASK SEQUENCE	EQUIPMENT	REMARKS
1.			Insert and pin lower-left horizontal tube Hand free of pin	Tube 1 (see Figure 5-2)	Skin divers present assembly equipment to subject.
2.			Insert and pin lower-right horizontal tube Hand free of pin	Tube 2	
3.			Position and attach connecting lower divider tube Hand free of tube	Tube 3	
4.			Insert left vertical tube in divider tube connector Hand free of tube	Tube 4	Subject repositions from semiprone to upright position, moving and attaching restraint straps as necessary.
5.			Insert right vertical tube in divider tube connector Hand free of tube	Tube 5	Both items 4 and 5 must be lowered well into their connectors to provide for placement of the two holding platforms.
6.			Position lower platform on vertical tubes and push into low position Hand free of platform	Platform 6	
7.			Position upper platform on vertical tubes and fasten (lightly) just above the lower platform Hand free of platform	Platform 7	
8.			Position spring and locking collar on the left vertical tube. Turn spring clockwise to engage platform collar Hand free of spring	Spring and collar (No. 8)	
9.			Position spring and locking collar on the right vertical tube. Turn spring clockwise to engage platform collar Hand free of spring	Spring and collar (No. 9)	
10.			Position tube assembly in both mockup receptacles, pin left tube, pin right tube Hand free of tube assembly	Tube assembly 10	Subject repositions from upright position to top of mockup, attaching restraint straps as necessary.
11.			Using a twist and lift motion on the right vertical tube, raise to tube assembly and engage thumbscrew connector Hand free of thumbscrew		
12.			Using a twist and lift motion on the left vertical tube, raise to tube assembly and engage thumbscrew connector Hand free of thumbscrew		Subject repositions from top right of jig to top left of jig, attaching restraint straps as necessary.
13			Position top platform to approximately 24 in. of top of vertical tubes. Engage thumbscrew on spring collar Hand free of thumbscrew		Subject repositions from top left of jig to left midpoint of jig, attaching restraint straps as necessary.
14.			Position lower platform to approximately 44 in. of top platform and engage thumbscrew on platform Hand free of thumbscrew		
15.			Align top platform and engage thumbscrew on spring collar Hand free of thumbscrew		Subject repositions from left of jig to right of jig, attaching restraints as necessary.
16.			Align lower platform and engage thumbscrew on platform Hand free of thumbscrew		

Figure 4-4. Task Sequence for Assembly of Panel Holding Jig

TEST NO. ASSEMBLY OF RIGID MODULES	DATE	SUBJECT	OBSERVER

TASK NO.	TASK TIME		TASK SEQUENCE	EQUIPMENT	REMARKS
1.			Procure first panel and position in jig.	Panel 1	Panels have guide pins and holes for aligning. Panels feed along the mockup on trolley rail. Skin diver makes attachment.
2.			Procure second panel and align on panel 1 and activate captive fastener.	Panel 2	All panel fasteners are captive.
3.			Release jig tension and slide panel 1 to the right bringing panel 2 into position in jig. Engage jig on panel 2.		
4.			Repeat steps 3 and 4 for remaining six panels.	Panel 3 through 8	The final task of connecting the back edge of panel 1 to the front edge of panel 8 will actually be a separate step, since the two surfaces must be pulled together and held together while the fastener is being engaged.
5.			Pull panel 1 to edge of panel 8 and hold together with bungee cord. Align pins and engage fasteners.		
6.			Procure first panel for top erection. Align pins and engage fasteners between top and lower panel.	Top panel 1	
7.			Release jig tension and slide module one panel width to left. Engage jig tension on new position.		
8.			Procure second panel align on panel 1 (top) and activate captive fastener.	Top panel 2	
9.			Repeat steps 7 and 8 for remaining six panels.	Top panels 3 through 8	

Figure 4-5. Task Sequence for Assembly of Rigid Modules

However, none of the subjects performed well with strap restraints. The only apparent explanation is that adjustment was too troublesome and time consuming for them. The subjects generally used only one restraint at a time at its maximum length. When fully extended, the strap restraint functions as a tether rather than as a restraint. Altering the restraints to make them easily and quickly manipulated could possibly change the way they tend to be used.

Part of the panel-holding-jig assembly procedure was performed from the cage restraint (Figures 4-6 and 4-7). The only one-handed tasks performed by the subject in the cage was the tightening of the thumbscrew locking devices at the connectors (see Figure 4-8). Handling of the two adjustable shelves of the jigs was performed from the cage restraint using both hands in an exceptionally satisfactory manner. The control, placement, fitting, and securing of the panels were the most difficult and demanding of the jig erection subtask. The difficulty encountered in the one-handed tasks could, to a large extent, be avoided by two-hand performance from a stable work position (see Figures 4-9 through 4-16).

A list of the most likely simulation events was made and a random selection of film was analyzed to tabulate the number of times the events occurred, the time duration of events, and the total time of actual productive work. Table 4-2 summarizes the events. It shows that the time spent manipulating the strap restraints almost equals the productive work time (see Figures 4-17 through 4-22). This is especially significant since only two traverses were made throughout 6 min and 45 sec of uninterrupted performance shown on the film. Of the 18 events, six were work events; the other 12 were support activities.

Observations on the Assembly of the Large Module

The two major faults existing with the assembly and erection of the large rigid modules from the previous tests (NASA Contract No. NAS 1-5875, NASA CR-859) were corrected for the present study. The first problem, i.e., providing the necessary rigidity to the panels, was accomplished by support wires under turnbuckle tension connected from corner to corner on the panel. The second problem, i.e., providing fasteners that secure the panels firmly, are easily and quickly engaged. Associated with the hardware alteration was the change of task procedures from the subject going to the work, to the work being presented to the subject. The latter was believed essential to apply the principles involved regarding restraints, positioning, stability, and work presentation for EVA.

For this test, the subject performed in the cage restraint, tethering himself with a single adjustable strap to the top rung of the cage. This work position allowed the subject the use of both hands to position and engage the panels. Since the subject remained in a stationary work spot, each panel assembly was a repetition of the previous one, except for the difference in the fasteners used. Figures 4-23 through 4-33 illustrate a photographic sequence of the subject procuring, installing, and fastening two of the panels.

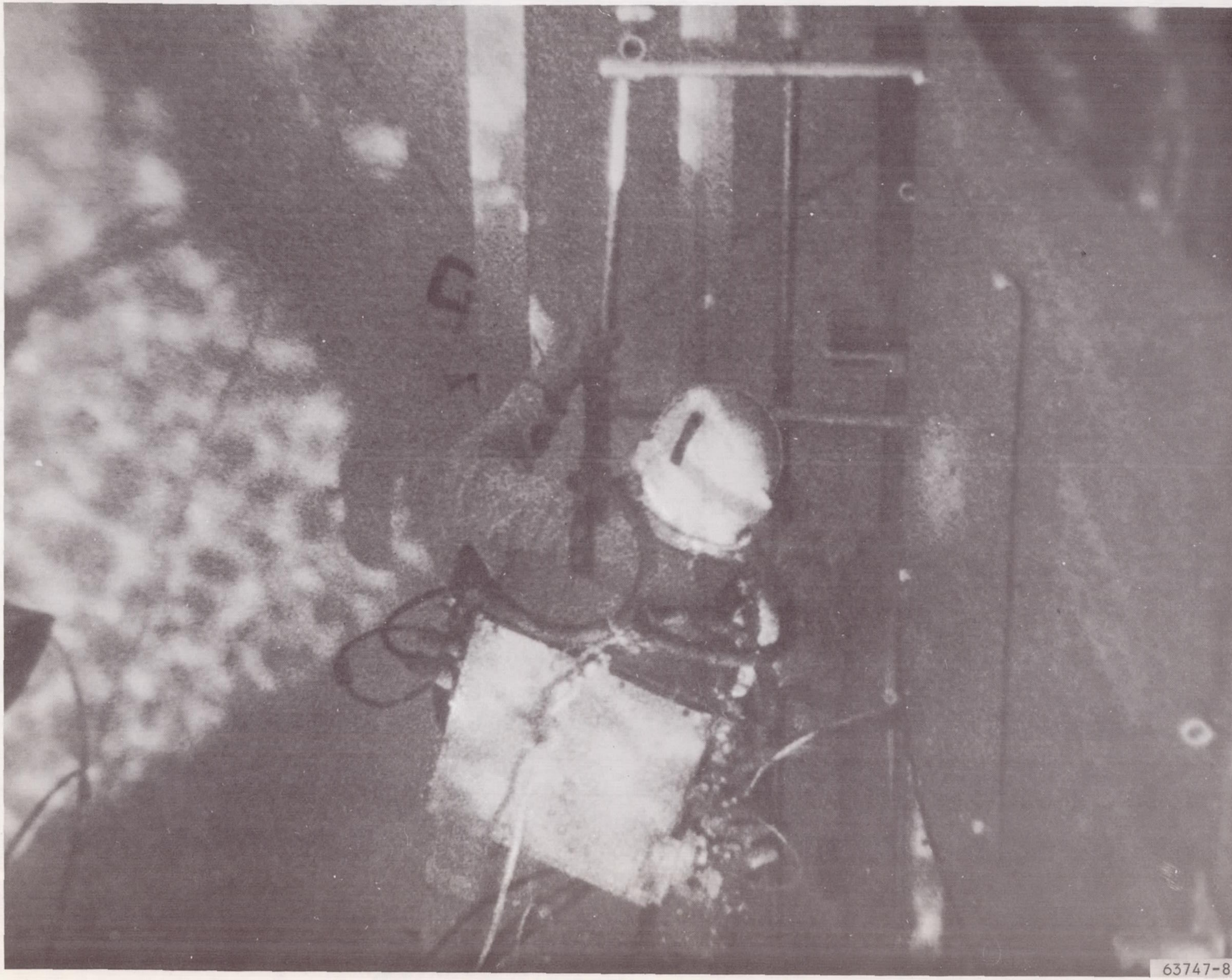


Figure 4-6. Overhead View of Subject Starting Assembly of Panel Holding Jig

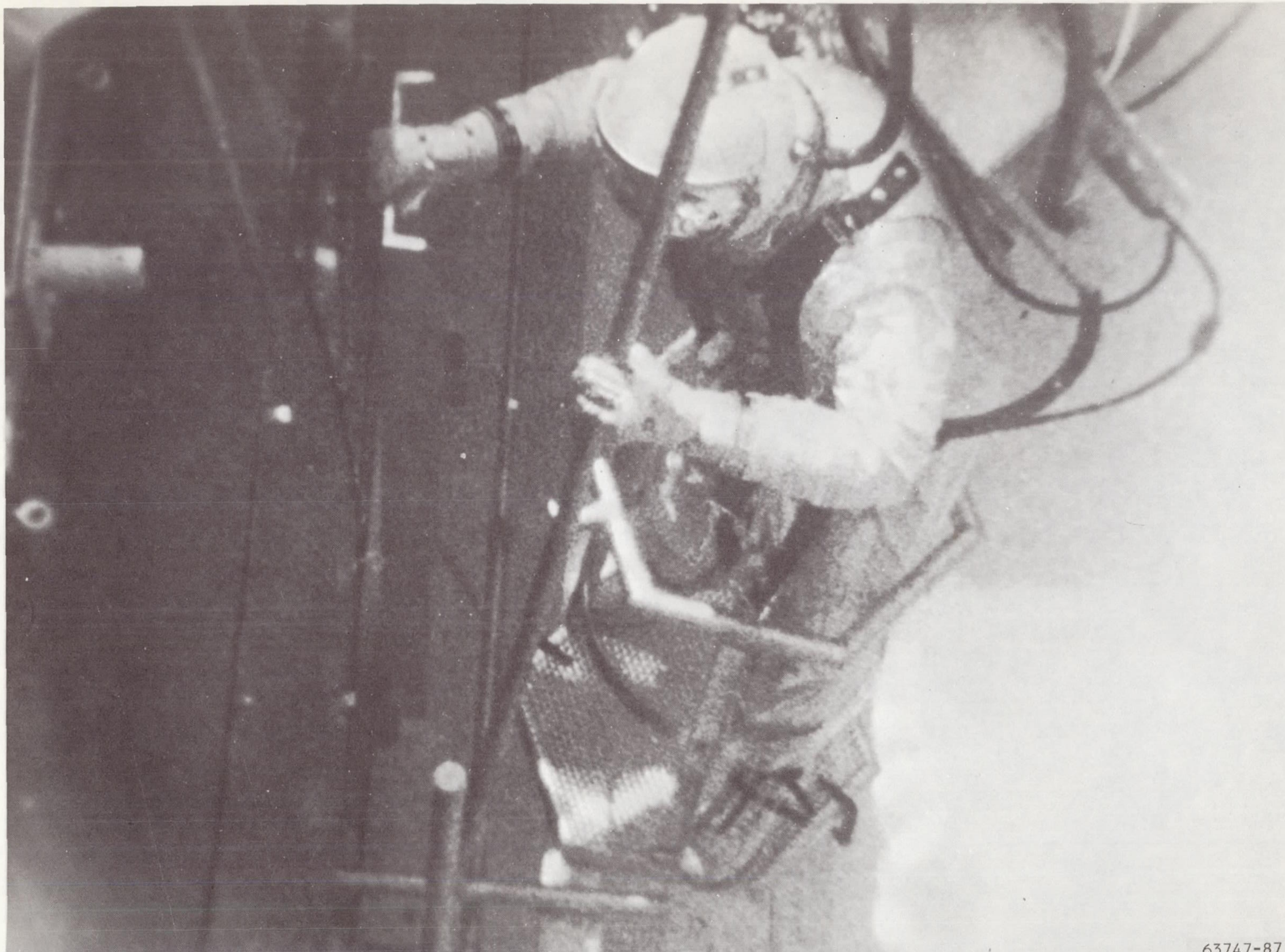


Figure 4-7. Subject Working from Cage During Assembly of Panel Holding Jig

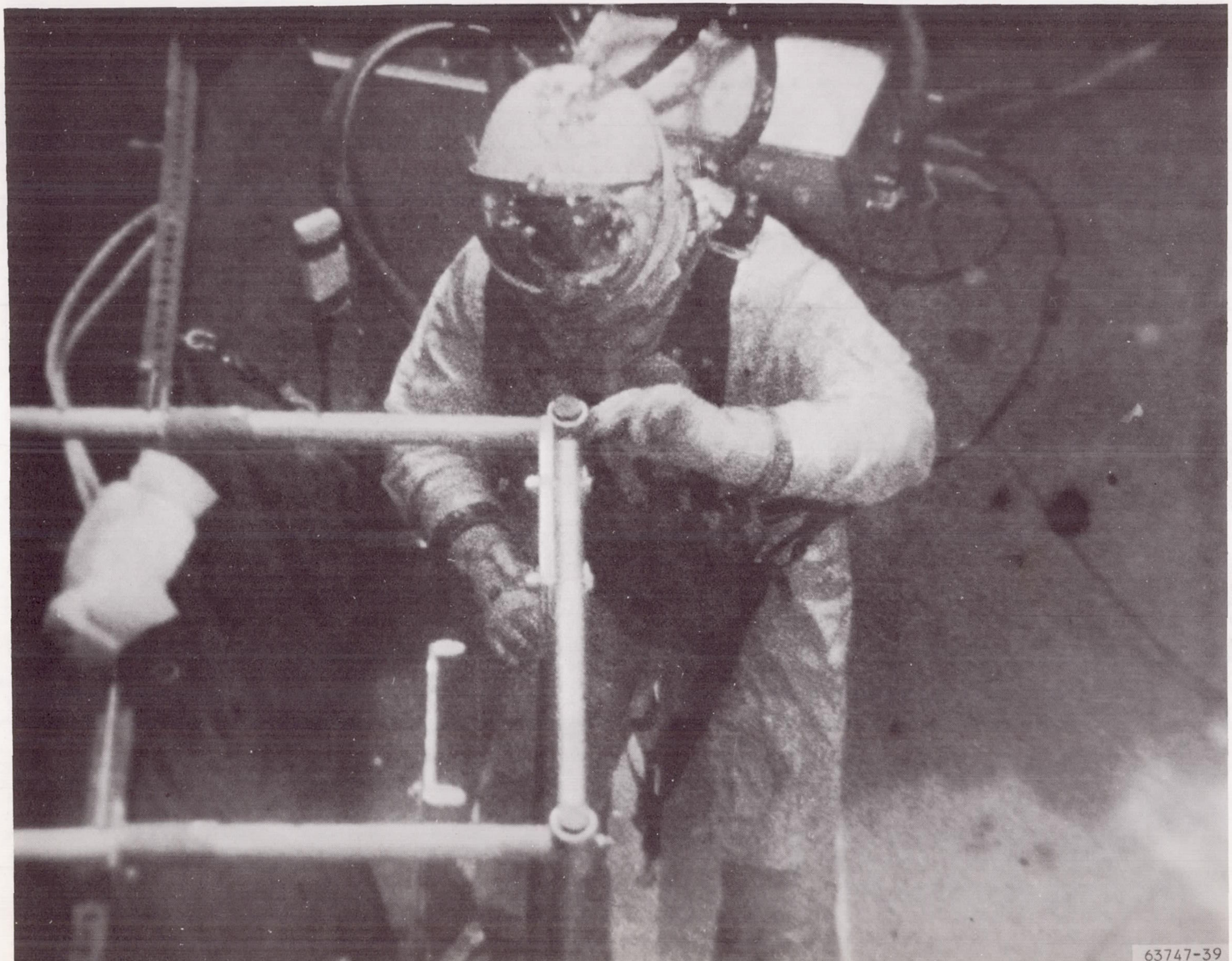


Figure 4-8. Subject Making Thumbscrew Connection on Jig Assembly

Figure 4-9. Subject Working from Cage Making Shelf Alignment During Jig Assembly

Figure 4-10. Subject Making Final Adjustment of First Shelf Installed During Jig Assembly

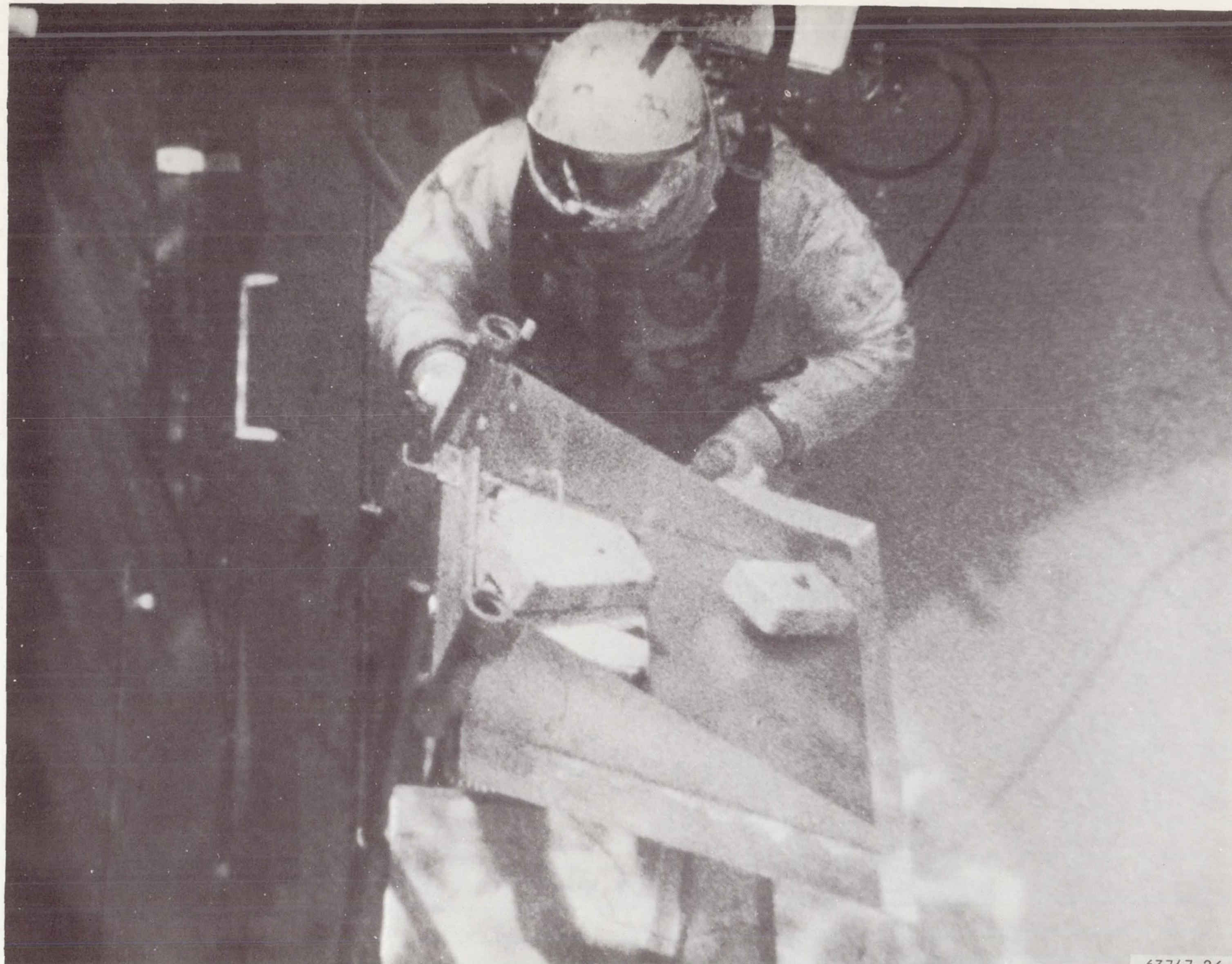


Figure 4-11. Subject Making Two-Handed Alignment of Top Shelf of Jig While Working Out of Cage.

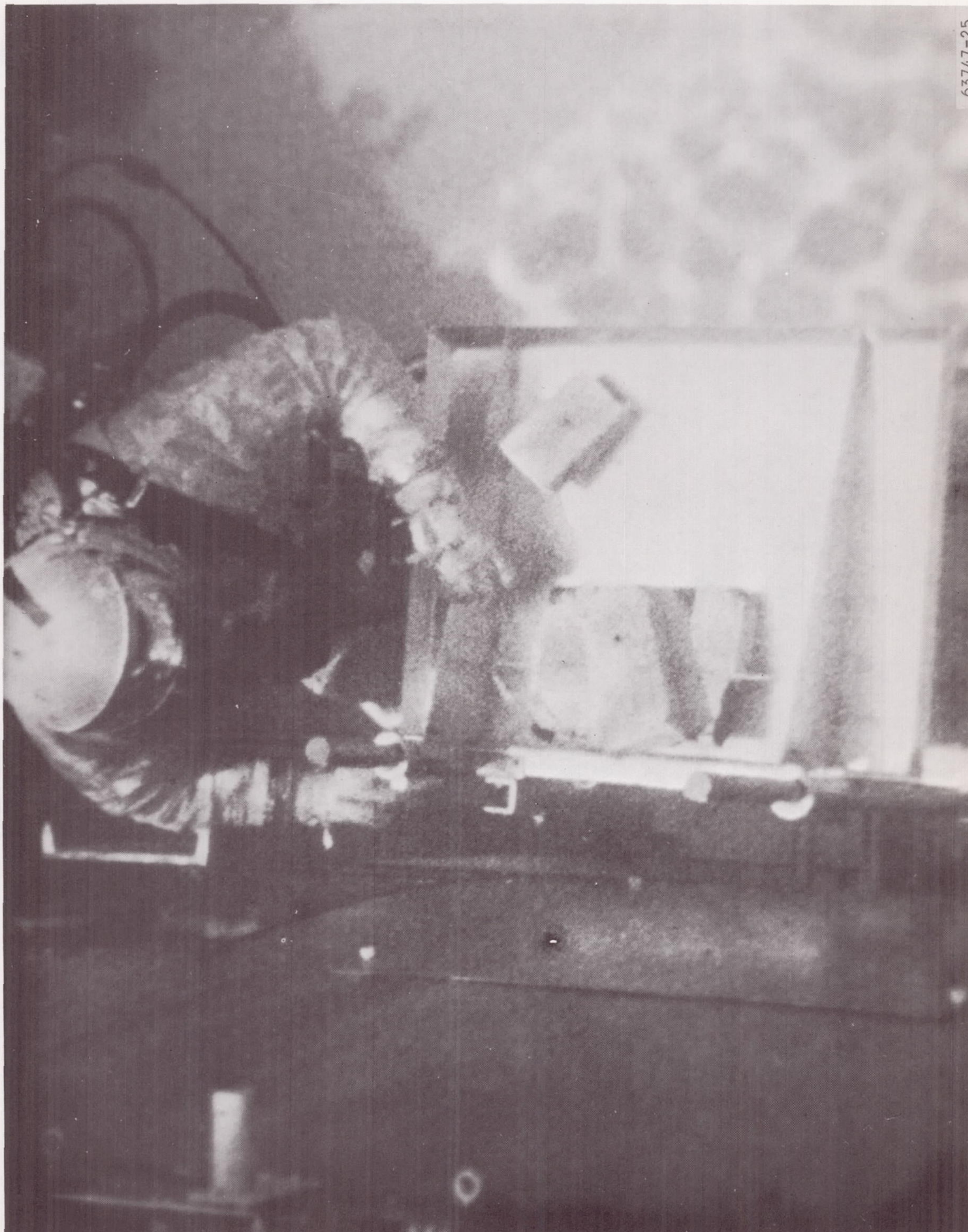


Figure 4-12. Subject Positioning Top Shelf During Jig Assembly

Figure 4-13. Subject Connecting Shelf Spring During Jig Assembly

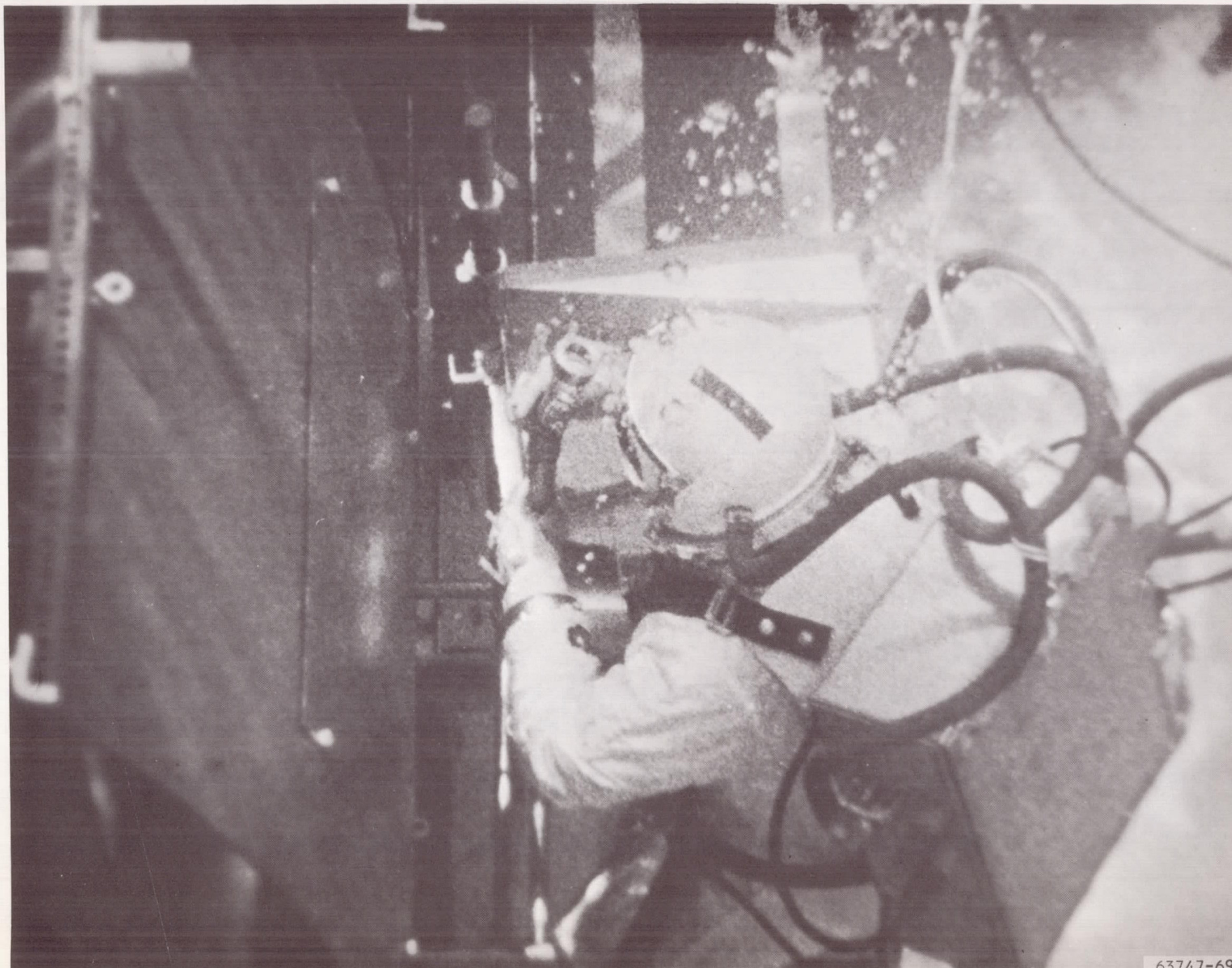


Figure 4-14. Subject Making Second Spring Connection During Jig Assembly

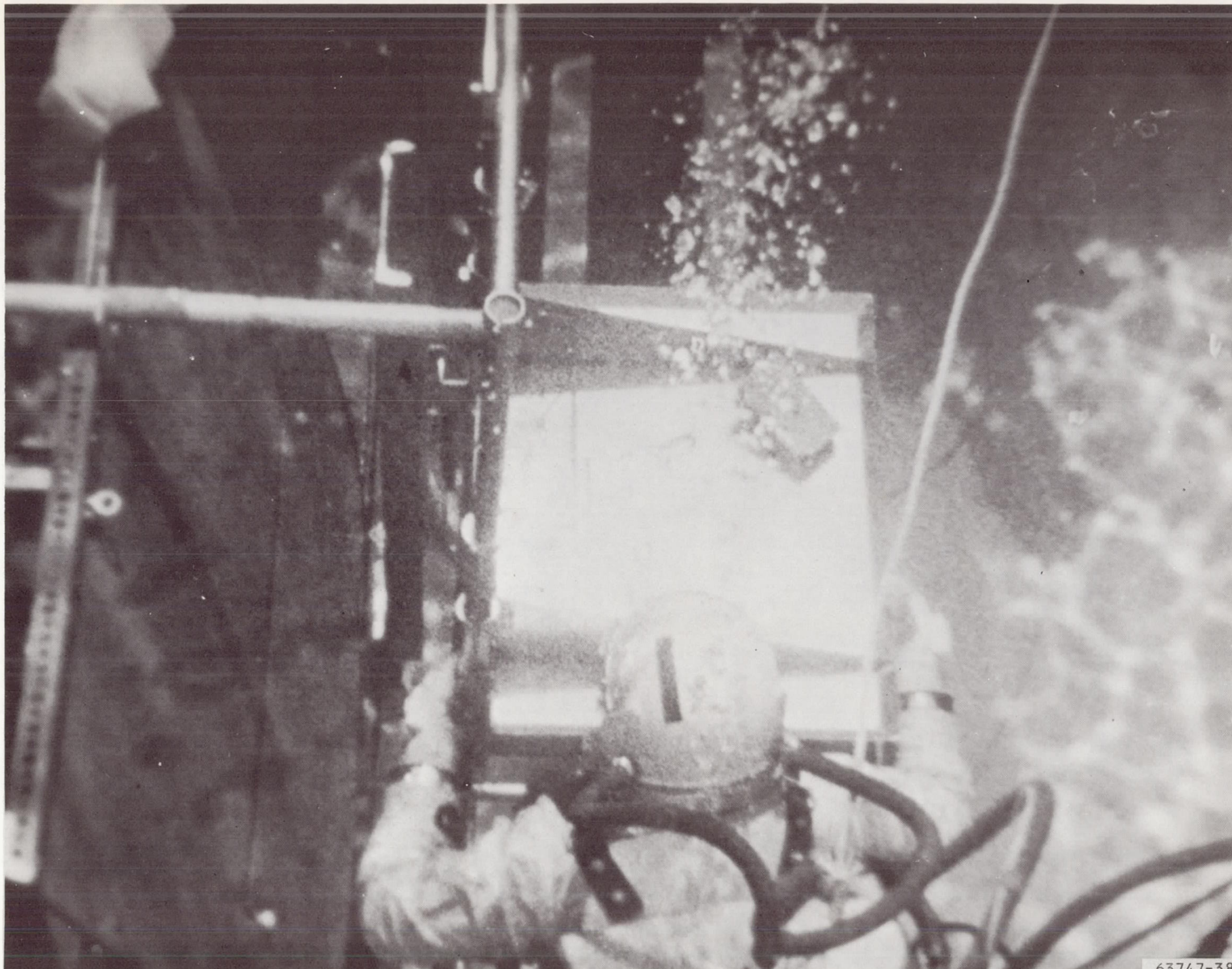


Figure 4-15. Subject Making Shelf Adjustment of Assembled Jig

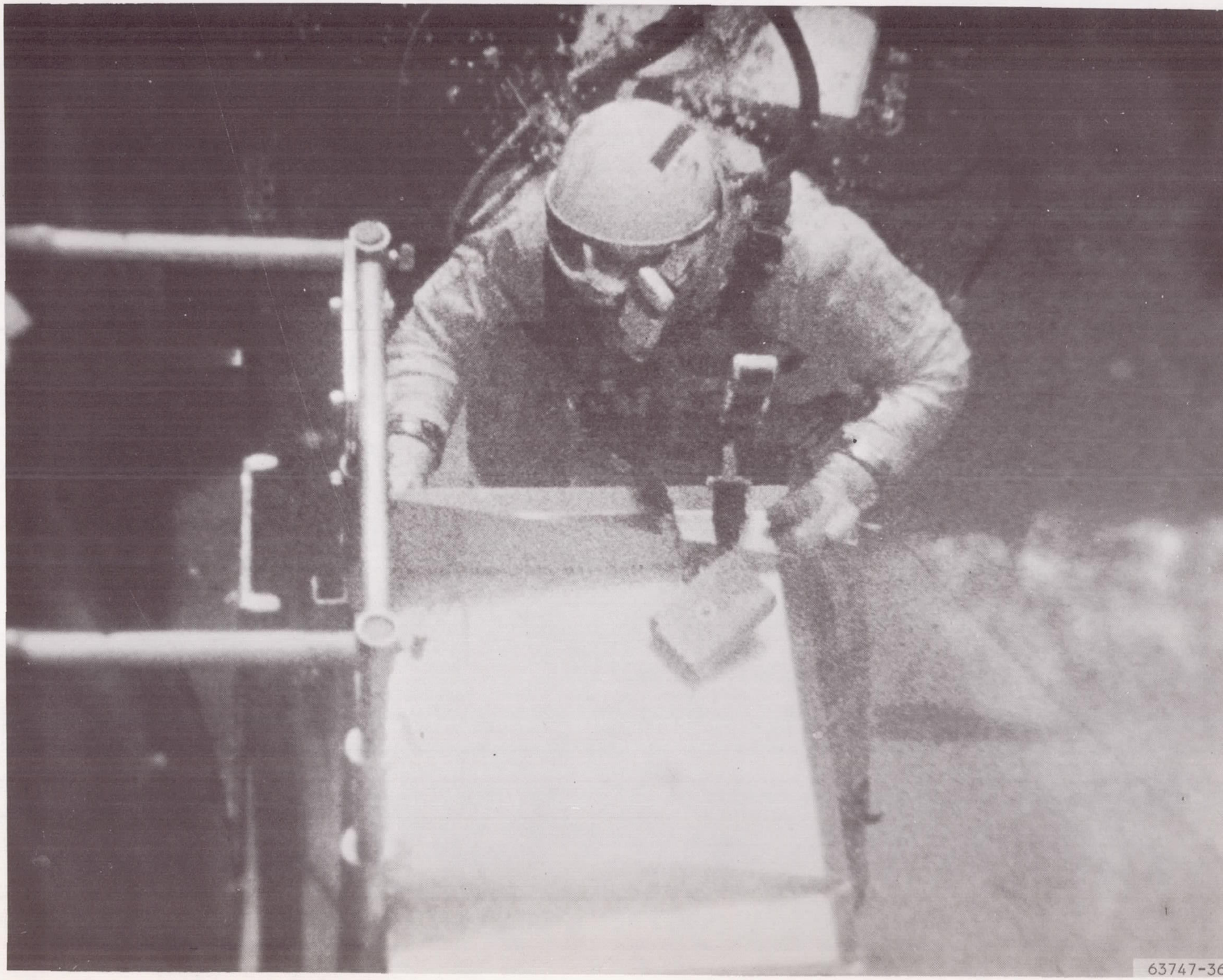


Figure 4-16. Subject Tightening Shelf in Place as Final Assembly Act of Jig Erection

Figure 4-17. Subject Placing Top Support for Panel Holding Jig; Note Strap Tether to Mockup Surface

Figure 4-18. Subject Inserting Top Support Into Fitting During Panel Holding Jig Assembly

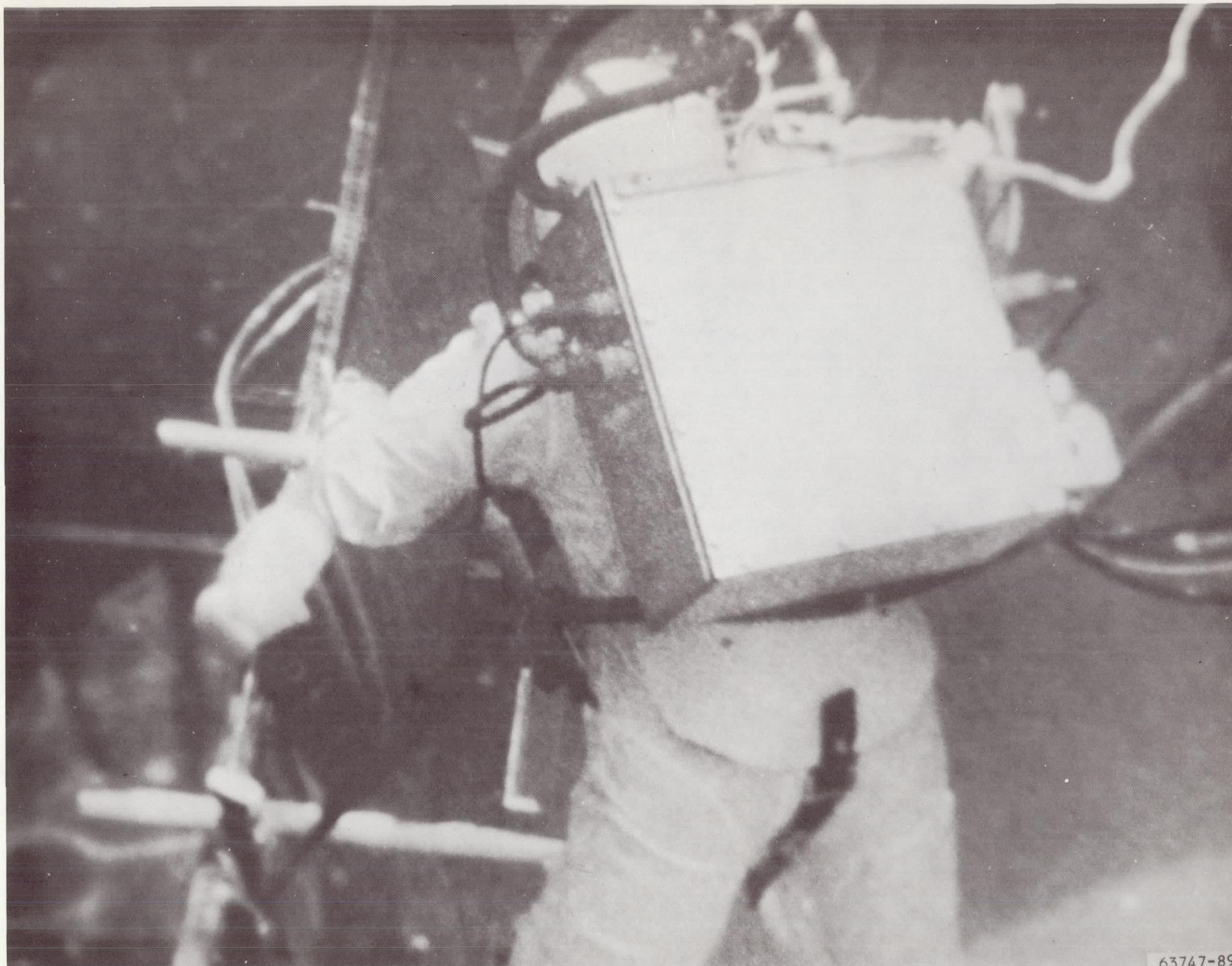


Figure 4-19. Subject Fastening Top Support After Positioning in Fitting During Panel Jig Assembly

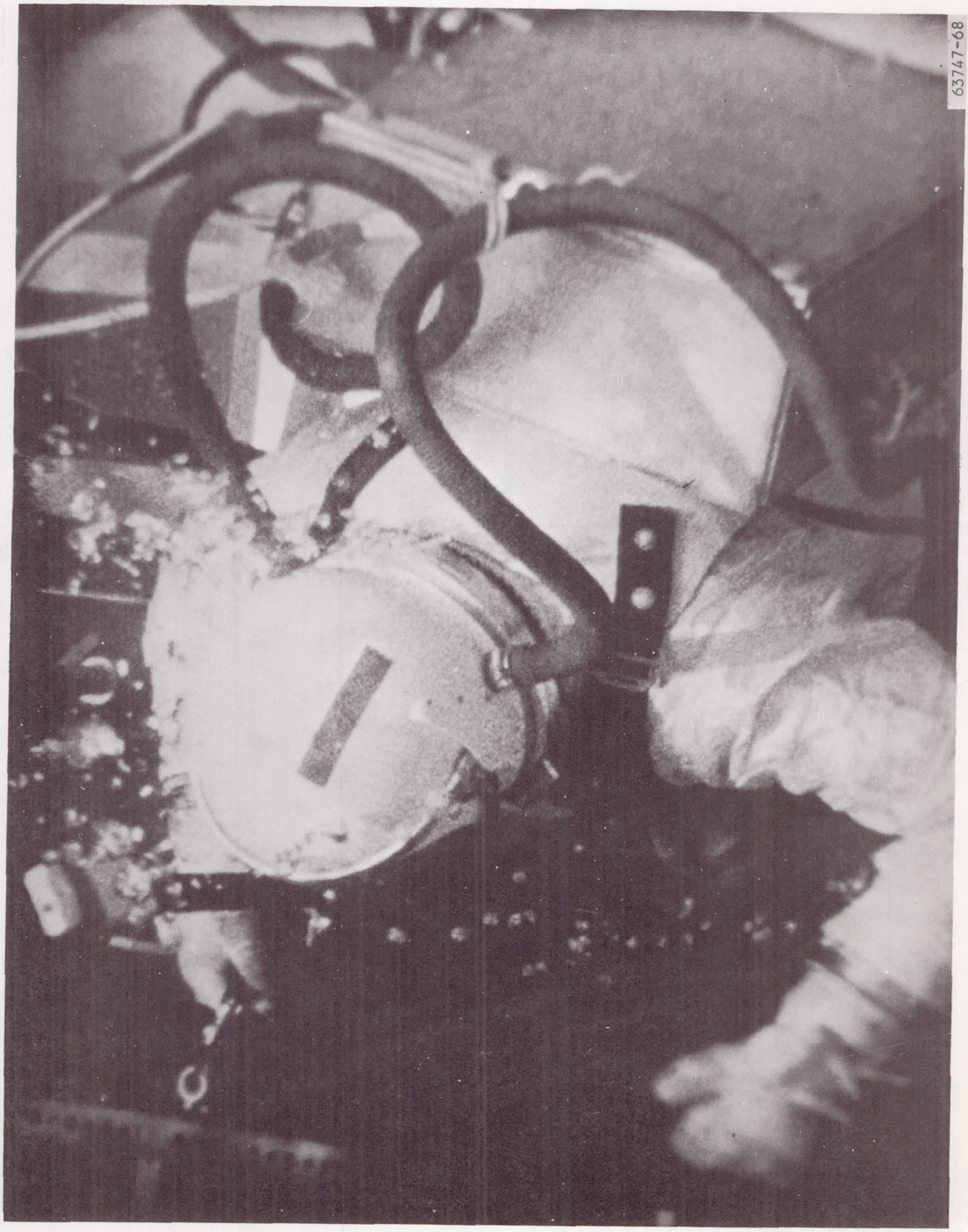


Figure 4-20. Subject Making Strap Restraint Connection on Mockup Surface

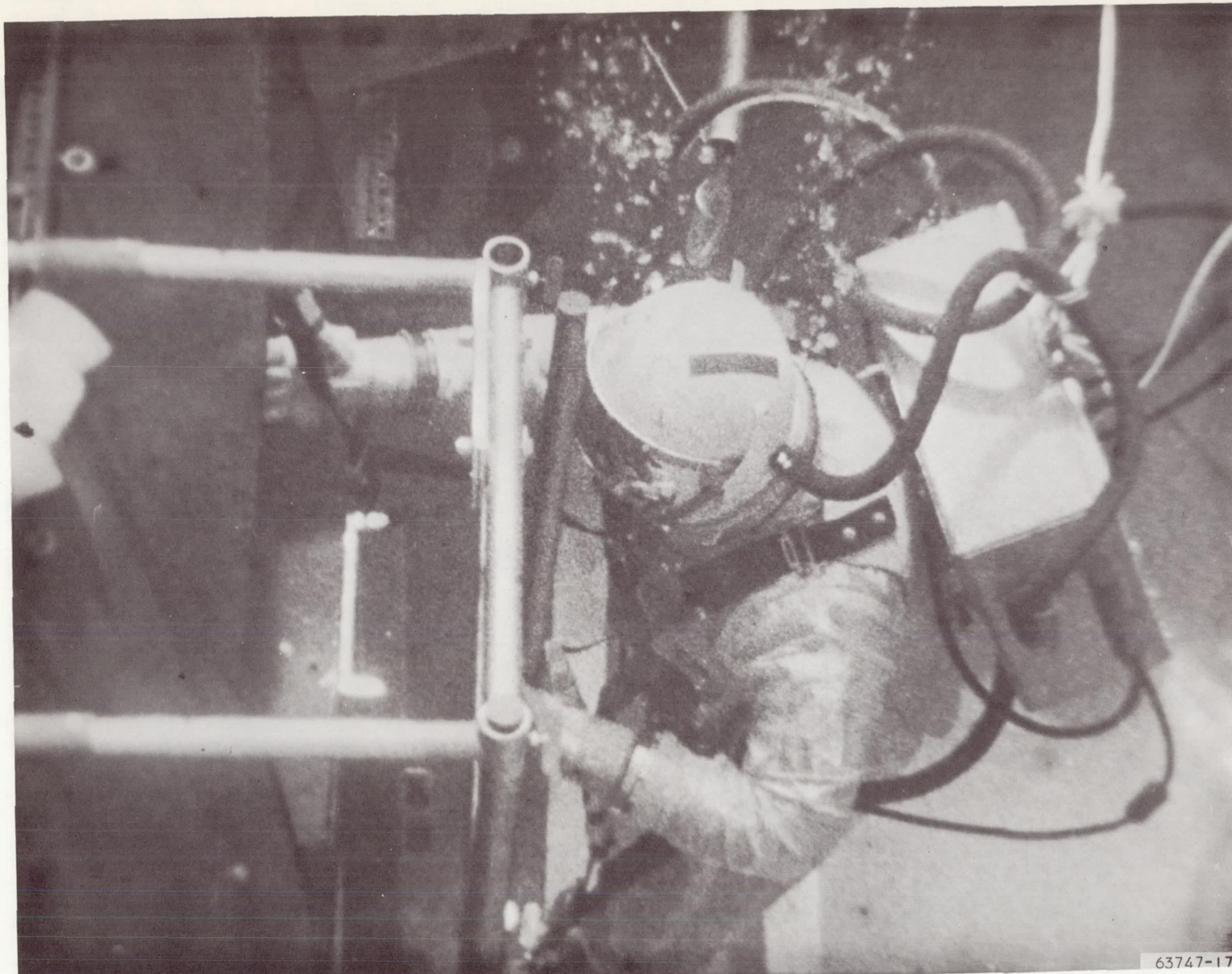


Figure 4-21. Subject Positioning to Insert Upright Support to Top Assembly During Jig Erection

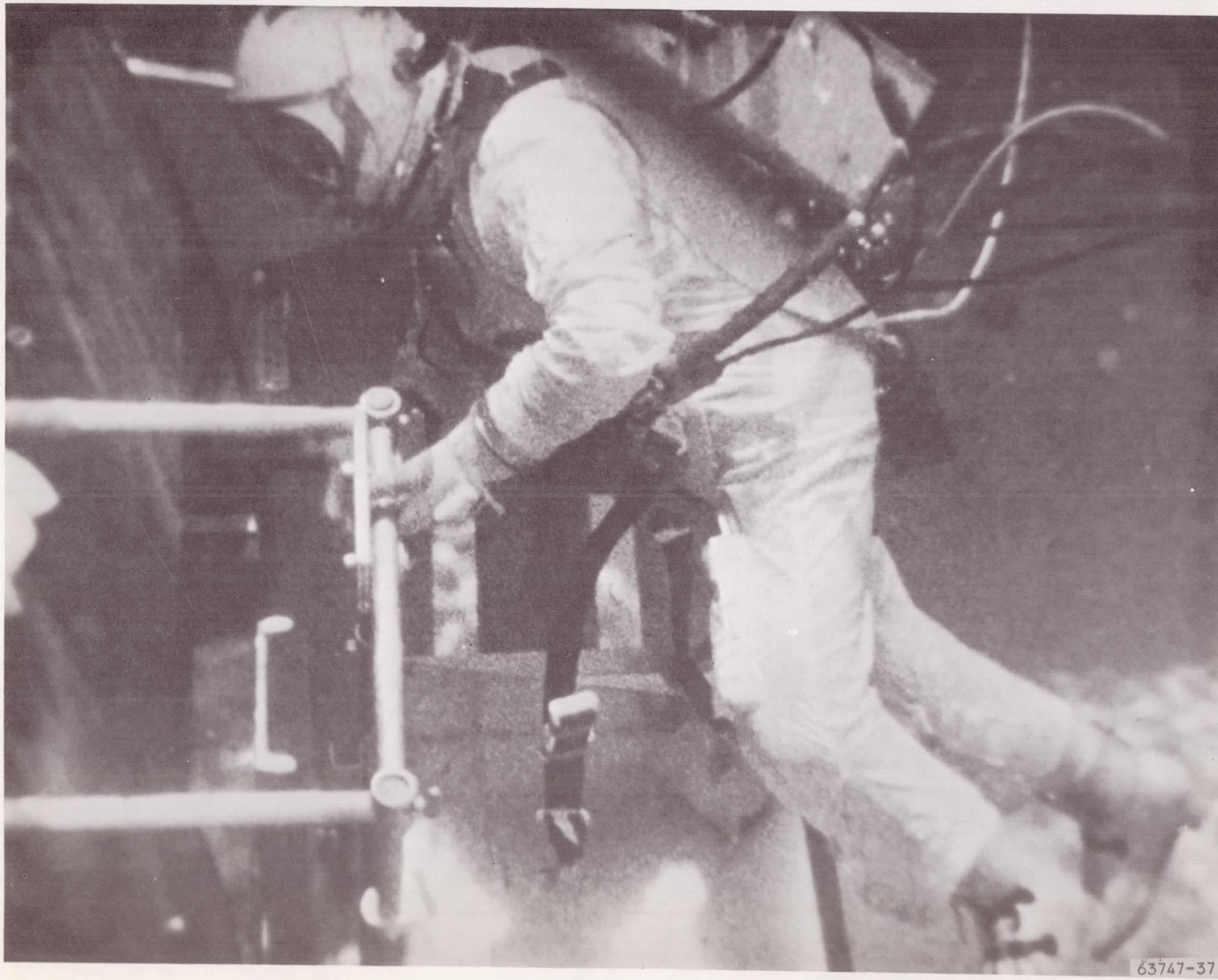


Figure 4-22. Subject Traversing to New Position During Jig Assembly

Figure 4-23. Subject Pulling Panel to Himself to Start Building the Large Rigid Module

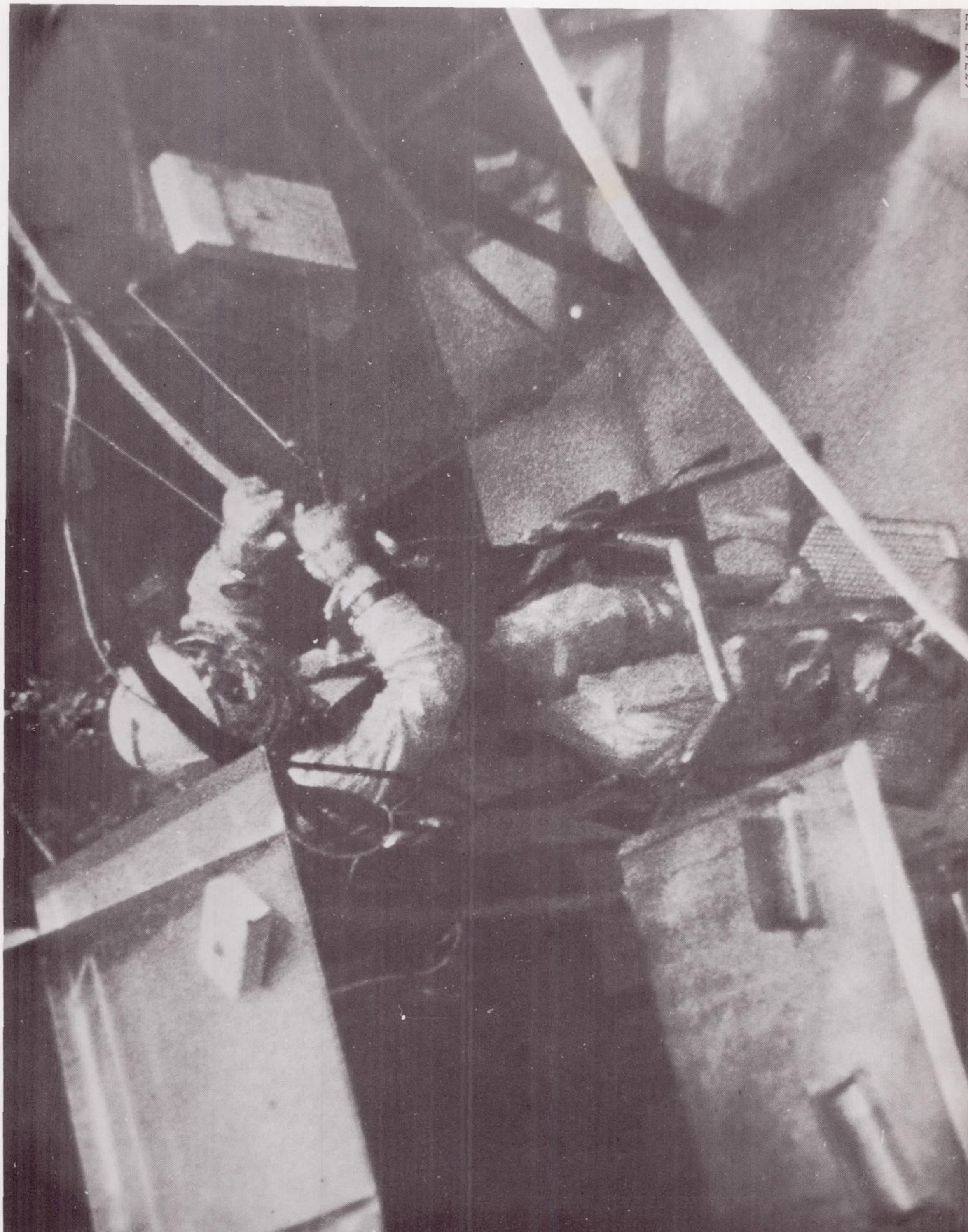


Figure 4-24. Subject Taking First Panel From Transport Rail

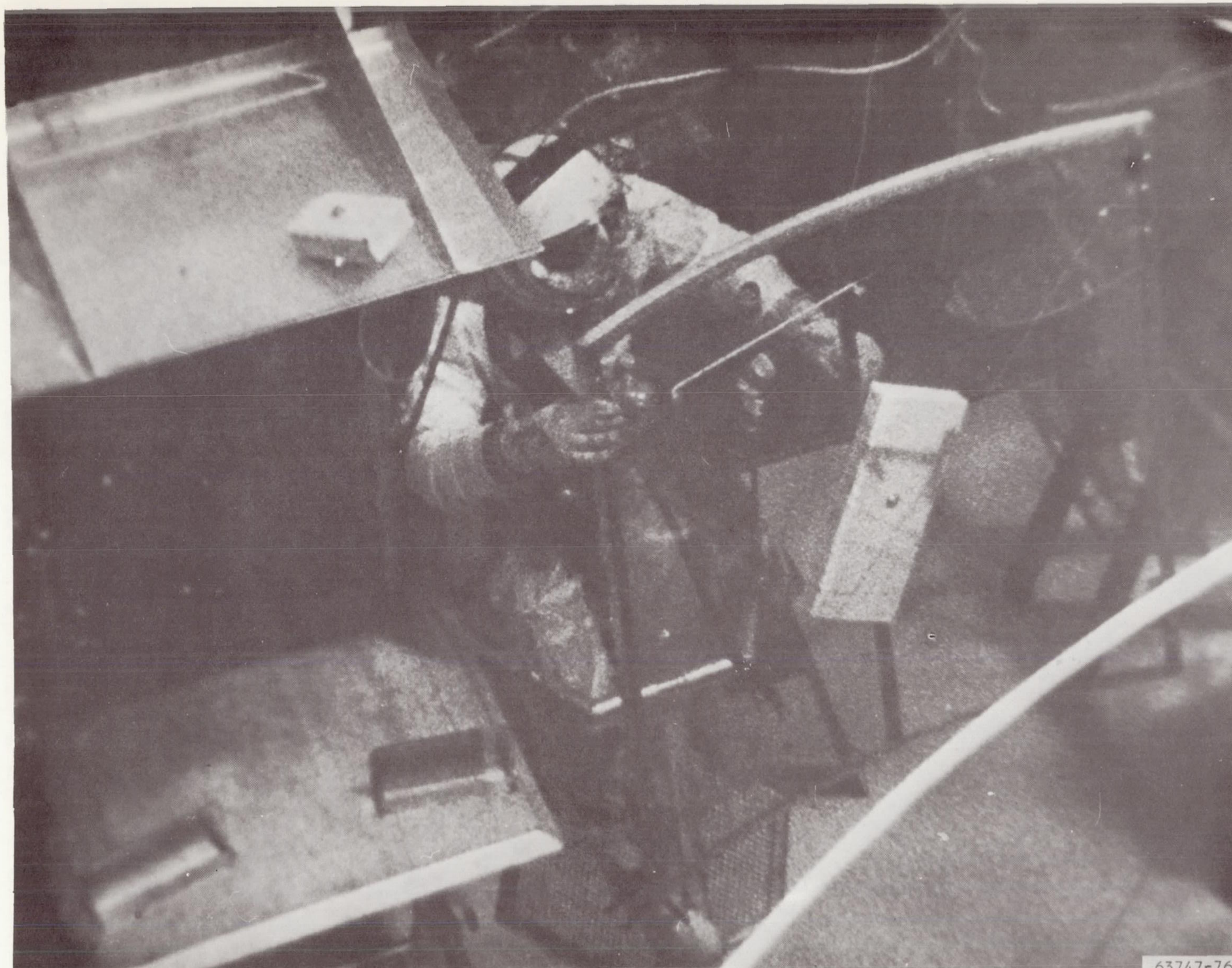


Figure 4-25. Subject Positioning Panel for Placement in Panel Holding Jig

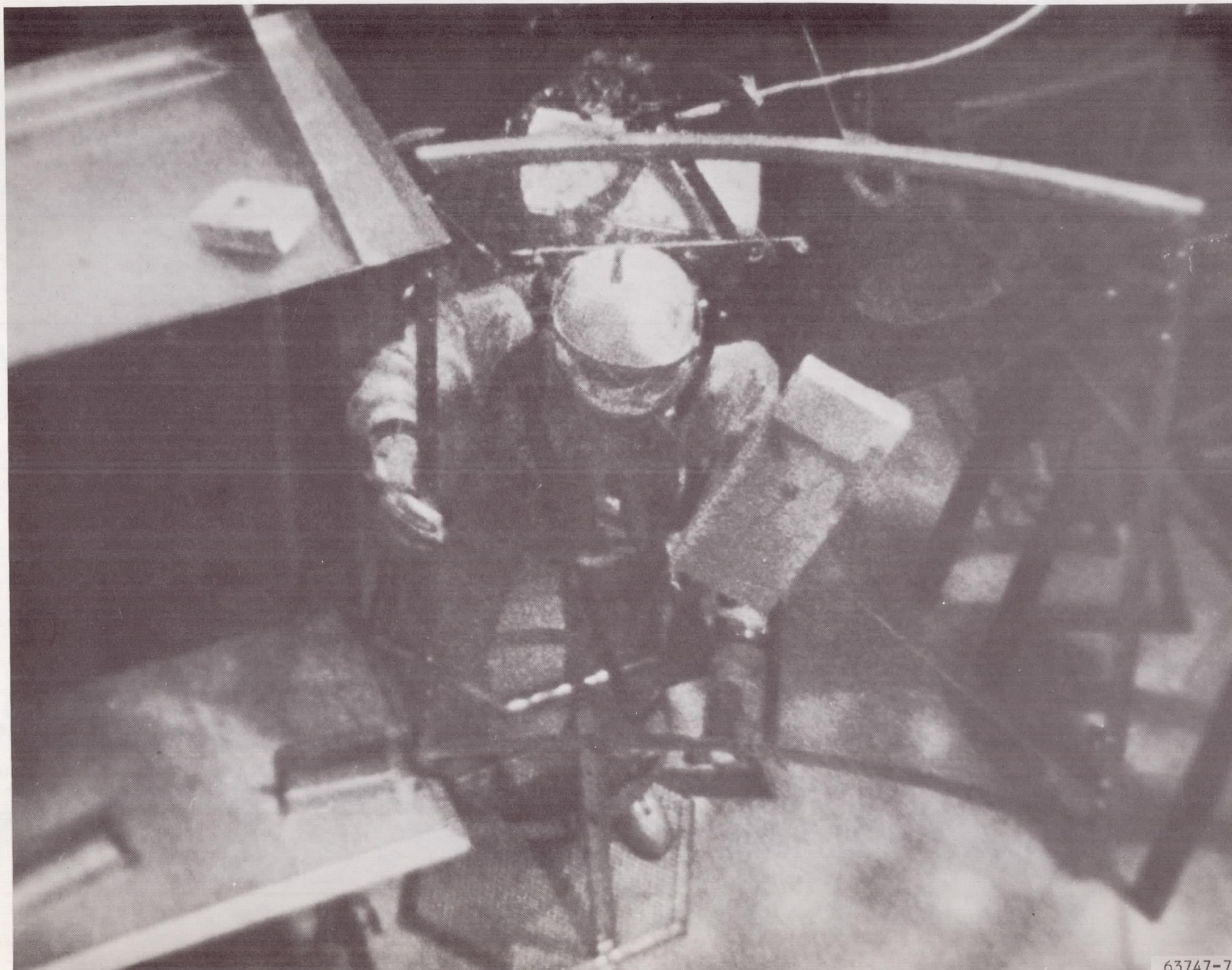


Figure 4-26. Subject Starting Panel Placement in Jig

Figure 4-27. Subject Positioning Panel in Jig

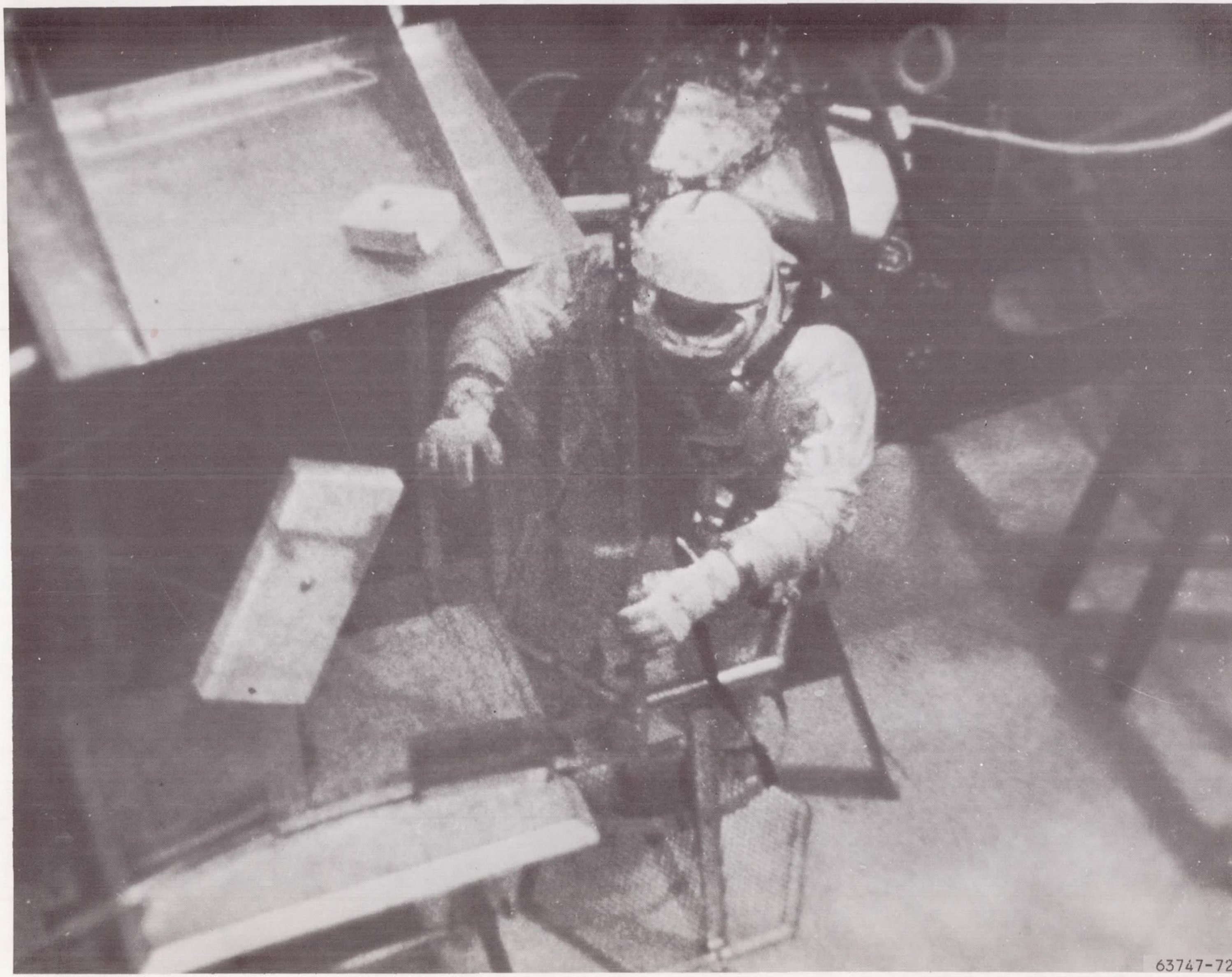


Figure 4-28. Subject Placing Panel in Jig for Connecting the Second Panel to its Edge

Figure 4-29. Subject Procuring Second Panel

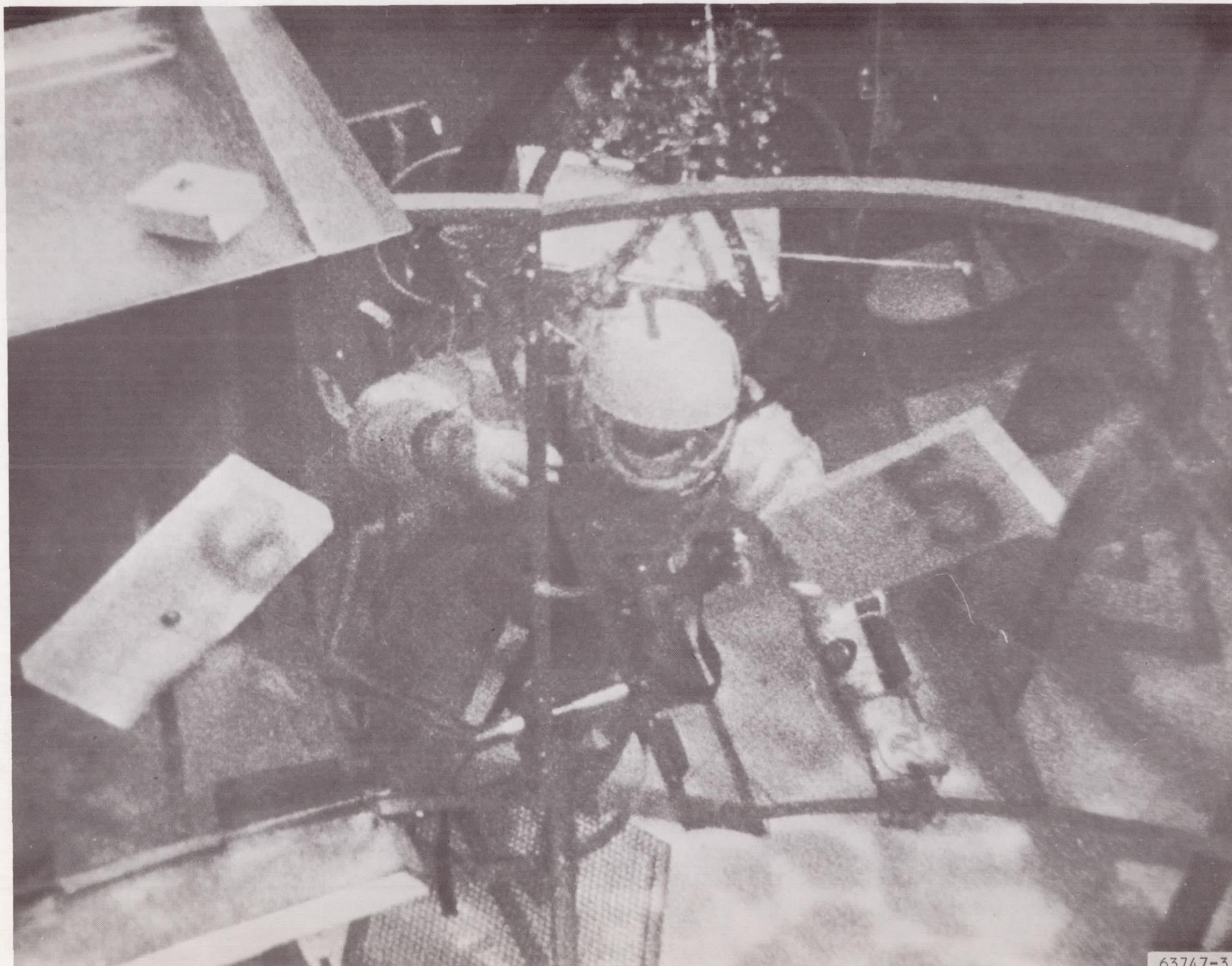


Figure 4-30. Subject Positioning Panel to Panel Held in Jig

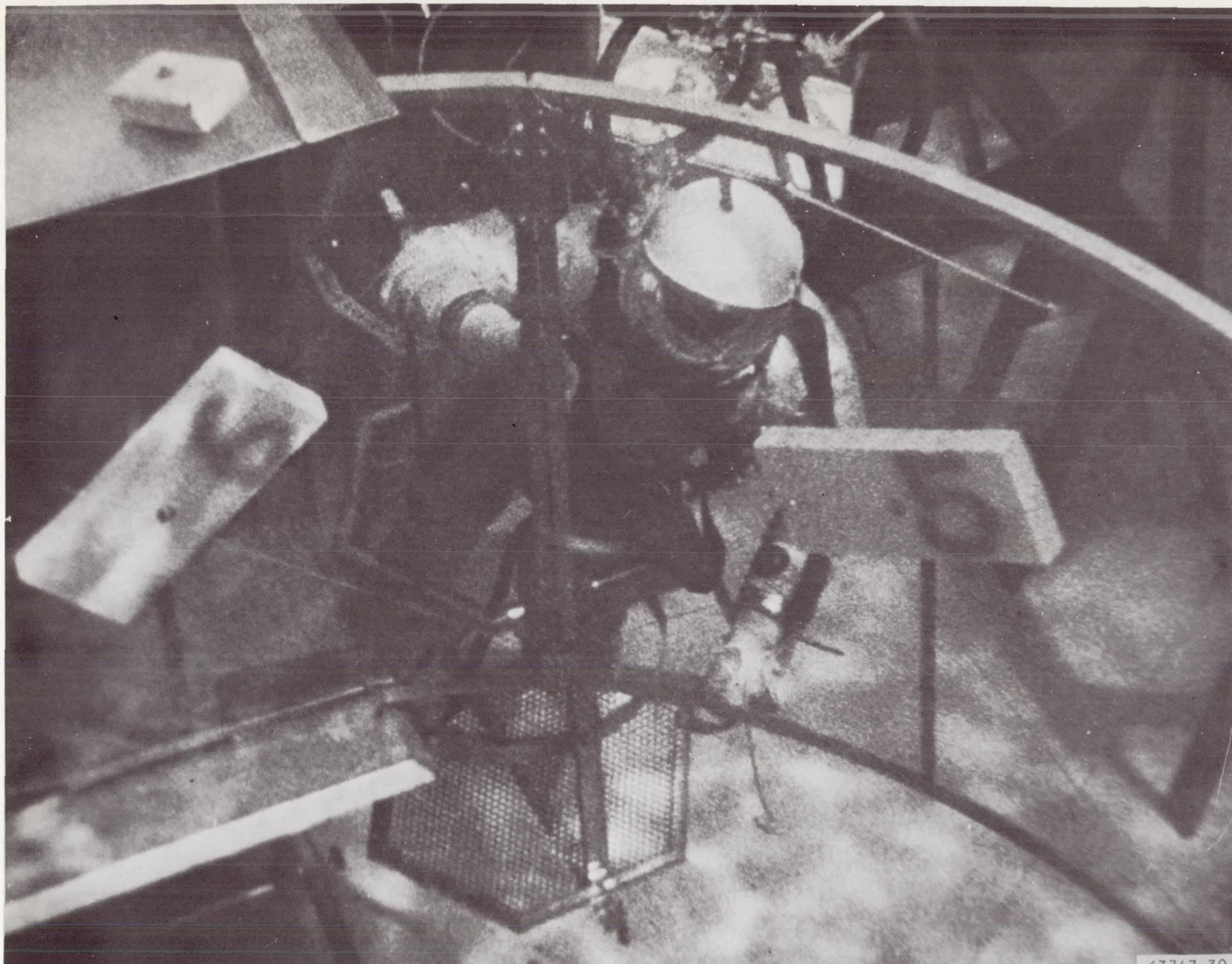


Figure 4-31. Subject Fitting Alignment Pins of Panel 5 to Panel 6

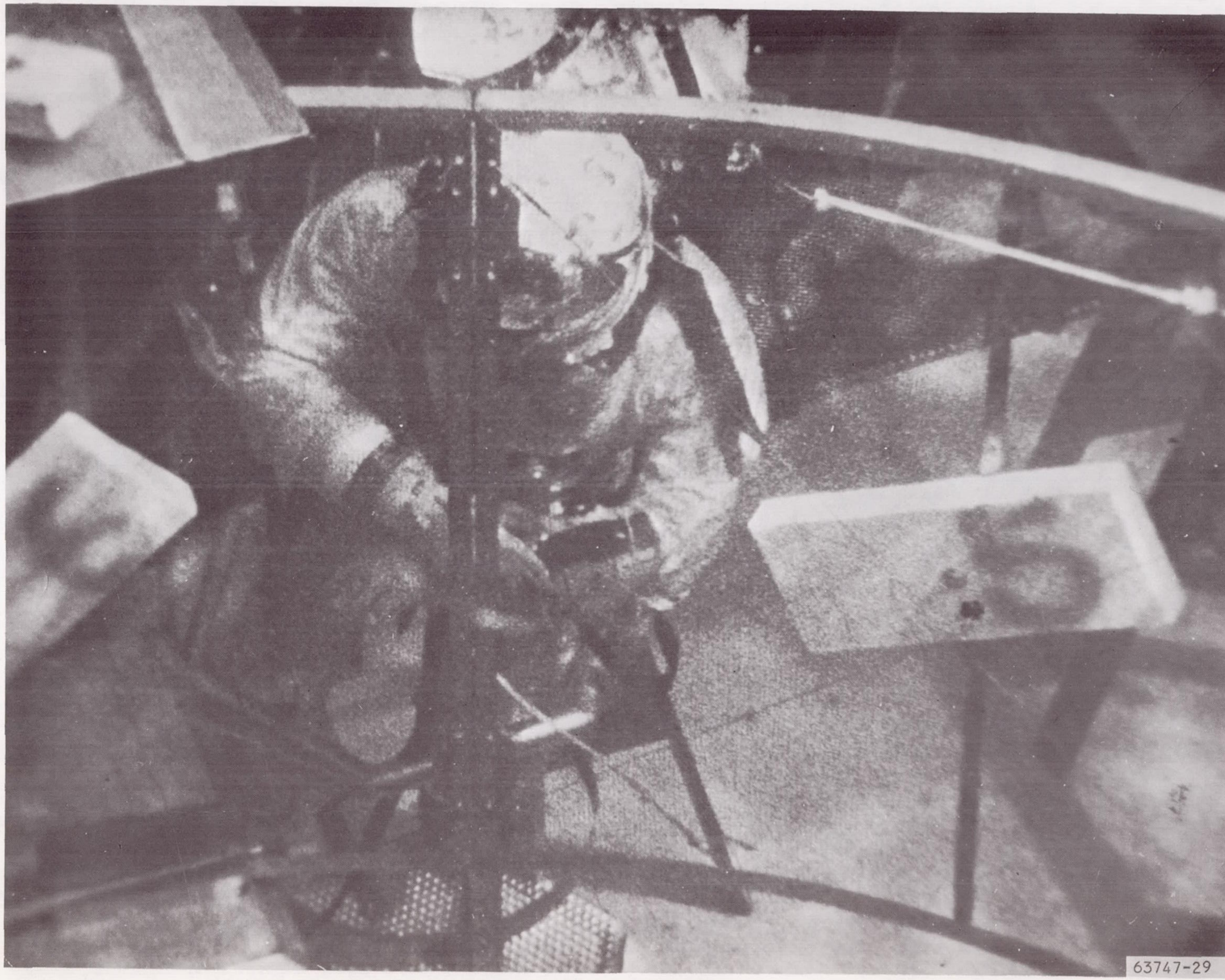


Figure 4-32. Subject Locking Fastener of Connected Panels

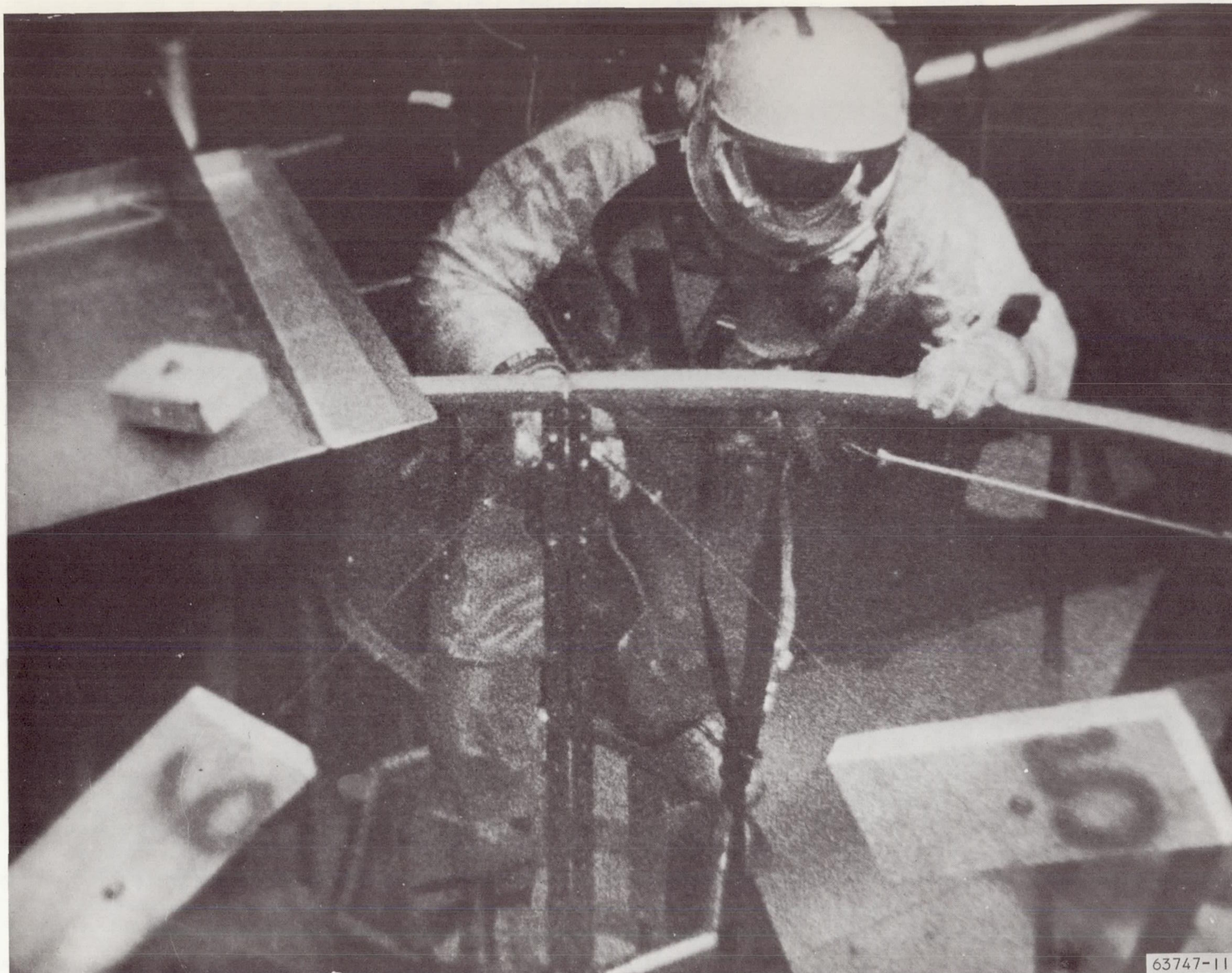


Figure 4-33. Subject Locking Top Fastener of Connected Panels

TABLE 4-2

TOTAL ACTIVITY TIMES FROM FILM OF JIG ASSEMBLY

Activities	Number of Events and Time, sec	Total, sec	Work Time, sec
Restraint manipulation	17, 12, 42, 43, 12, 42	168	42
Two-handed work	42	42	41
One-handed work (second hand used for positioning)	26, 11, 4	41	
Floating (out of control, i.e., lost restraint connection and cannot reach mockup)	None	0	
Inspecting work (in position to work but studying task)	None	0	
Vision problem (try to work but failing because subject cannot see the task)	31	31	
Floating - two-hand work	92, 11	103	103
Floating - one-hand work	None	0	
Traversing (going from one work spot to the next)	10, 11	21	
Positioning (at work spot but manipulating to get a better position for task performance)	23, 10	33	
Regaining position (at position then lost it and had to get back in position)	13	13	
TOTAL	18	452	186

During the assembly, the subject had control difficulty resulting from a failure to keep the strap tether sufficiently short so that when he stood up in the cage he would load the restraint and consequently assume a stable position. Instead, the subject would tend to hold the desired position by engaging his feet or legs in and around the cage structure. Such positioning was usually stable and effective for the tasks although it required considerably more effort than a position maintained by exerting leg pressure against a strap restraint. The solution is to provide a strap restraint that is easy to manipulate.

The overall task performance for the assembly of the first circular module was successful.

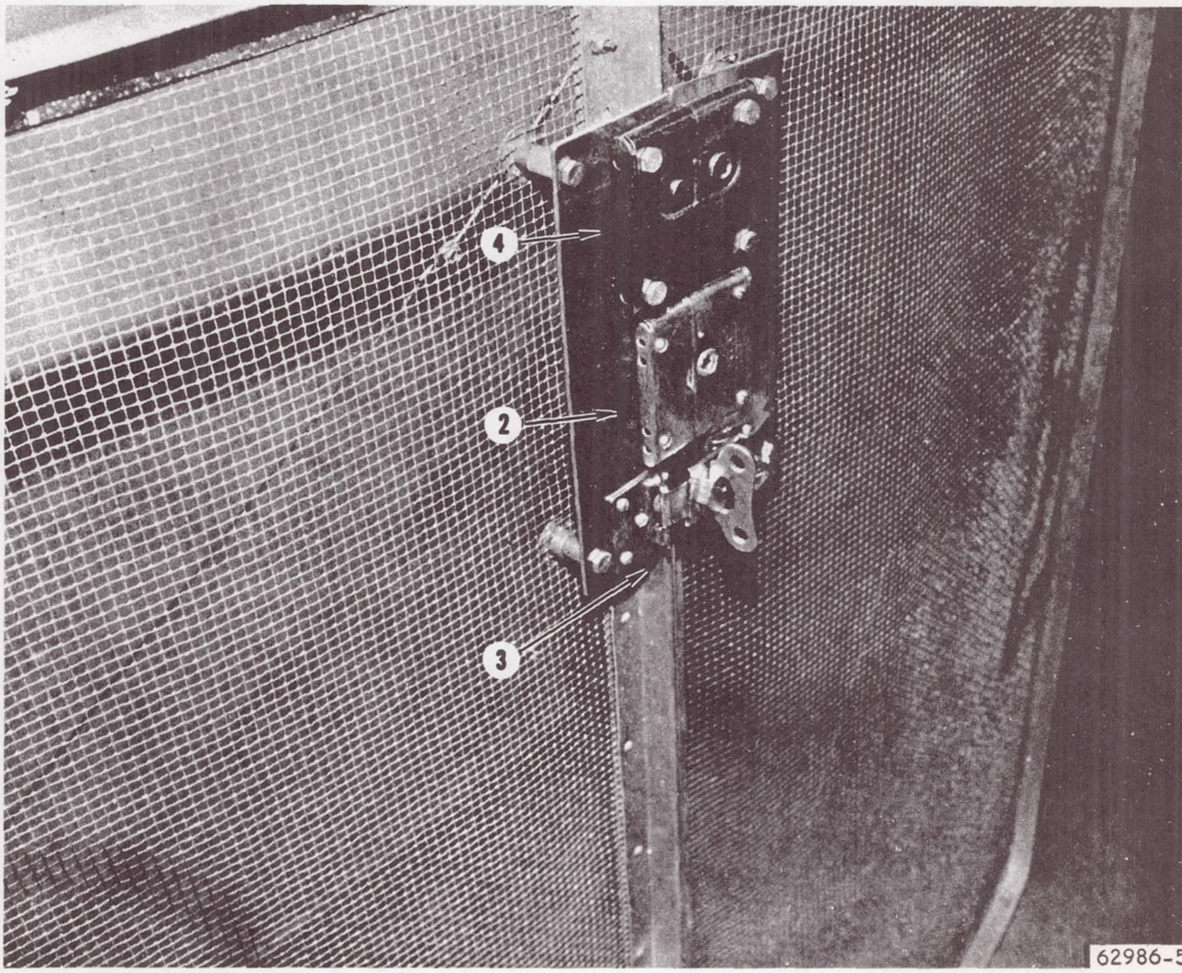
The second circular module, however, posed some problem due to the design of the jig. The overall length of the jig would not accommodate both the top and bottom panels mounted one on top of the other. The procedures were preestablished to hold only the bottom module after erection and then to mount the top panels directly to the completed lower module. By turning the lower module in the reverse direction so that the top mounted panels would move away from the jig rather than through it, the top could be assembled, with the exception of the final panel. It was planned that at this place in the procedure, the total module would be secured to the mockup by tension devices, and the top shelf of the removed jig would allow the placement of the final panel.

In conducting the test, the first top panel was mounted and secured; the second was placed in position. At this time it was found that by turning the module away from the jig, the subject could no longer reach the panel fasteners. Consequently, testing was discontinued. Two solutions to the problem were (1) to produce new extensions for the upright portion of the jig and increase its opening between the shelves which would provide the holding capability for two panels at a time, and (2) to allow the subject to move to the work spot by leaving the cage and to provide a simple strap restraint for securing himself to the module as he moved about it. These alternatives were rejected since it had already been demonstrated in the first EVA study that such an approach did not function for EVA simulation and also, in the case of the first alternative, because of the time required and its delay to the program. In addition, the first module assembly established that the jig-holding erection procedure was a satisfactory means of assembling the first module and thus the second module, if the jig was modified to accommodate it.

Observations on Fasteners

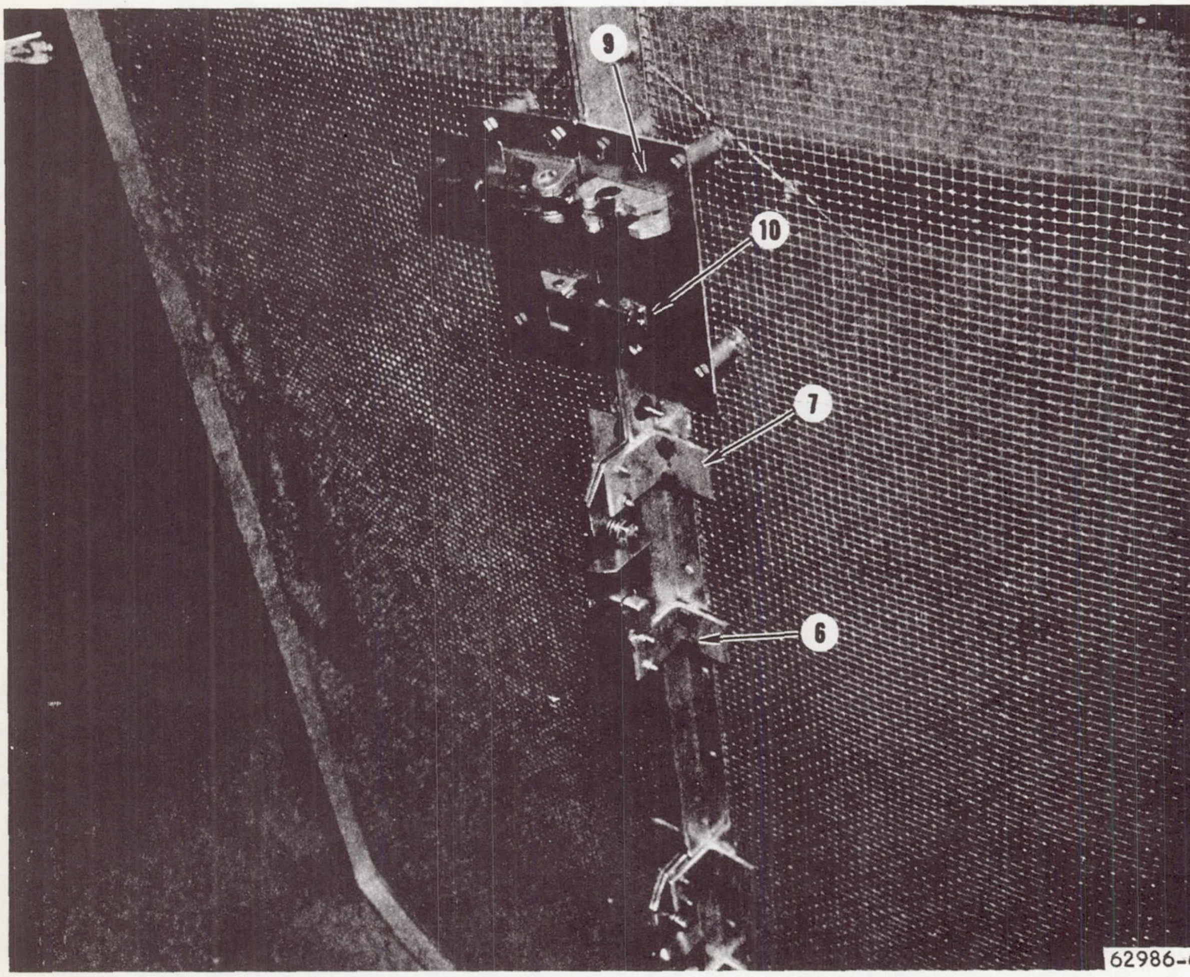
Several fasteners were selected and mounted on the panels to replace the captive nuts and loose bolts used in the previous study. The selection was made to minimize the need for tools to engage the fasteners and, when tools are required, to reduce the torquing requirement for repeated levering acts.

The fasteners considered are listed in Table 4-3. The table is coded in Figures 4-34 and 4-35 which show the fasteners selected for the test. The fasteners not illustrated were rejected as not applicable to the test situation.



F-9478

Figure 4-34. Fasteners Used on Panels



F-9480

Figure 4-35. Fasteners Used on Panels

TABLE 4-3

FASTENERS CONSIDERED FOR LARGE MODULE

Code	Quantity	Part Number	Part Name	Company
1*	12	No. 3	Snapslide fastener	Dimco-Gray Co.
2	12	N.A.	Roto-lock	Simmons Fastener Co.
3	12	No. 2	Link-lock	Simmons Fastener Co.
4	12	N.A.	Dual-lock	Simmons Fastener Co.
5*	12	No. 4-1/2	Clamp-lock	Simmons Fastener Co.
6	12	N.A.	Cam-bolt	Simmons Fastener Co.
7	12	9152 - RWD	Stud assembly	Camloc Fastener Corp.
8* One Unit	12	119 - 1BA	Receptacle	Camloc Fastener Corp.
	12	9153-1	Washer, retaining	Camloc Fastener Corp.
9 One Unit	12	37L11-4	Handle assembly	Camloc Fastener Corp.
	12	37L14-1	Hook	Camloc Fastener Corp.
10 One Unit	12	51L5-1AA	Latch assembly	Camloc Fastener Corp.
	12	51L8-1AAA	Hook	Camloc Fastener Corp.

*Not used in test

All fasteners tested performed satisfactorily except Simmons Roto-lock (Code No. 2). The roto-lock as installed was turned 90 deg to engage but did not have a stop at this point and could be turned on past the engaging point, i.e., 180 deg which disengaged the fasteners. The first time the subject used this fastener, he turned it past the locking position and the fastening failed. This fault is probably due to an inappropriate use or installation of the fastener rather than to design fault of the fastener itself. No other failures happened with this fastener after the subject was instructed to turn the engaging wrench only 90 deg.

Fasteners requiring tools to engage them required more overall time to lock than the fasteners that were manipulated by hand. The difference in time is not reflected in the fastener but in the time required to store and obtain the tool to engage the fastener.

One conclusion concerning the fasteners is that quick-acting fasteners are advantageous for EVA from both a time and an energy cost when compared to nut and bolt fastening.

The applicability of the fasteners tested to actual EVA assembly and erection must be one of analysis of the fastener needed for specific EVA hardware. For actual EVA assembly, the individual fastening requirement will have to be known and then a fastener selected and empirically tested for EVA application.

Physiologic Observation

The results of the physiologic measurements for these exploratory tests are shown in Figures 4-36 through 4-38. The format of the presentation is identical to that used for the exploratory cargo transport task. Test 516 (Figure 4-36) depicts the results of the jig assembly tests used for studying the problems associated with the mating and securing of beams. Test 525 (Figure 4-37) and Test 528 (Figure 4-38) give the results obtained during the mating and securing of modules and panels.

The subject who performed the jig assembly task exhibited the highest metabolic rates noted during any of the tests. The peak value noted was approximately 18 kcal per min (4200 Btu per hr) with a heart rate of 165 beats per min. The high rates noted were probably due to performance of the tasks without prior experience and to the flexibility of the structure which hampered the subject in gaining adequate support and in his ability to manipulate the parts of the structure.

These results emphasize the need for training to perform any task either in neutral buoyancy or in weightlessness. A hand-to-hand analysis of the task and training would result in the subject pacing his efforts to the work task and would minimize the wide excursions in metabolic cost as exhibited by this test. The human engineering observations made during this test clearly support the above statements. As the notations indicate, improper use of the restraint systems undoubtedly added to the peak metabolic loads either by not providing the reactive forces needed by the subject (straps too loose) or by not

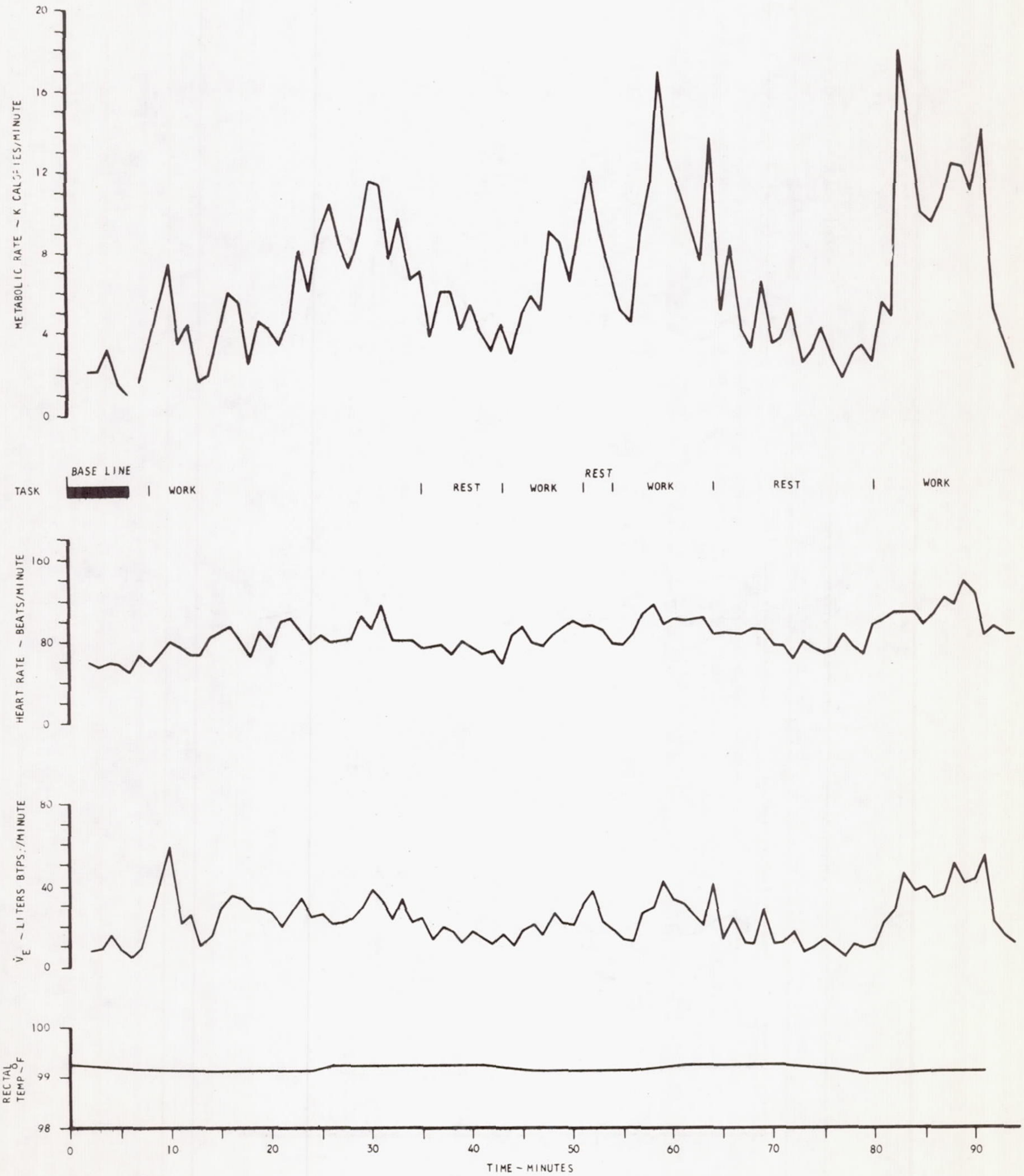


Figure 4-36. Physiologic Data for the Jig Assembly Test (516) Used for Studying Mating and Securing of Beams

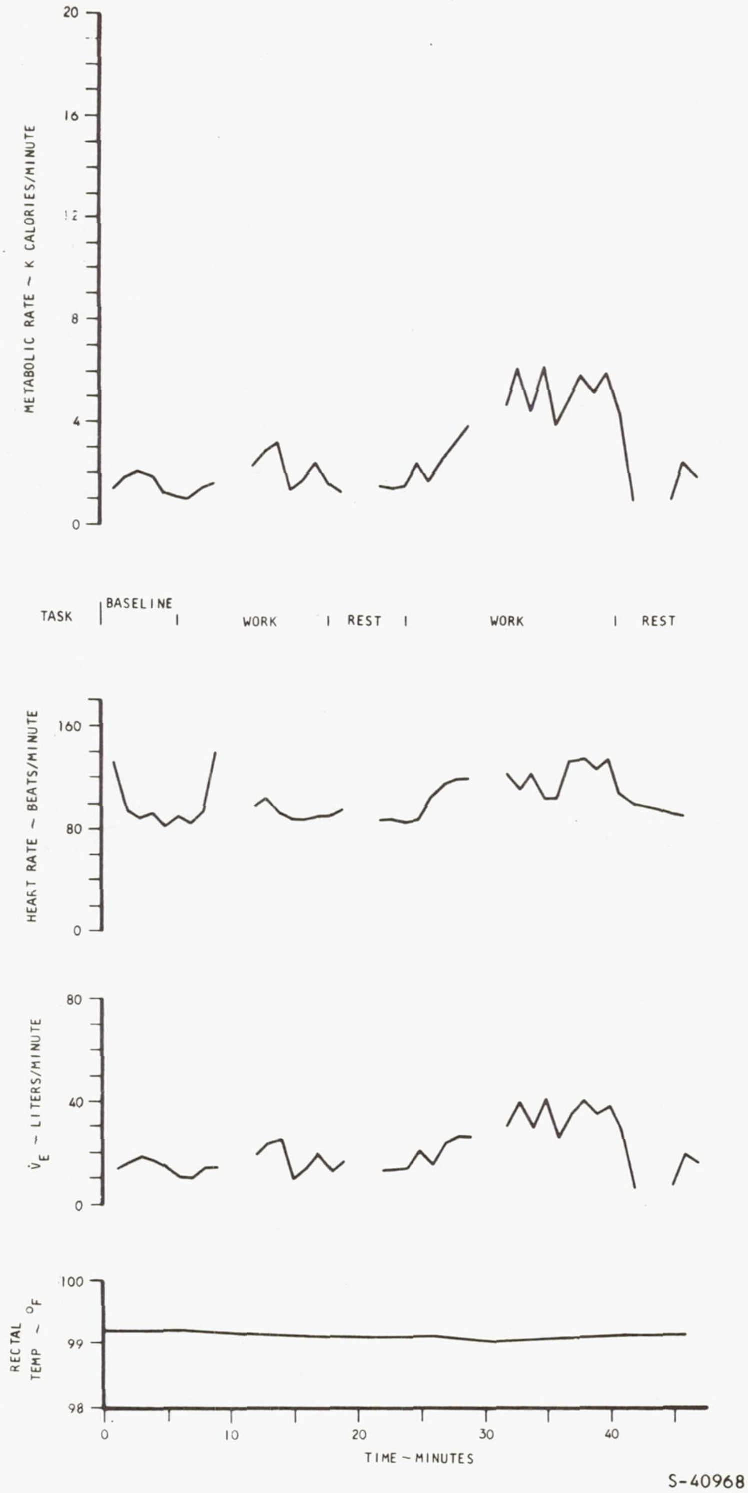


Figure 4-37. Physiologic Data for Test 525, Mating and Securing Beams

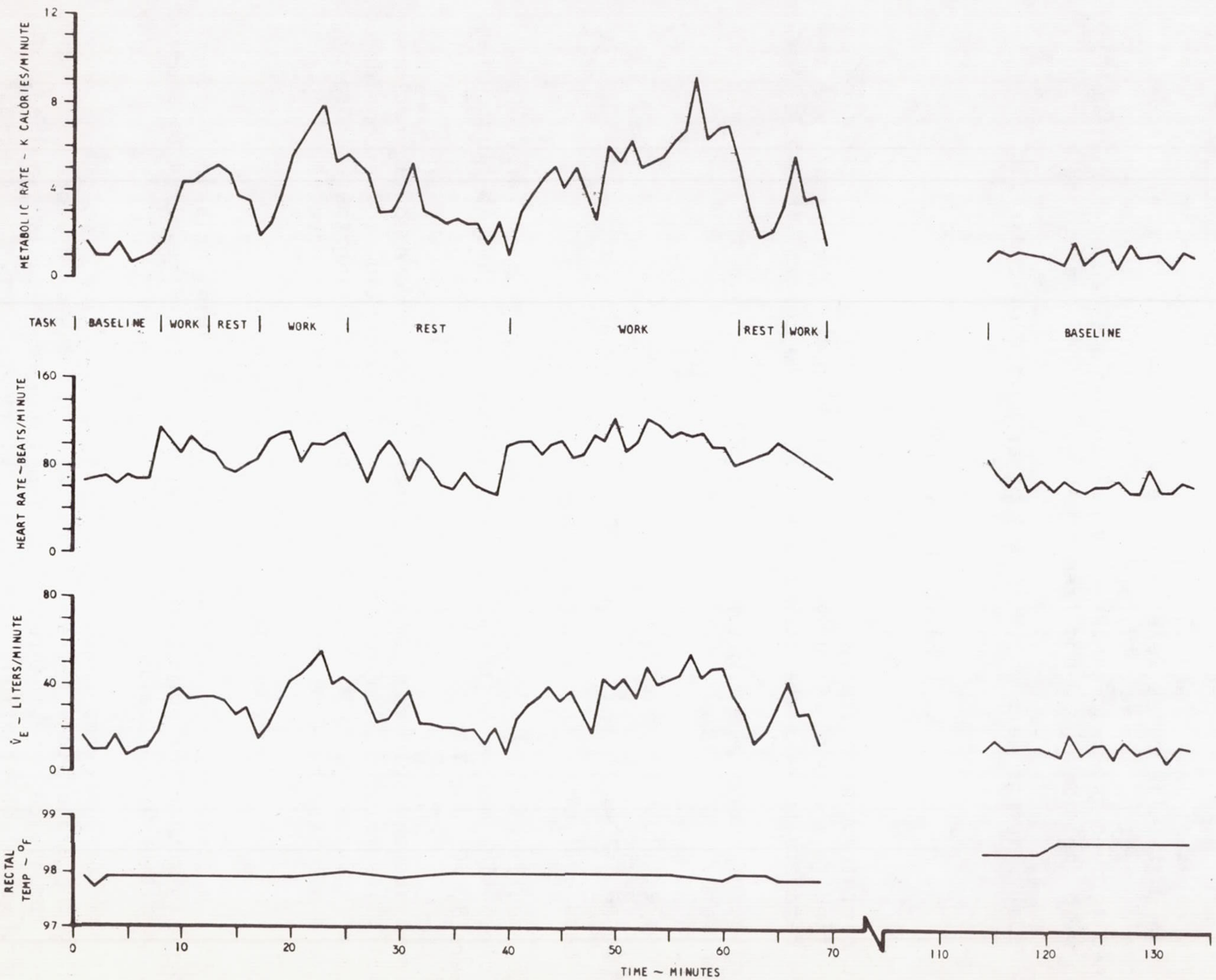


Figure 4-38. Physiologic Data for Test 528 Mating and Securing Beams

adjusting the straps so that the subject performed work outside his optimum reach envelope, working against the restraints.

During the large module assembly tasks (Figures 4-37 and 4-38), each subject tended to pace his work effort better and, with one exception, operated at metabolic rates of less than 8.5 kcal per min (1500 Btu per hr). In every case where the metabolic rates were relatively increased, the subjects used their restraint systems improperly, and the actual loss of the reactive force field gained through the restraints while performing one-handed tasks, holding a position with the other hand and free floating in the lower torso.

No unusual findings were noted in the other physiologic data.

EXPLORATORY CARGO TRANSPORT

The exploratory cargo transport tests emphasized getting objects from one secure position to another. Of primary consideration for these tests was the associated hardware to make the task functional and to control the task.

Anticipated problem areas given specific attention from the man/machine orientation were

- Subject locomotion aids
- Cargo tethering
- Mass and volume of cargo packages

Cargo modules of varying sizes and masses were constructed for use as test articles. The masses of the cargo modules were 1, 5, and 15 slugs; the volumes were 8, 40, and 120 cu ft.

These masses and volumes provided a total of nine module configurations. Figure 4-39 illustrates typical cargo modules. The potential tests considered are depicted in Table 4-4. The actual tests conducted during the exploratory testing are designated by X; P represents the pilot tests conducted.

Procedures and Test Apparatus

The test procedures were established in part by use of existing hardware and the need to reduce the potential 200 comparative tests required to examine each test condition individually.

The tests were directed toward identifying and testing problems as they arose during the exploratory tests. Potential solutions of a procedural nature were structured into the test situations and empirically examined. In this manner, actual observations, insights, recommendations, and conclusions resulted from the tests.

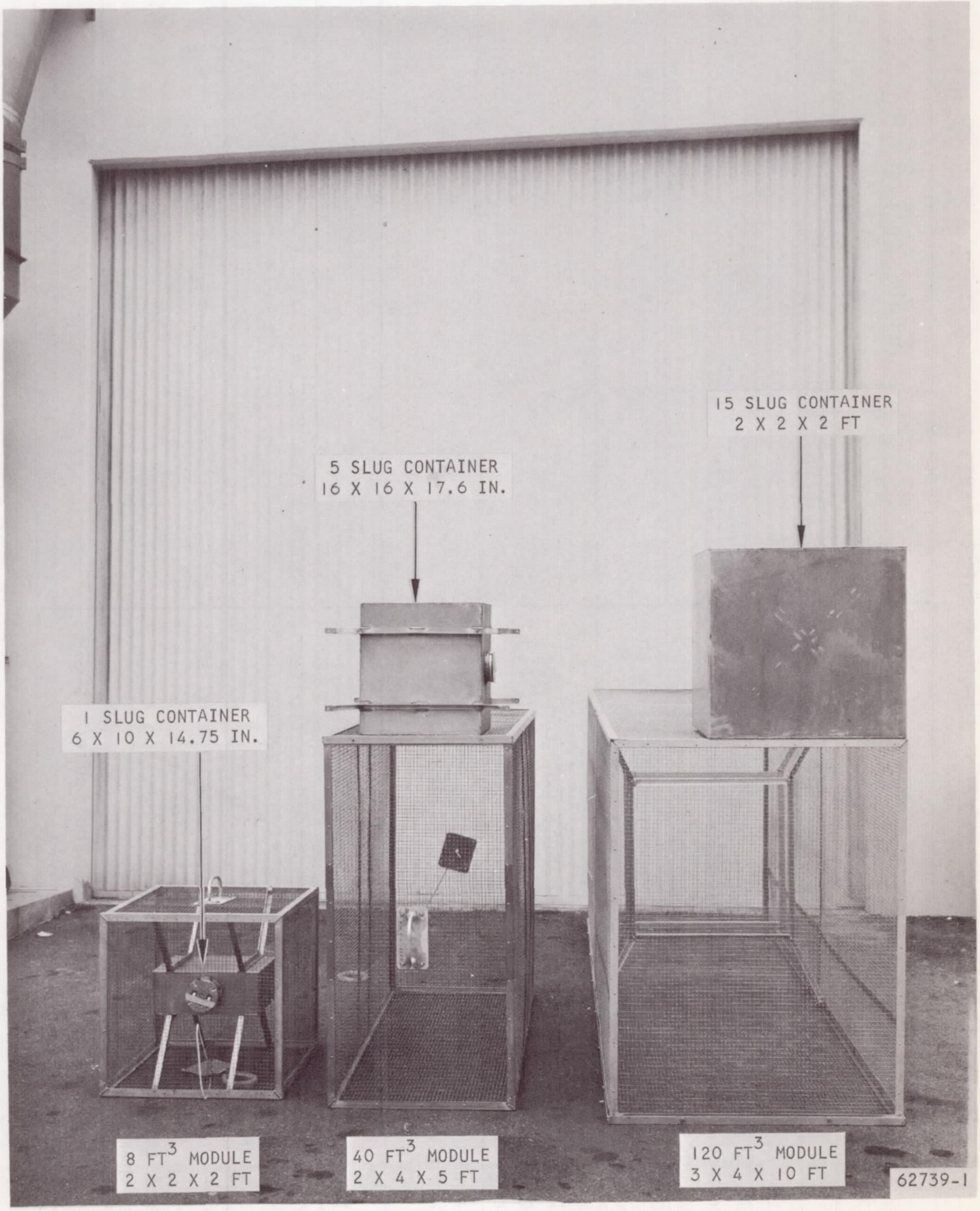


Figure 4-39. Cargo Modules

TABLE 4-4

CARGO TRANSPORT TESTS

Pilot and Exploratory Tests	Cargo Module Configurations: Volume, cu ft	8	8	8	40	40	40	120	120	120
	Mass, slugs	1	5	15	1	5	15	1	5	15
Subject on strap restraint connected to trolley truck in rail. Handle mounted flush on cargo. Cargo free. Subject traverses rail pushing cargo ahead of himself.		P		X		P				
Same condition as above with subject pulling the cargo behind himself.		P X	X	X	X	P		X	X	X
Subject on strap restraint connected to trolley truck in rail. Telescoping handle mounted to cargo module. Cargo free. Cargo module pulled by subject.		P X				X X				
Subject on strap restraint connected to trolley truck in rail. Rigid trolley assembly on cargo. Cargo module pulled by subject.		P				X				
Same condition as above except the subject pushing the cargo module ahead of himself.		P								
Subject on strap restraint connected to trolley truck in rail. Cargo module attached to subjects backpack with special harness.		X	X	X	X	X				
Subject on strap restraint connected to trolley truck in rail. Flush handle and forearm handle mounted to cargo module. Subject pulling cargo behind himself.			X	X	X	X				
Same condition as above except the subject pushes the cargo module ahead of himself.						X				

P Pilot
X Exploratory

The task required the subject to traverse with the cargo modules along a rail structure 14 ft in diameter. In addition to the rail system illustrated in Figure 4-1, the largest module volume was manipulated along a straight pipe rail placed across the tank interior. Tests were also conducted with various handles and a backpack adapter illustrated in Figure 4-40. Item 1 is the backpack adapter; Item 2, a telescoping handle; and Item 3, various fixed-length handles.

The surface of the cargo modules was covered with hardware cloth. This additional surface area created a drag problem considerably greater than anticipated. Skin divers experimented with the 130-cu-ft module by manipulating the module during and following neutral-buoyancy adjustments; these experiments showed that the drag resulting from the added screen wire to the module surface would seriously hamper the simulation technique. Based on the difficulties of the pressure-suited subject in manipulating the 40-cu-ft module during the pilot tests, it became apparent that the drag effect of the 120-cu-ft module would be too great for the subject to handle. Consequently, the screen wire was removed from the 120-cu-ft module for the cargo transport test.

Observations

The observations made relative to each test condition are summarized below.

Test series 1

1. Conditions.--The subject was connected by a strap restraint to the trolley truck in the circular rail. The handle was mounted flush on the cargo; the cargo module was free. The subject traversed along the rail pushing the cargo ahead of him.

The test performed comprised the following:

- Pilot runs using cargo modules with an 8-cu-ft volume and 1-slug mass and a 40-cu-ft volume and 5-slug mass
- Exploratory runs using cargo modules with an 8-cu-ft volume and 1-slug mass and an 8-cu-ft volume and 15-slug mass

2. Observations.--Pushing the module while the subject is free and unrestrained and traversing a single rail locomotion aid is not a satisfactory means of moving cargo in underwater simulation. The subject has difficulty in controlling the module and himself. Also, there is too much drag to get a good simulation. Pushing modules as a means of transport was discontinued for the remaining tests, except for tests 5 and 8.

Test series 2.

1. Conditions--The subject was connected by a strap restraint to the trolley truck in the rail. The handle was mounted flush on the cargo, and the cargo module was free. The subject traversed the rail pulling the cargo behind him.

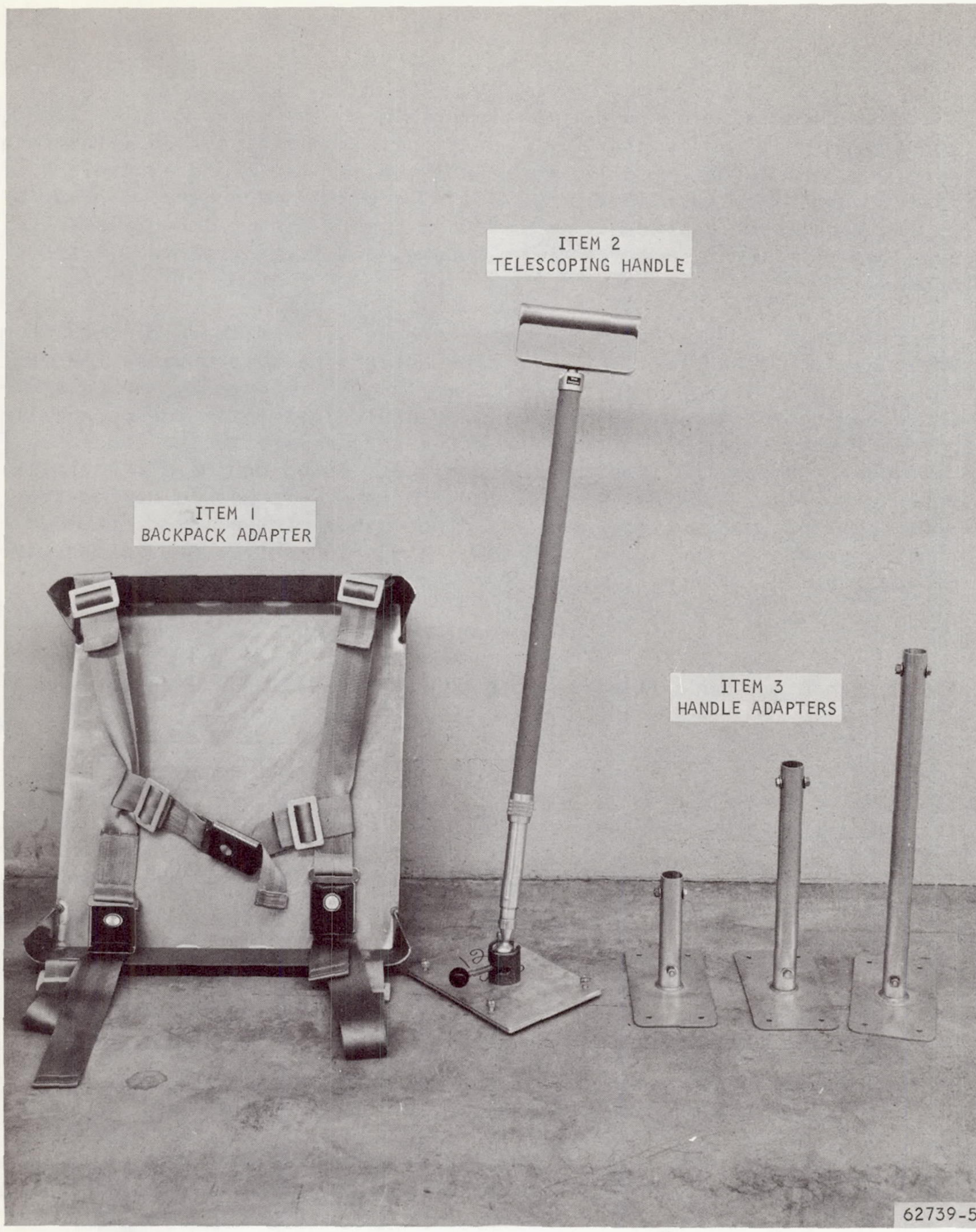


Figure 4-40. Cargo Manipulation Devices

The following tests were performed:

- Pilot runs with the following cargo module configurations:

  8-cu-ft volume and 1-slug mass

  4-cu-ft volume and 5-slug mass

- Exploratory runs with the following cargo module configurations:

  8-cu-ft volume and 1-slug mass

  8-cu-ft volume and 5-slug mass

  8-cu-ft volume and 15-slug mass

  40-cu-ft volume and 1-slug mass

  120-cu-ft volume and 1-slug mass

  120-cu-ft volume and 5-slug mass

  120-cu-ft volume and 15-slug mass

2. Observations.--Pulling the module while the subject is free and unrestrained and traversing a single rail locomotion aid is much more satisfactory than pushing the module. The drag effect produces a different control problem than that found in pushing the module. Volumes and masses in the combinations tested all proved to be too unwieldy to provide adequate control. All handling and manipulation on the rail or on the module were borderline tasks when considered from a control aspect. One-hand cargo manipulation and one-hand locomotion with cargo are not recommended. For placing or securing cargo, positioning in a secure restraint is required for the subject, i.e., dutch shoes, cage, or similar stability.

The cargo package, 8-cu-ft volume and 1-slug mass, is illustrated in Figures 4-41 through 4-46. The cargo package, 8-cu-ft volume and 5-slug mass, is illustrated in Figures 4-47 through 4-52. The cargo package, 8-cu-ft volume and 15-slug mass, is illustrated in Figures 4-53 through 4-55.

The cargo package, 40-cu-ft volume and 1-slug mass, is illustrated in Figures 4-56 and 4-57. The cargo package, 40-cu-ft volume and 5-slug mass, is illustrated in Figures 4-58 through 4-60.

The three runs conducted with the 120-cu-ft volume package were performed with the hardware cloth removed from the module and with the handle located at the top edge and end of the package. Since the package was so large and the tank diameter limited, the panel module and the trolley rail were removed from the tank. A pipe was placed in the tank and connected on the ladders on either side of the pool; rings were placed on the pipe to connect restraints to the large cargo module for tethering. The manipulation of the module was to follow the procedure illustrated in Figure 4-61. It was anticipated that means of securing the package to the rail would be required. Several special provisions, such as rigid ring supports to be attached at both ends of the cargo package, were planned; however, they were not required. Removal of the screen wire with the resulting reduction in drag coupled with a straight-line traverse along the pipe made it possible for the subject to move the large module with any test mass (see Figures 4-62 through 4-64).

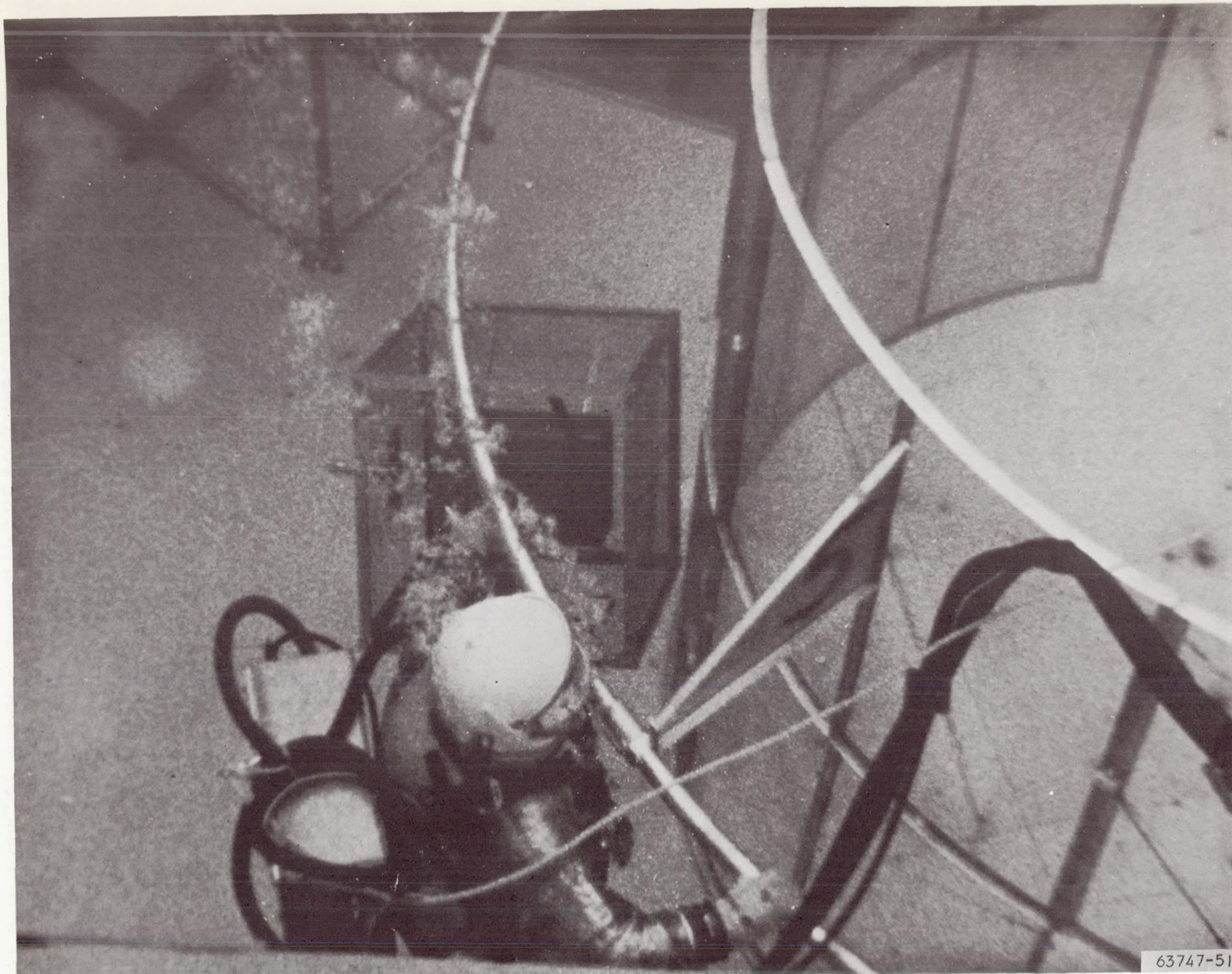


Figure 4-41. Subject With 1-Slug Mass and 8-cu-ft Package, Manipulating Cargo with One Hand as He Moves Along Locomotion Rail. Traverse is from left to right

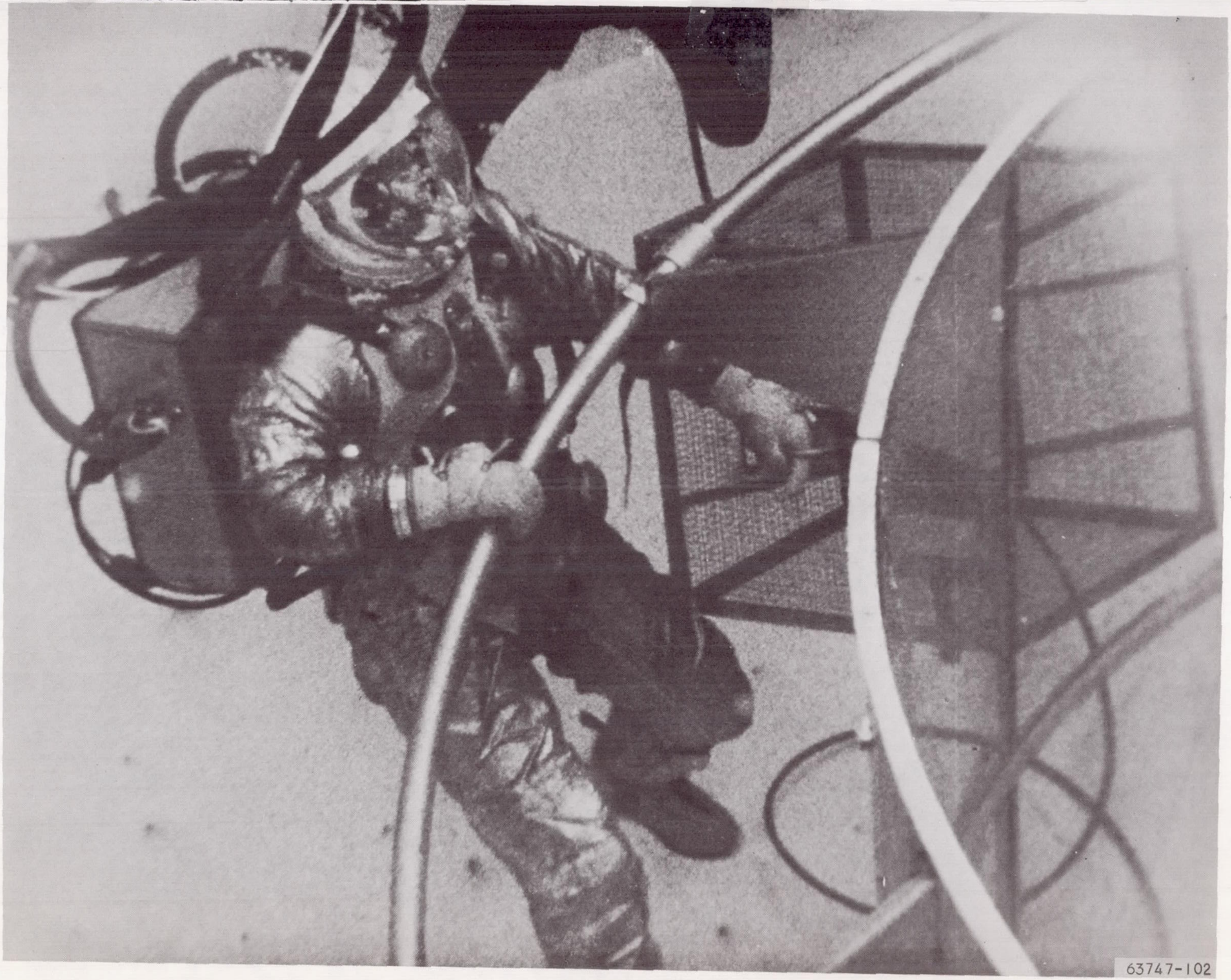


Figure 4-42. Subject Stabilizing Just Prior to Reaching Out for New Hand Position to Pull Self and Package Along Rail.

Figure 4-43. Continuation of 5-Slug and 8-cu-ft Package Traverse, Just Before Changing Package to Right Hand for Return Trip

63747-104

Figure 4-44. Subject With Package in Right Hand Following Changeover and Starting Return Trip Using the Left Hand to Pull on Rail

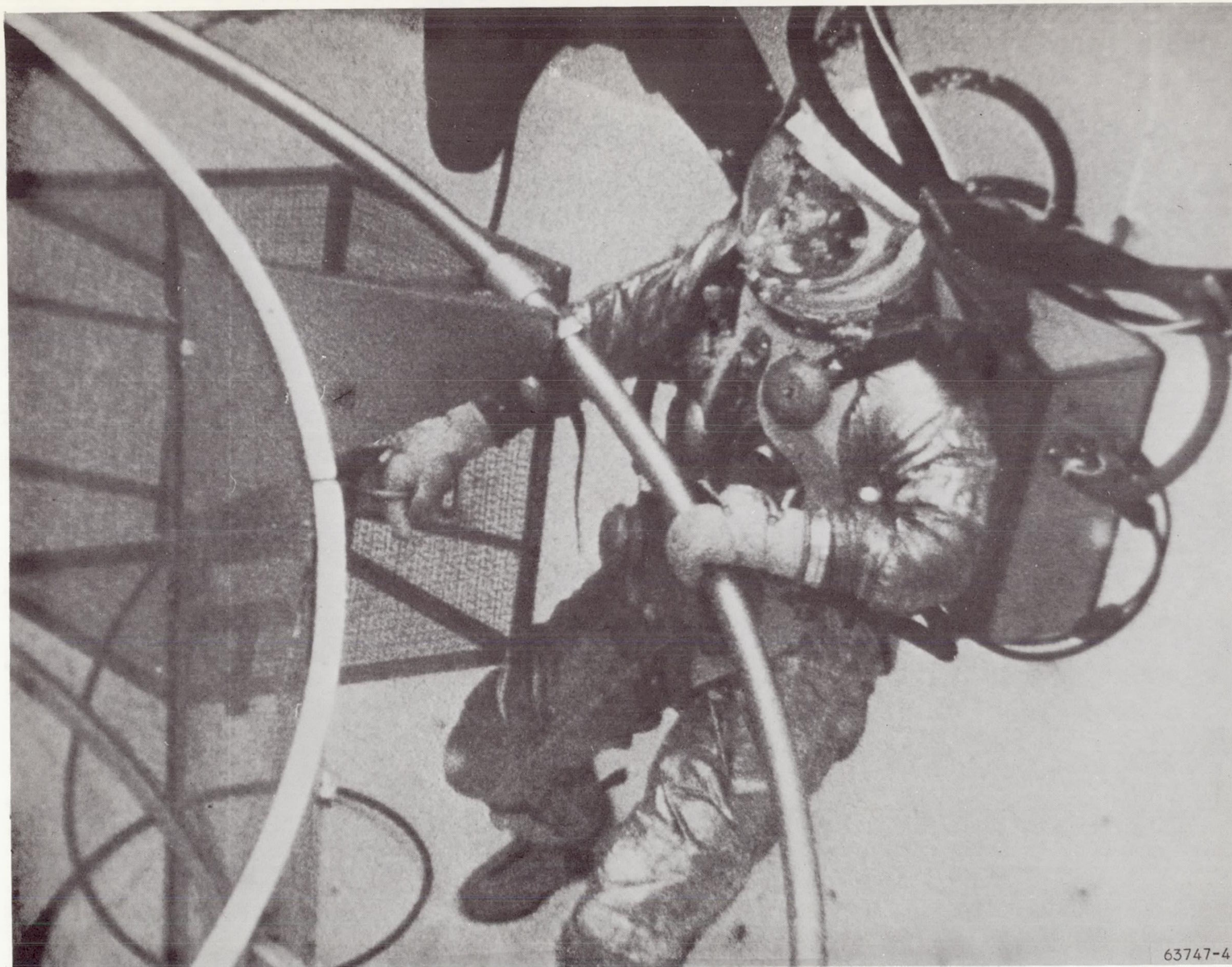


Figure 4-45. Continuation of 5-Slug and 8-cu-ft Package With Subject Cargo on Return Traverse

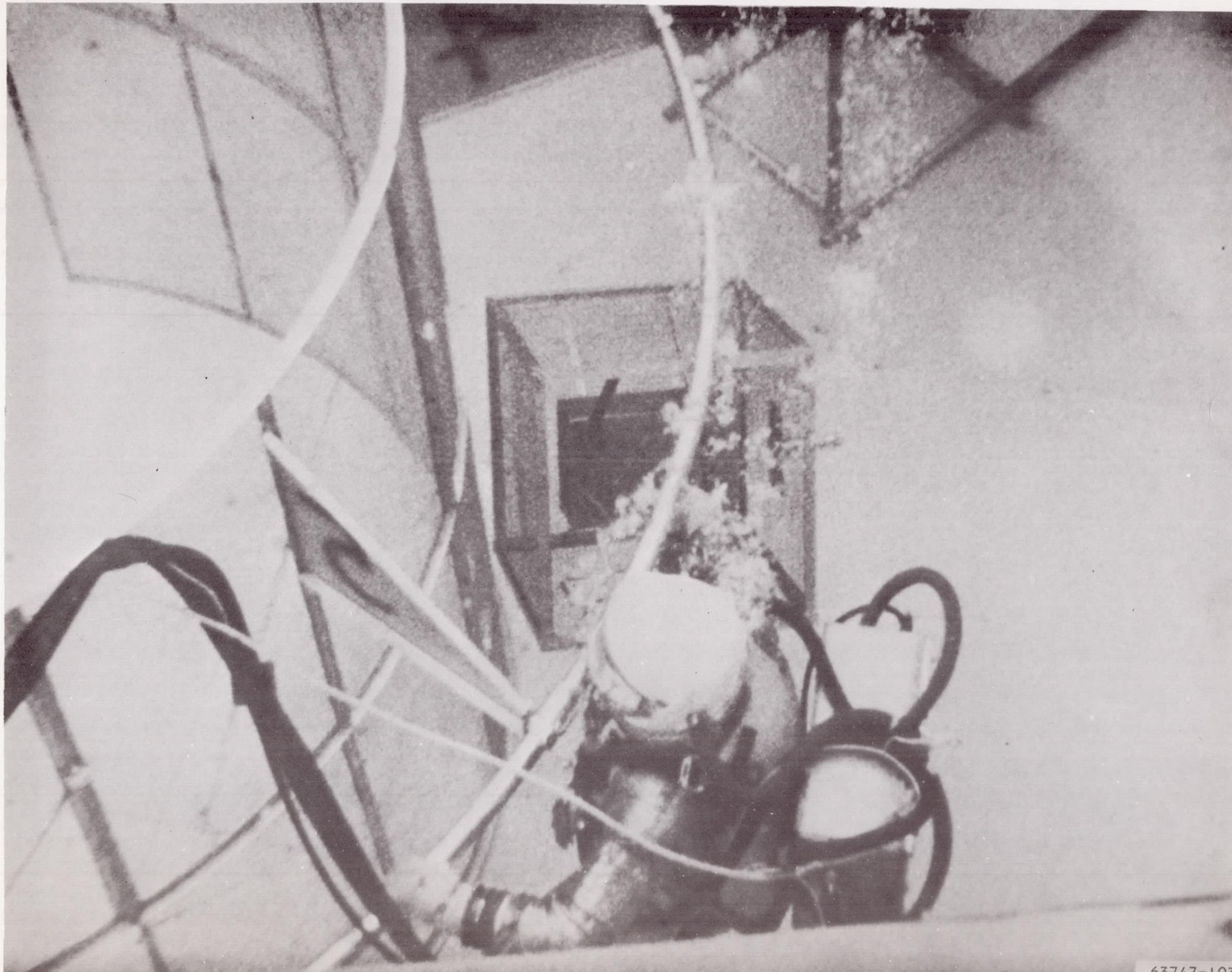


Figure 4-46. Continuation of 5-Slug and 8-cu-ft Package Return Traverse

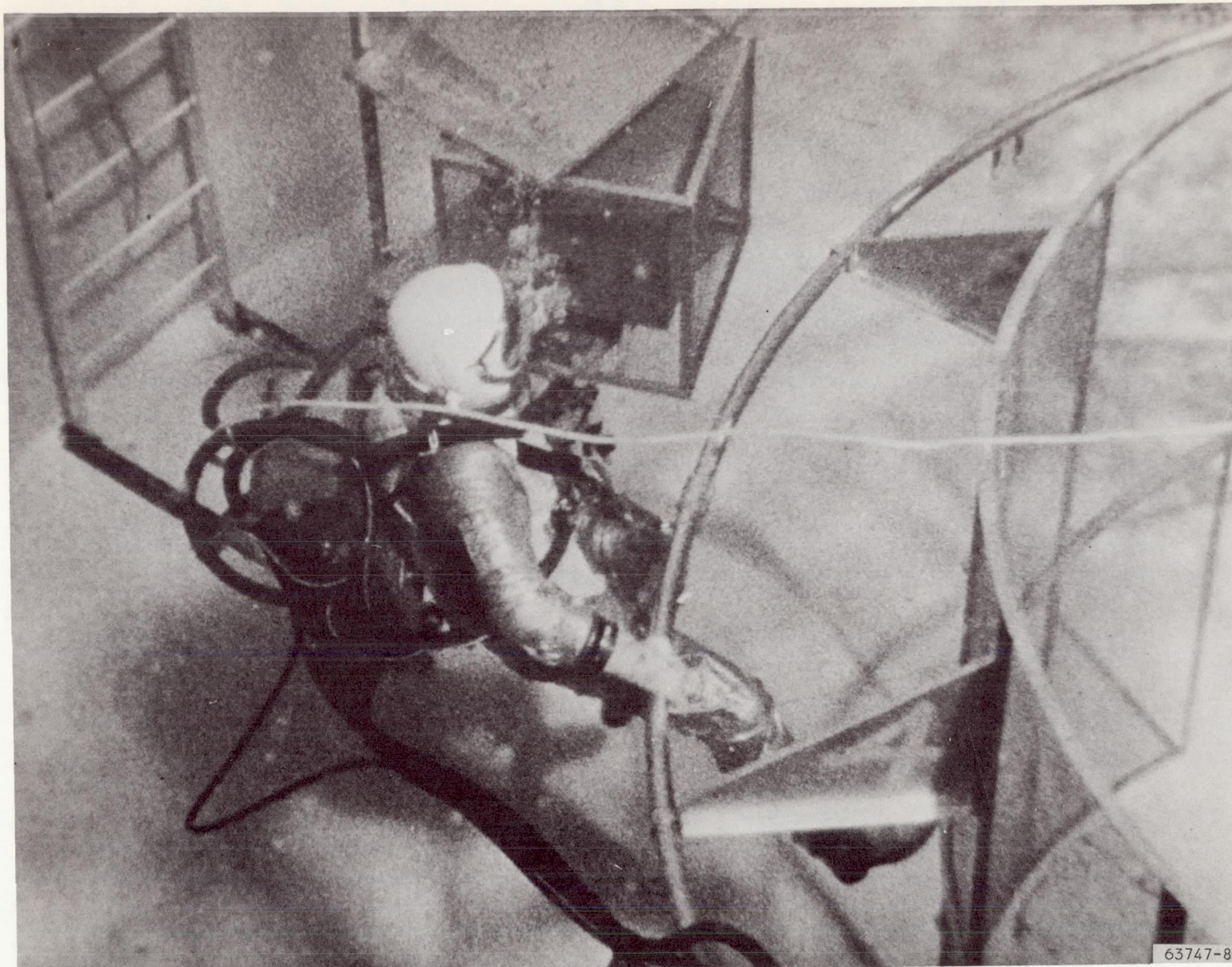


Figure 4-47. Subject Removing Cargo Module From Stowed Position and Starting Traverse

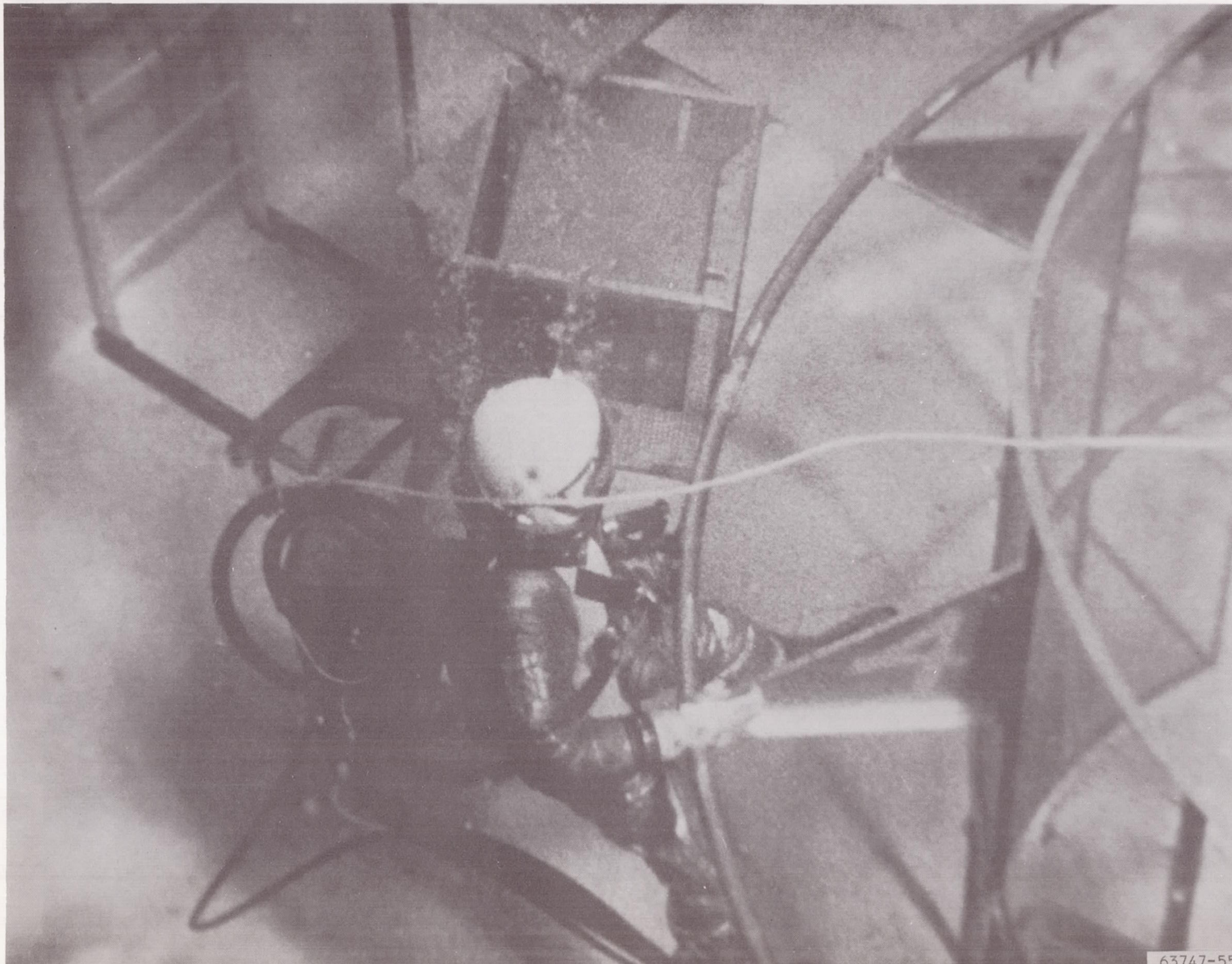


Figure 4-48. Cargo Module Clearing Holder as Subject Pulls with One Hand on Locomotion Rail

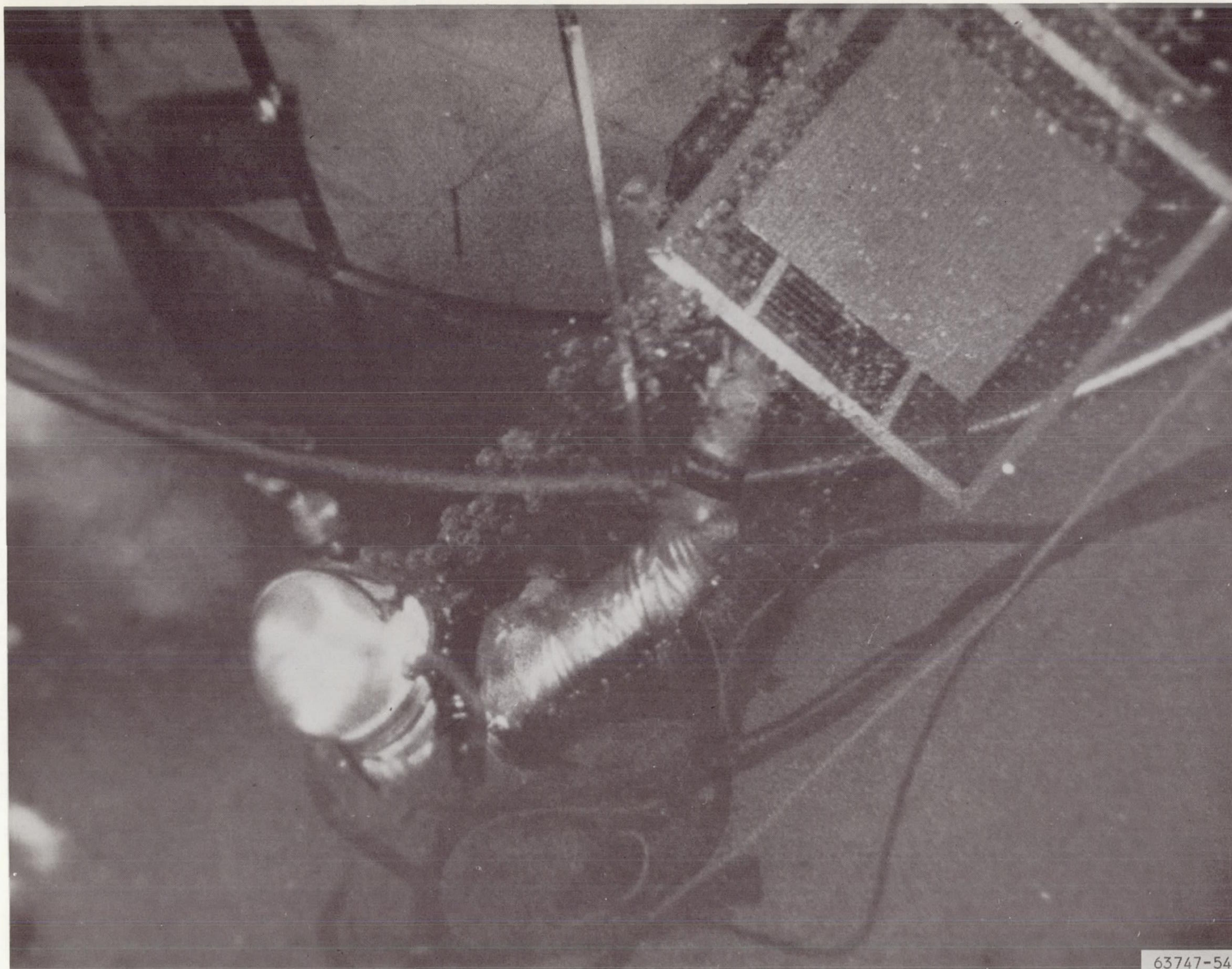


Figure 4-49. Subject Moving Package Above Rail to Change to Left Hand for Stowing in Cargo Holder

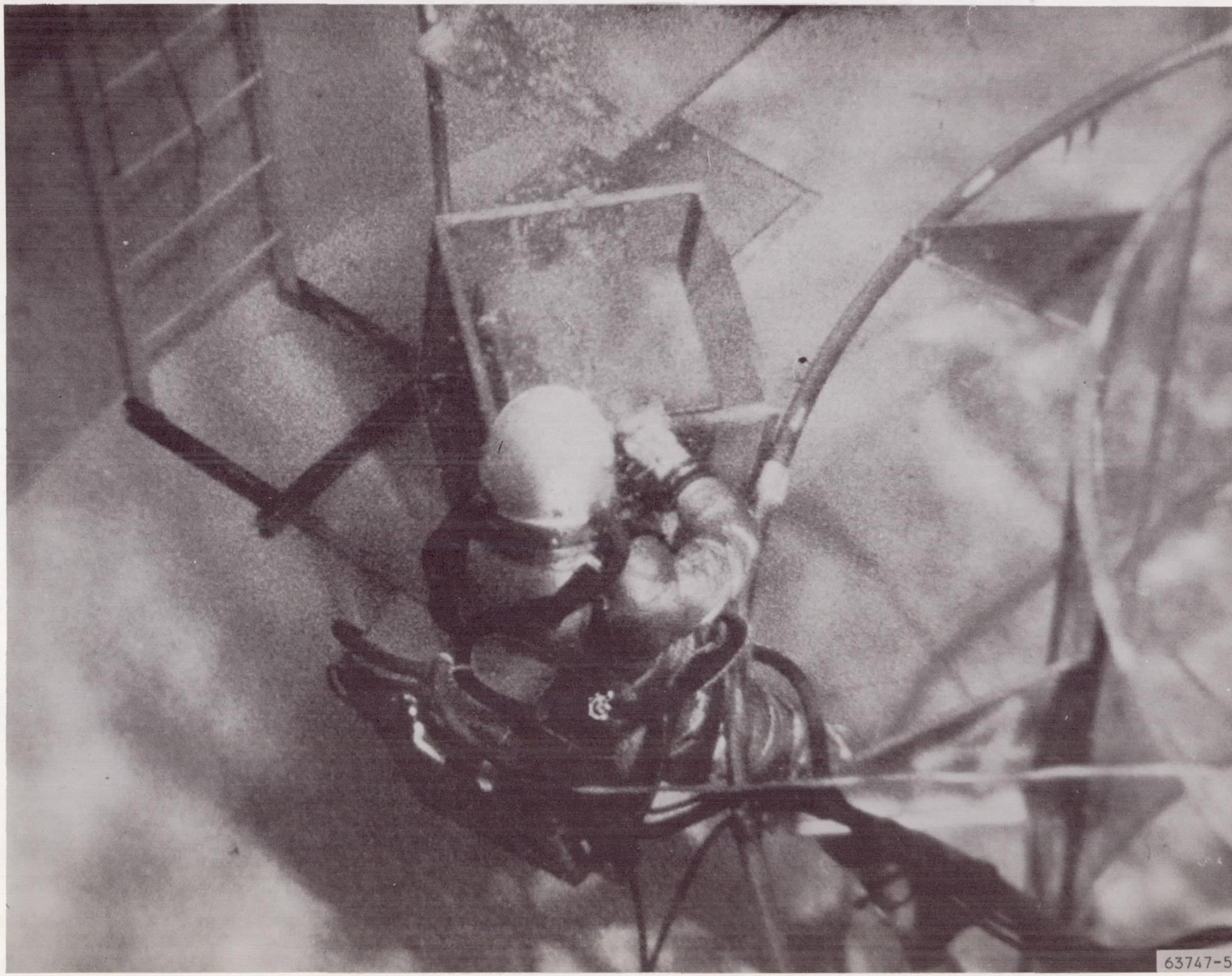


Figure 4-50. Subject Guiding Package to Holder for Stowing

Figure 4-51. Subject Pushing Module Into Holder to Complete Cargo Transport Run

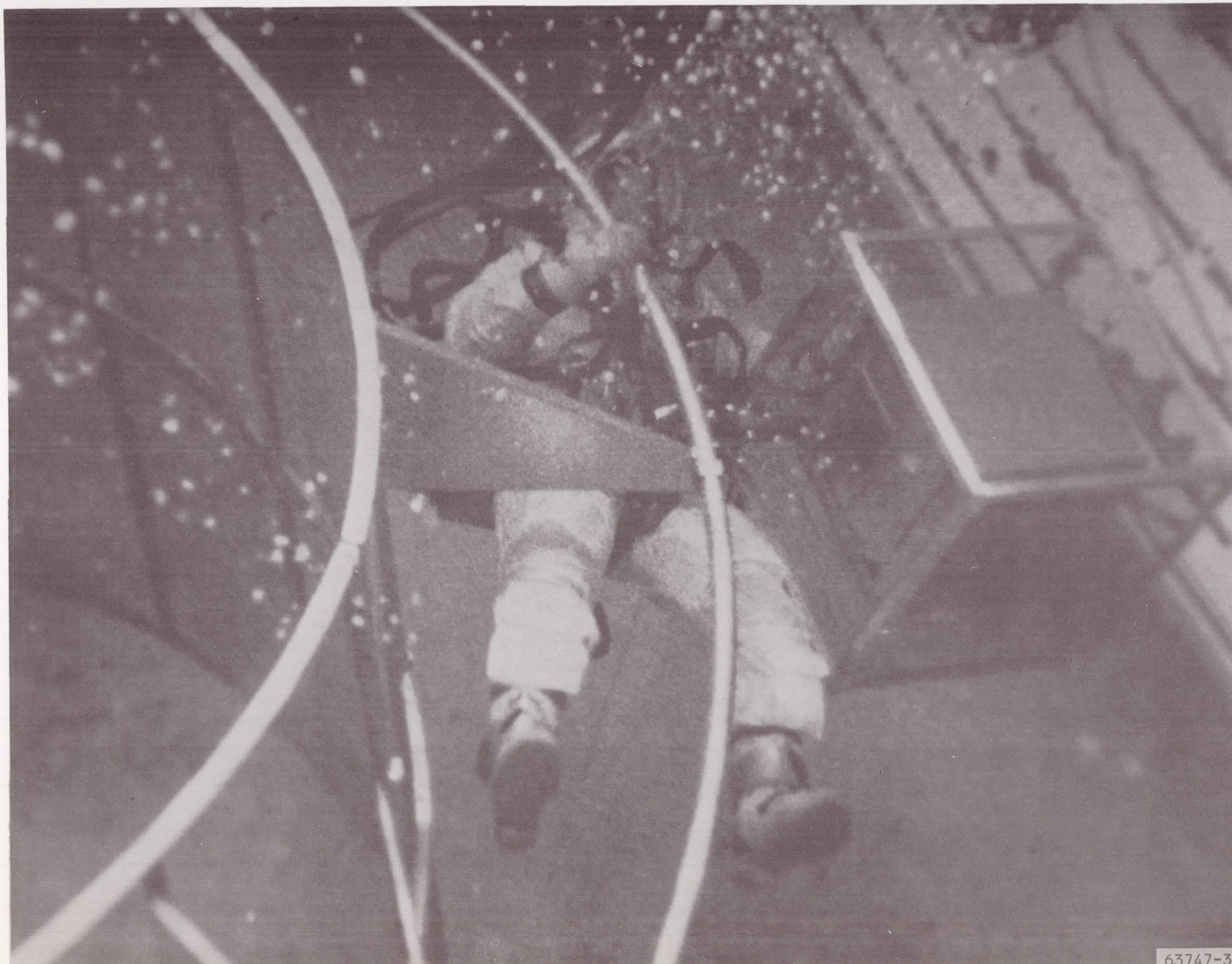


Figure 4-52. Subject Oriented Parallel to Rail Using Short, Quick Pulls to Traverse. 8-cu-ft Volume, 5-Slug Mass.

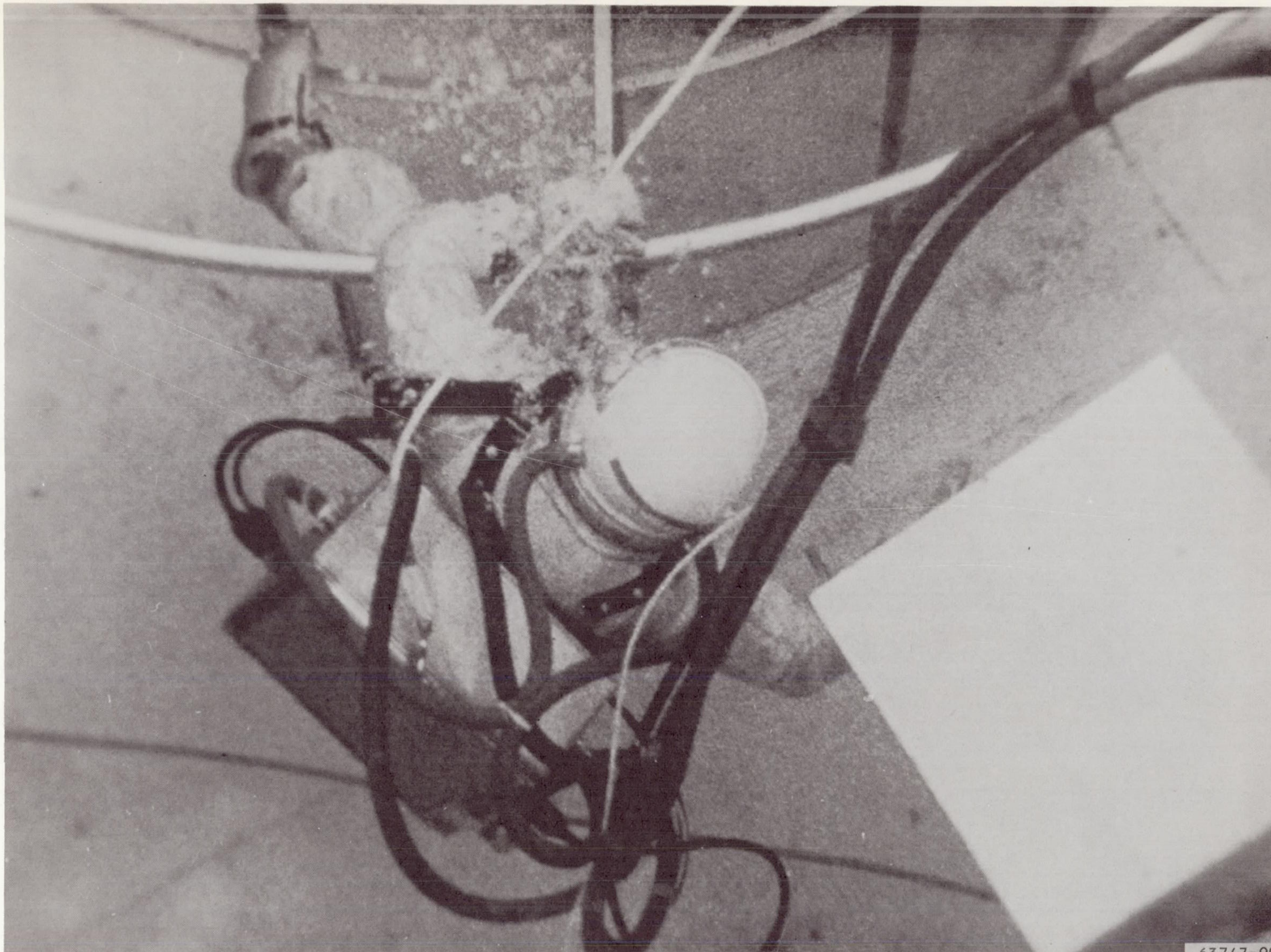


Figure 4-53. Cargo Transport With 15-Slug Mass, 8-cu-ft Volume Package; Note Subject's Foot on Module for Second Point of Contact

Figure 4-54. 15-Slug Mass, 8-cu-ft Volume Showing Use of Forearm Handle

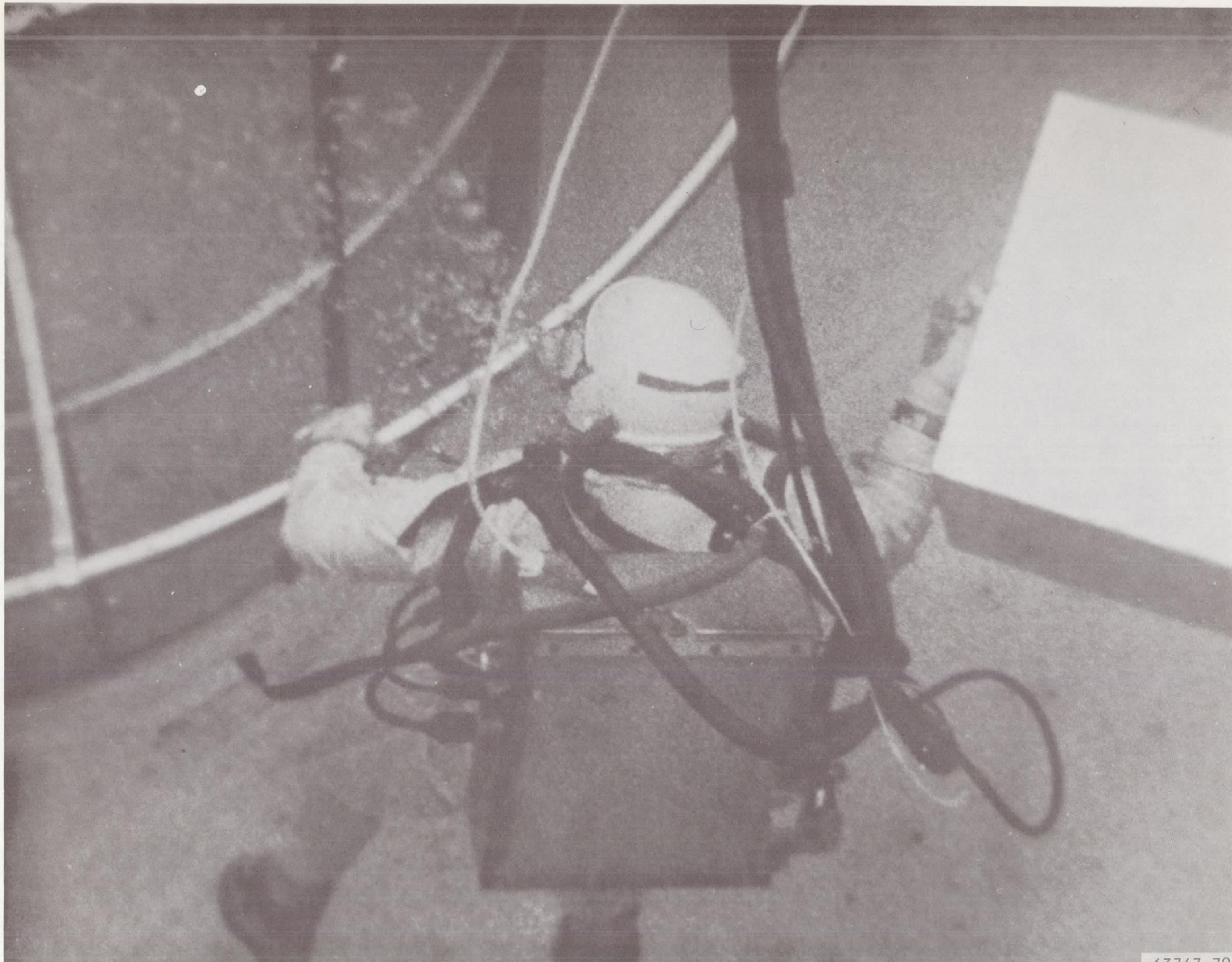


Figure 4-55. Sequence Photograph Following Figure 4-54, Showing the Subject Moving the 15-Slug Mass with the Two-Handle Configuration

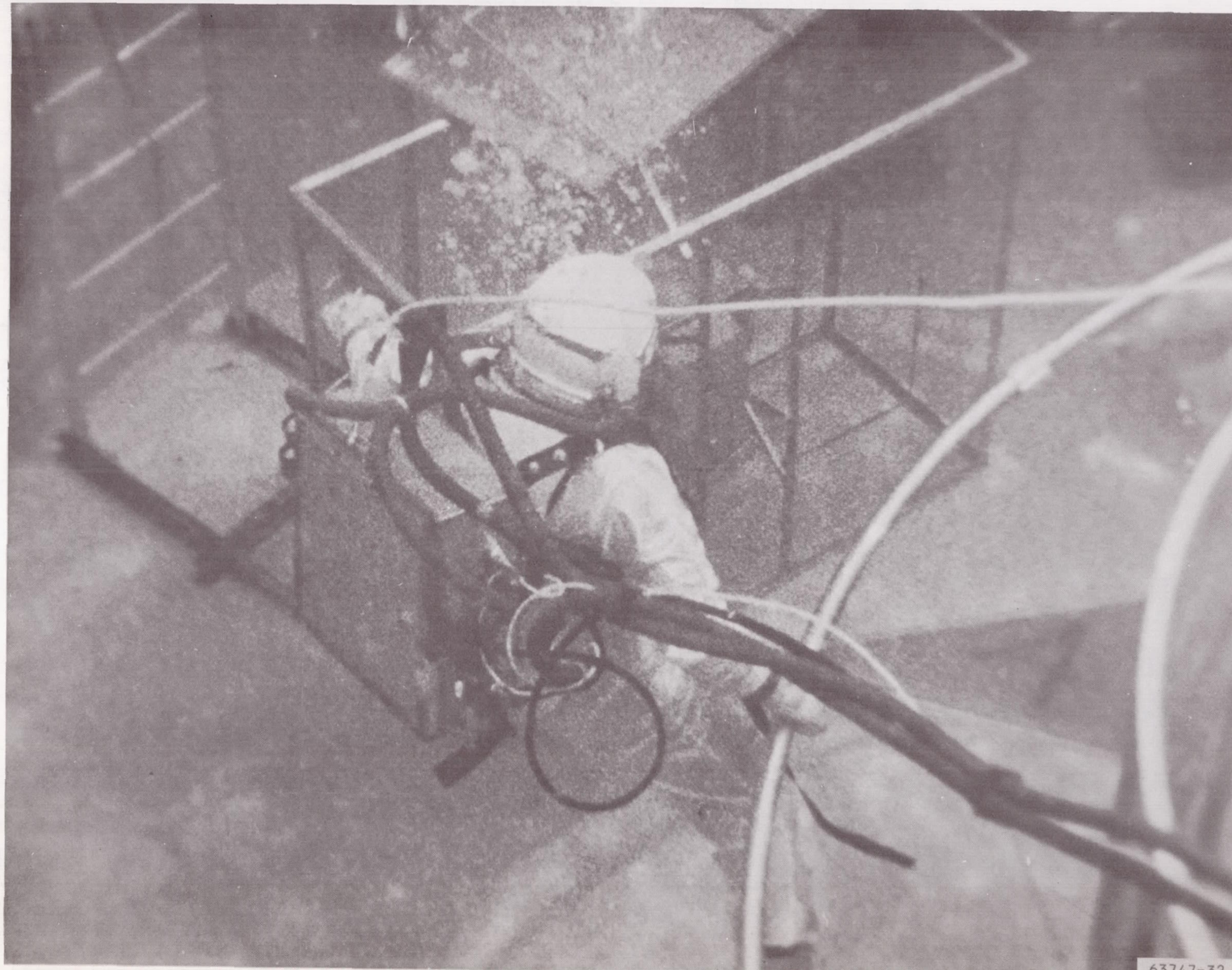


Figure 4-56. Positioning 40-cu-ft Package in Cargo Module Holder

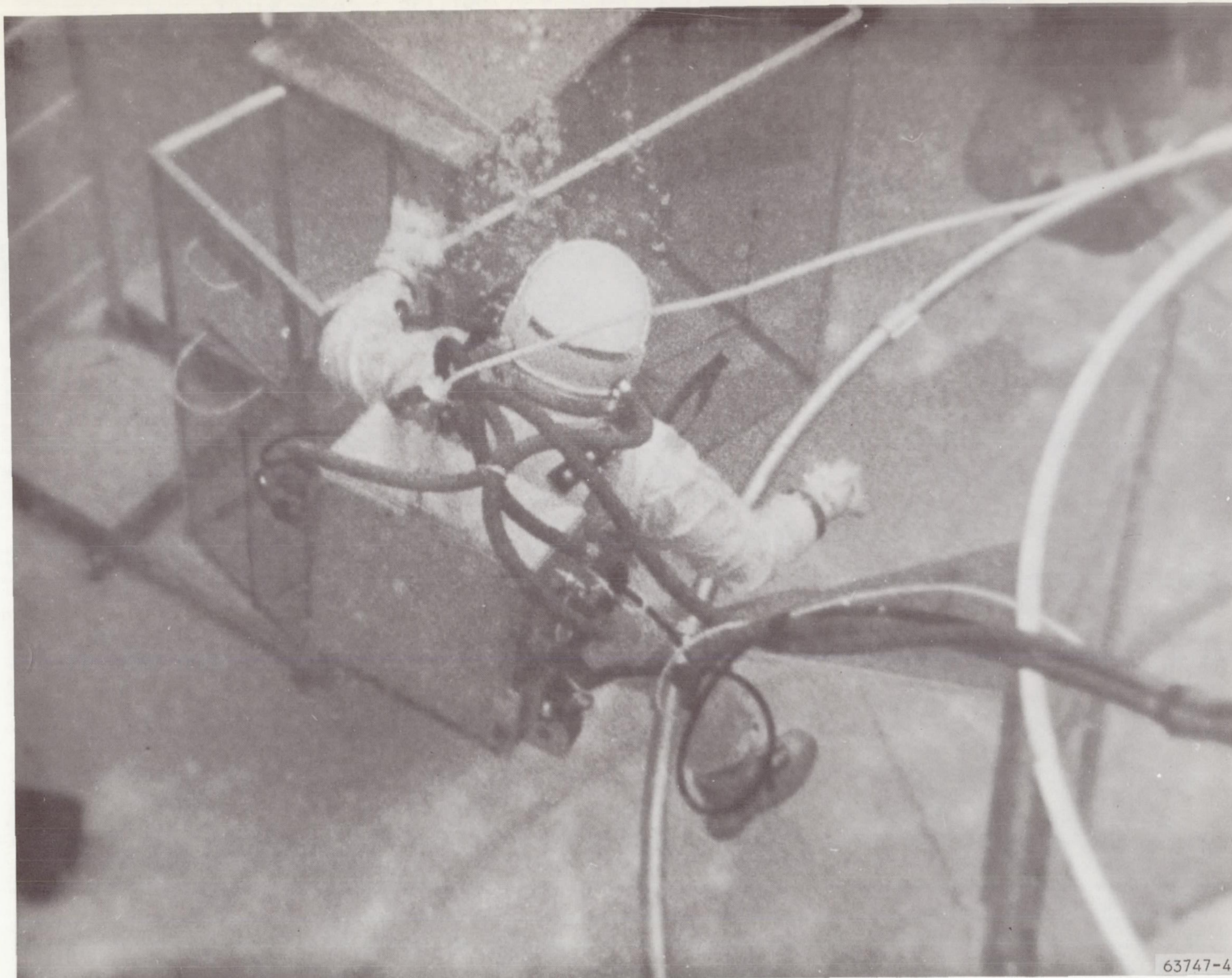


Figure 4-57. Subject Kicking at Module With Left Foot (Not Showing) to Make Final Positioning in Cargo Holder

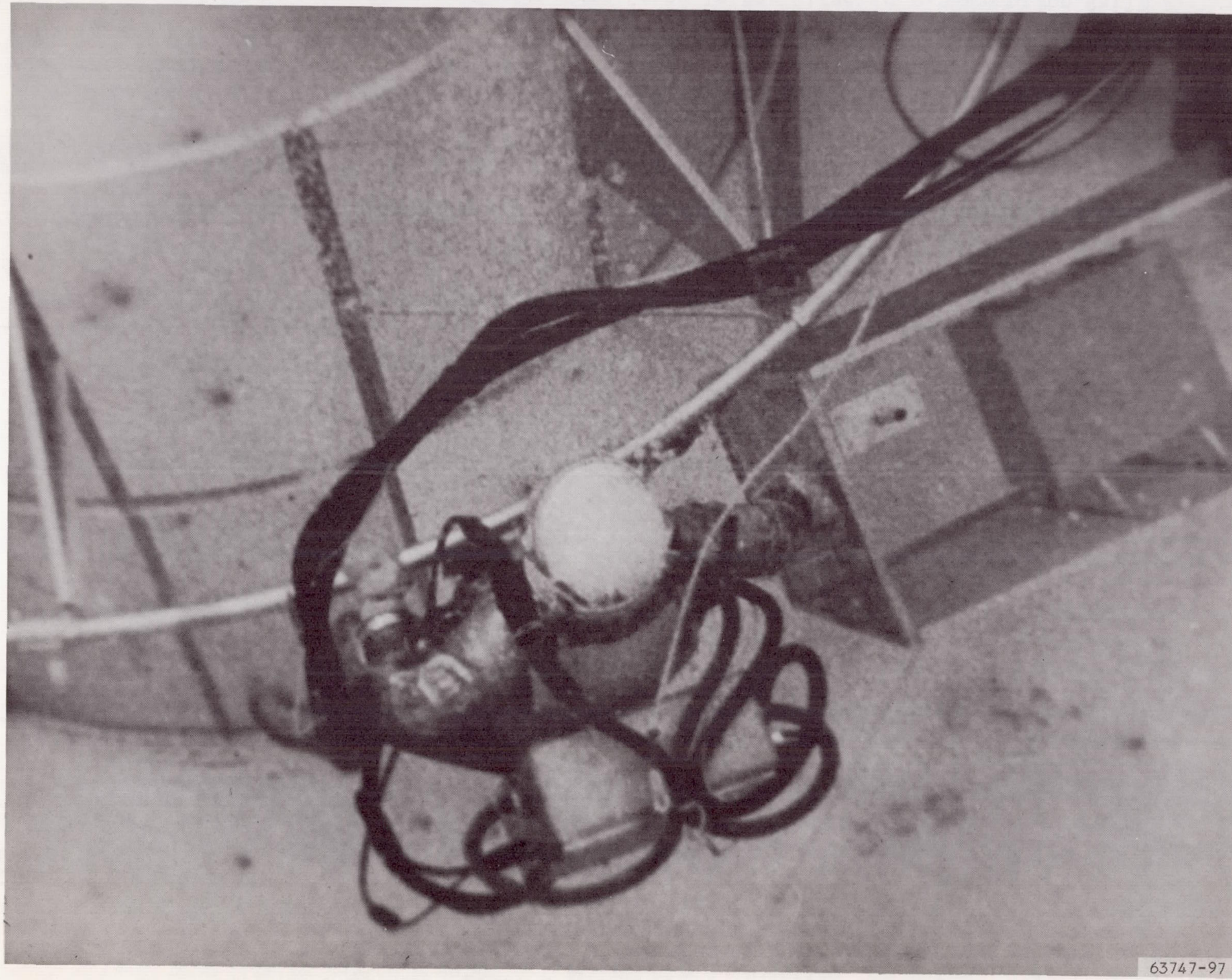


Figure 4-58. Return Traverse with 40-cu-ft Volume and 5-Slug Mass

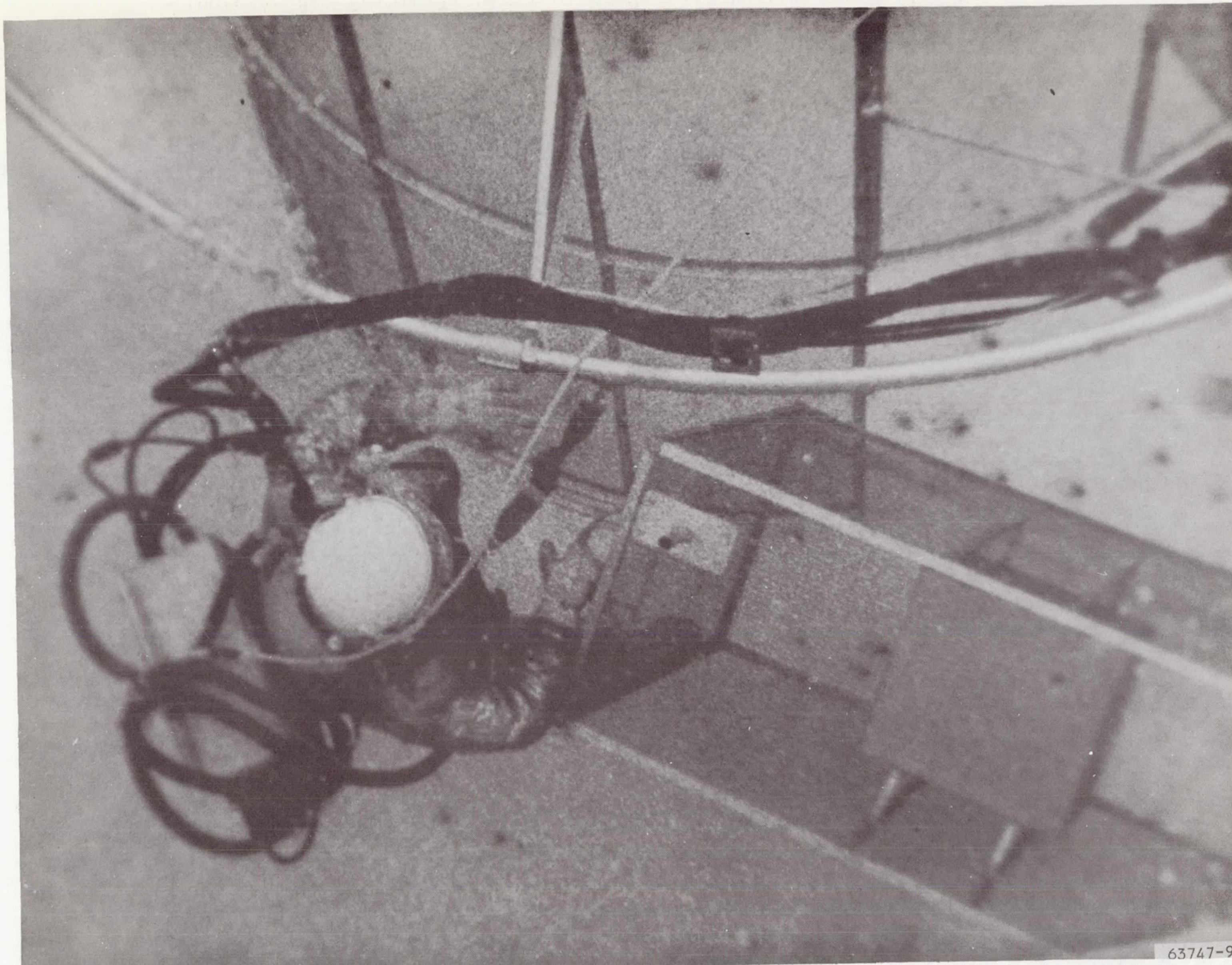


Figure 4-59. Subject Reaching to Free Strap Tether Attached to Locomotion Rail

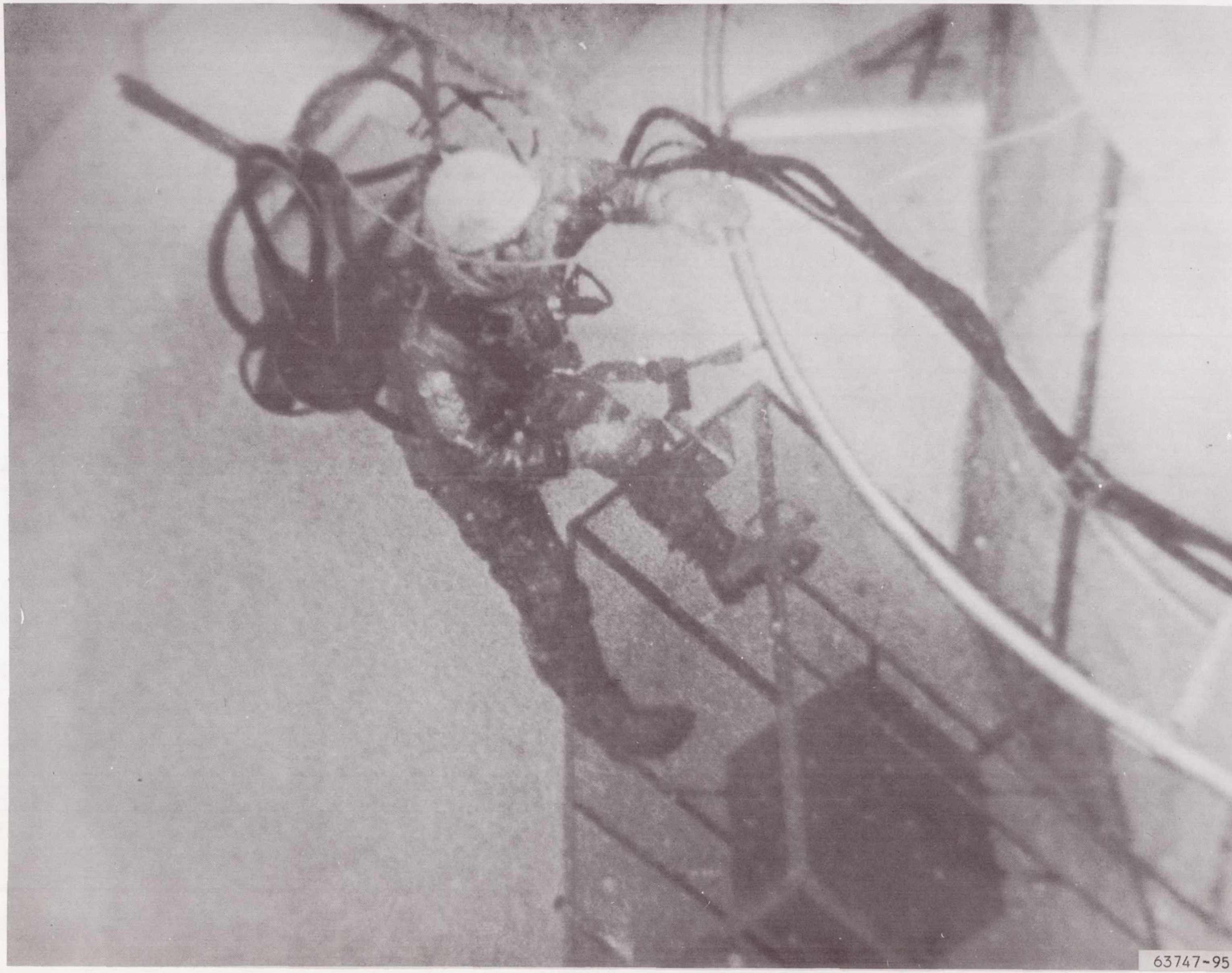
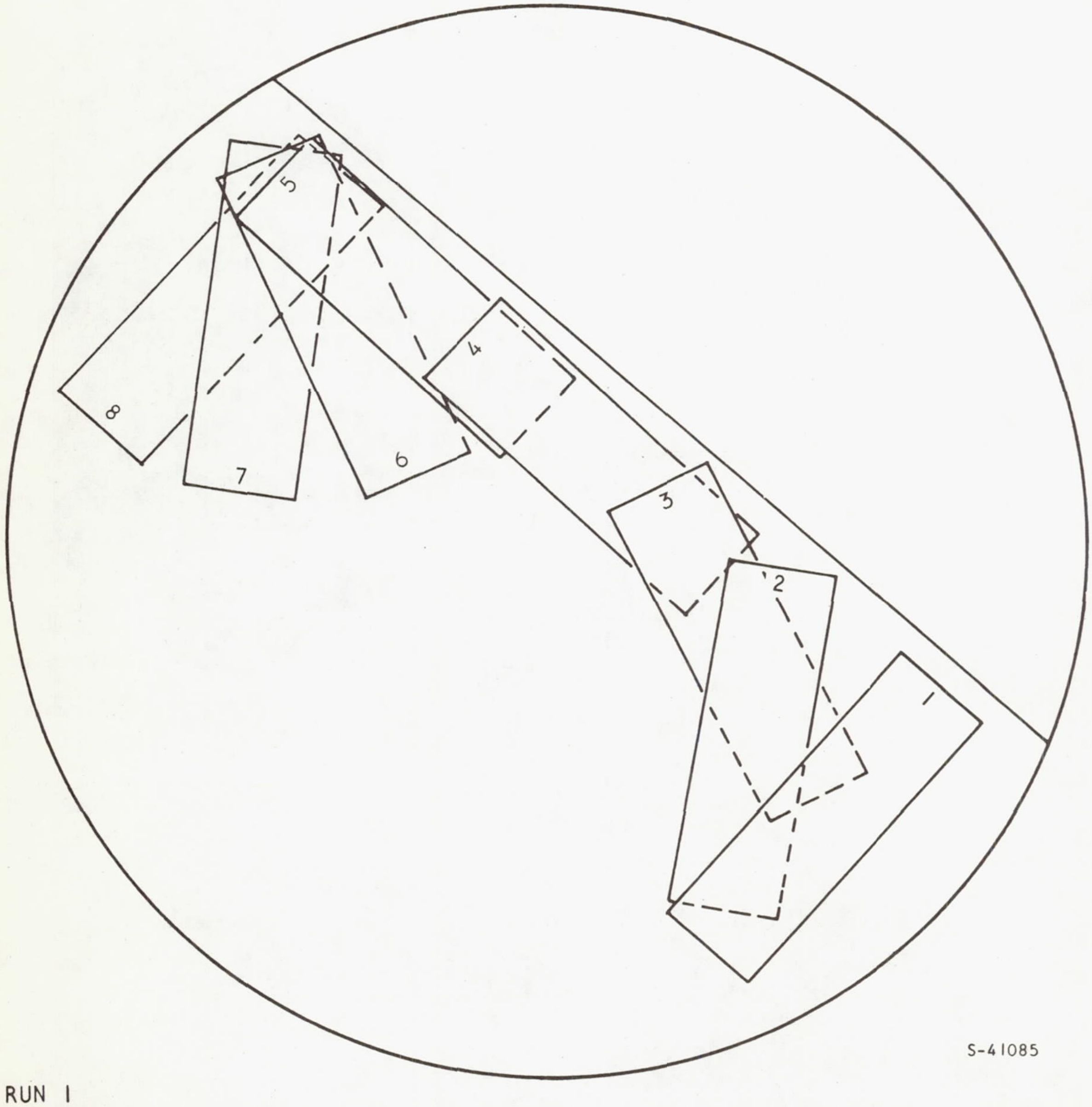


Figure 4-60. Subject Starting to Pass Package Across Front of Body to Left Hand in Preparation to Stow Package



RUN I

CONDITION: PACKAGE FREE, SUBJECT ON STRAP RESTRAINT CONNECTED TO RING ON POLE. SUBJECT TO USE FRAMEWORK FOR HANDLES IF EXPEDIENT.

TASK

MOVE PACKAGE FROM POSITION I THROUGH POSITION 8
MOVE PACKAGE FROM POSITION 8 THROUGH POSITION I

Figure 4-61. Cargo Transport, 120 cu ft

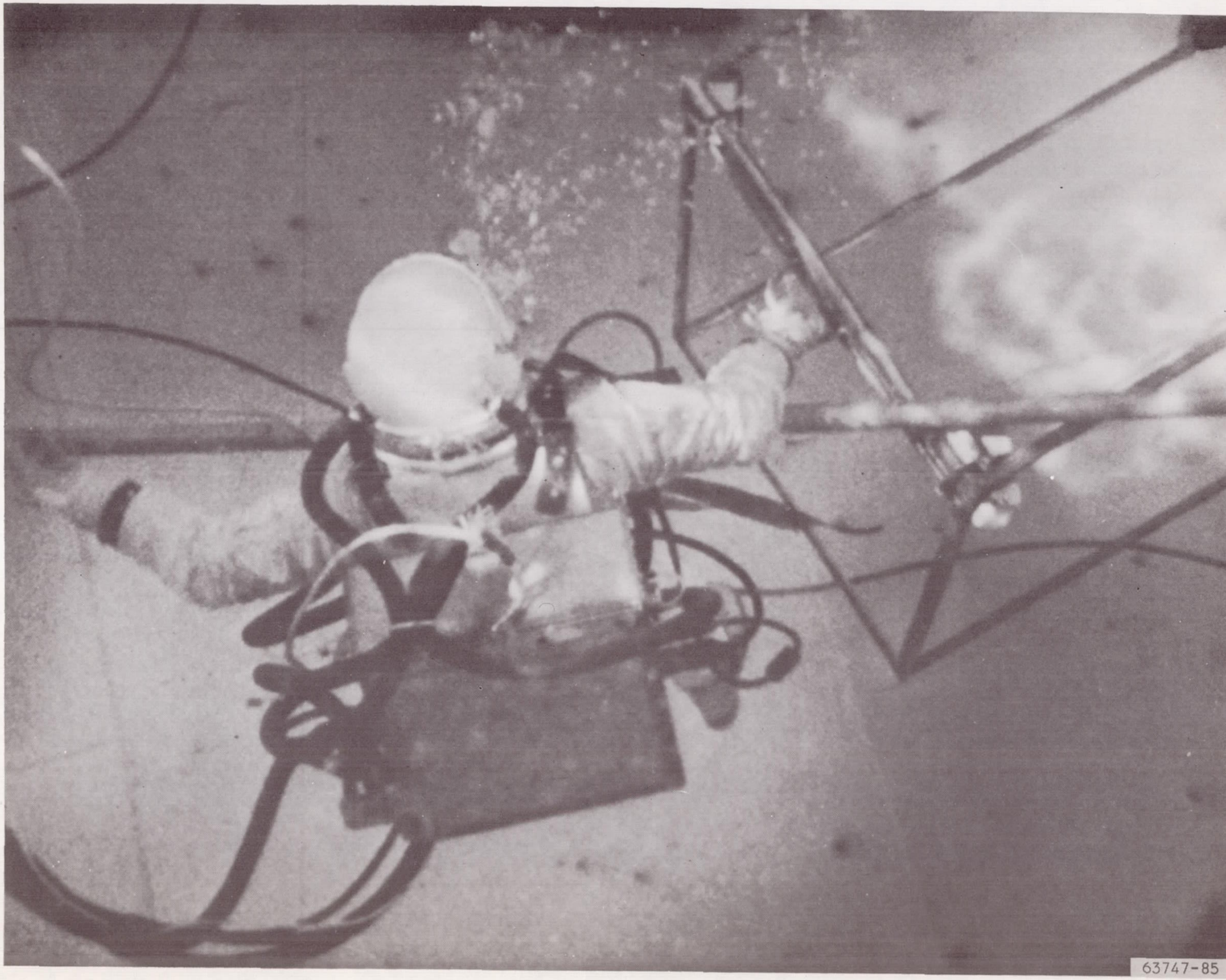


Figure 4-62. Subject Moving 120-cu-ft Volume with 1-Slug Mass Module

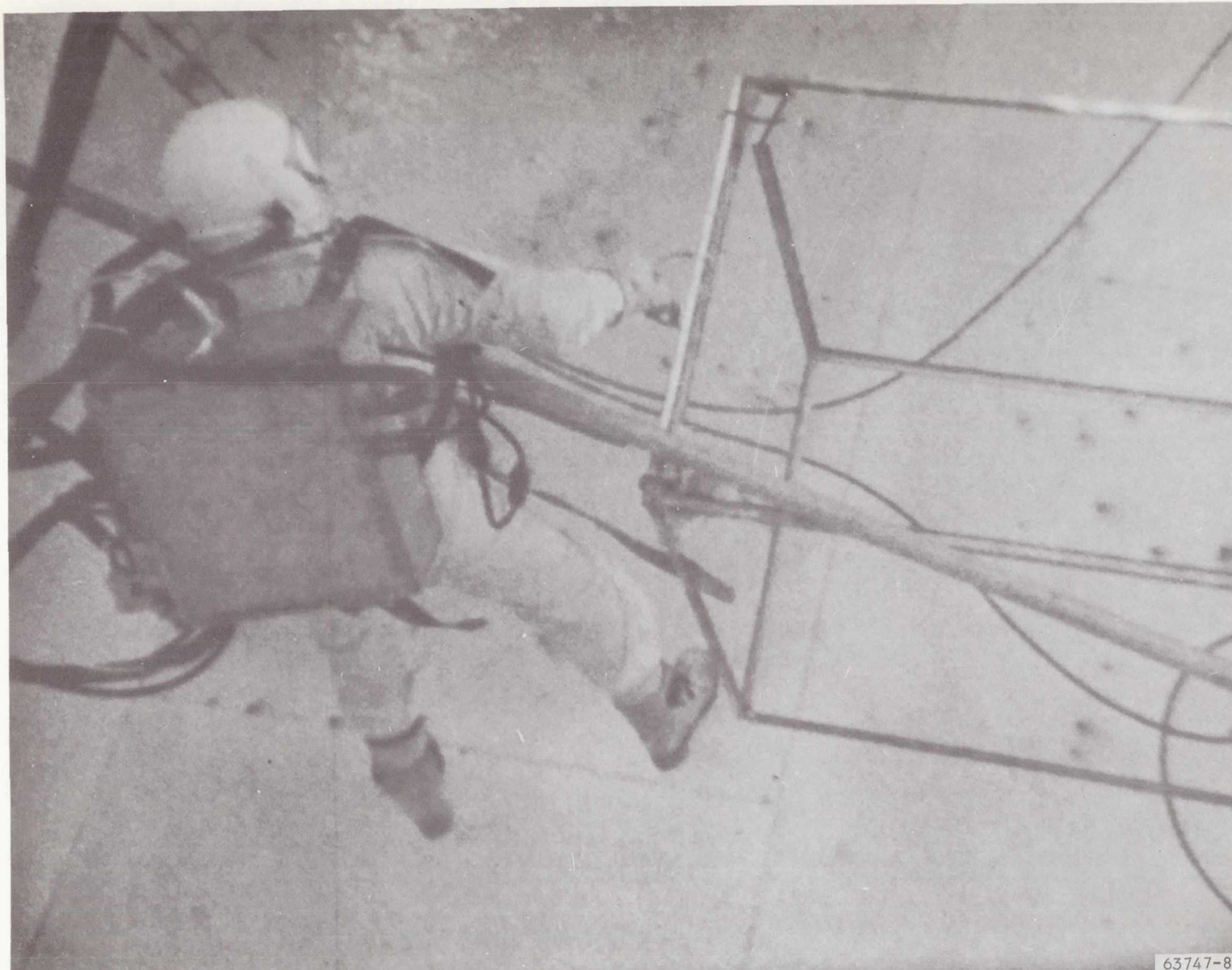


Figure 4-63. Subject Kicking Module to Align It During Traverse

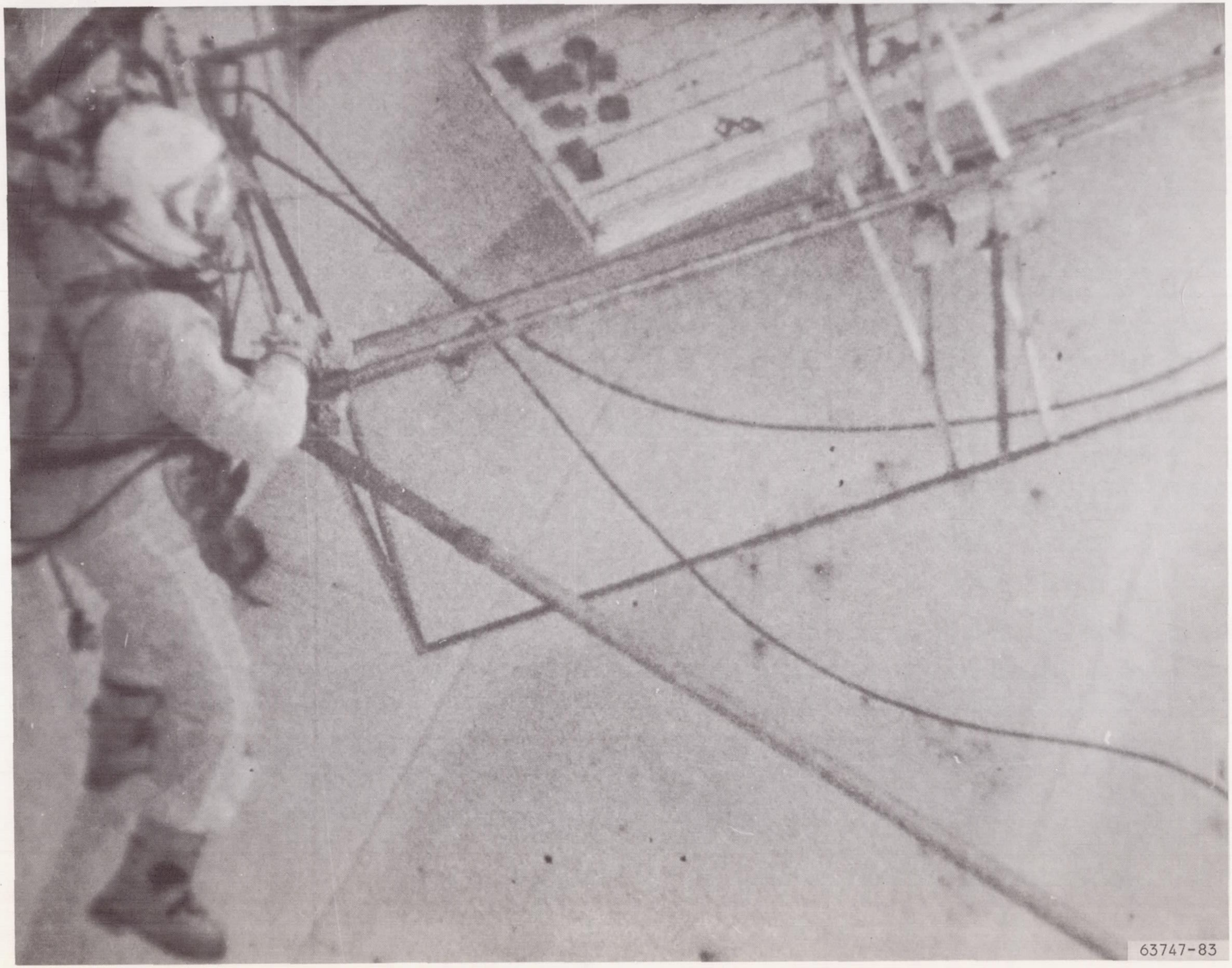


Figure 4-64. Subject Turning 120-cu-ft Module for Return Trip Along Rail

Tests with handling devices other than the single handle were discontinued since they had not demonstrated any improvement in performances during the other runs. The use of a backpack mode to transport the large volume was impractical from a hardware safety viewpoint. Since the telescoping handle had not been successful, it was dispensed with earlier in the tests.

Test Series 3

1. Conditions--The subject was connected by a strap restraint to the trolley truck in the rail. The telescoping handle was mounted to the cargo module, and the cargo was free. The subject pulled the cargo.

The tests performed were as follows:

- Pilot run with 8-cu-ft volume and 1-slug mass package
- Exploratory runs with the following packages:

  8-cu-ft volume and 1-slug mass

  40-cu-ft volume and 5-slug mass

  40-cu-ft volume and 5-slug mass

2. Observations--The telescoping handle was intended to keep the cargo module away from the subject and enable him to guide and manipulate the package past obstructions. However, this did not prove to be the case for either the 8-cu-ft or the 40-cu-ft volume; both packages provided control problems for the subject. Attempts to hold the package away from the rail and from the mockup generally were not successful. The module tended to follow directly behind the subject toward the mockup. When this occurred, the cargo package would "hang up" on the mockup panels and on the rail itself. Each contact of the cargo with a fixture in the tank resulted in a control problem for the subject; the traverse was more difficult than it was with handles that allowed the subject to be close to the cargo package (see Figures 4-65 through 4-67).

The difficulties observed in each run with the telescoping handle led to the decision to eliminate the concept from further testing.

Test Series 4

1. Conditions.--The subject was connected by a strap restraint to the trolley truck in the rail. The subject pulled the cargo.

Tests performed were as follows:

- Pilot run with an 8-cu-ft volume and 1-slug mass package
- Exploratory runs with the following packages:

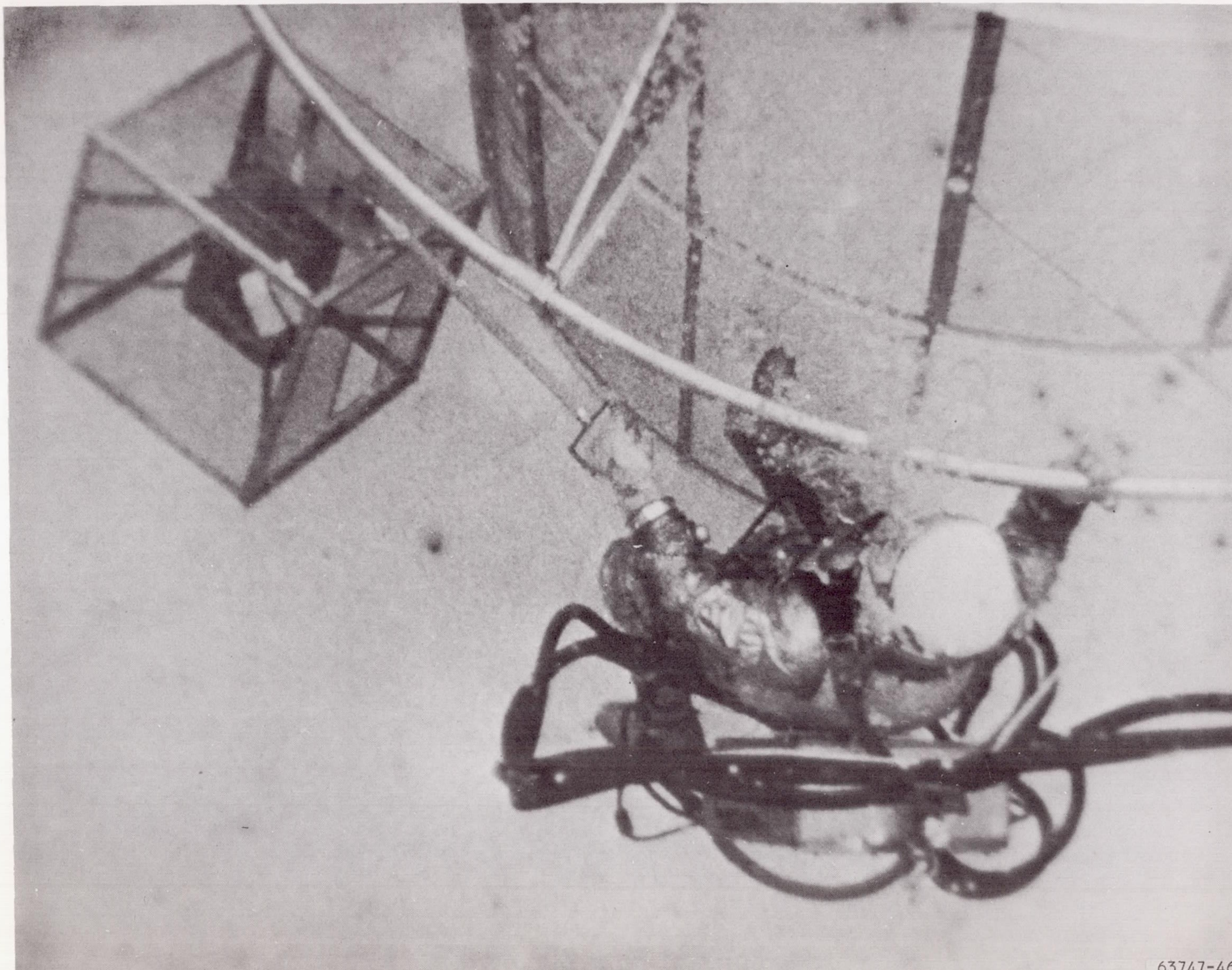


Figure 4-65. Sequence Photographs (Figures 4-65, 4-66, and 4-67) Using Extended Handle for Cargo Transport. 8-cu-ft Volume and 1-Slug Mass

Figure 4-66. Second Photograph of Series Depicting Use of Extended Handle on Package

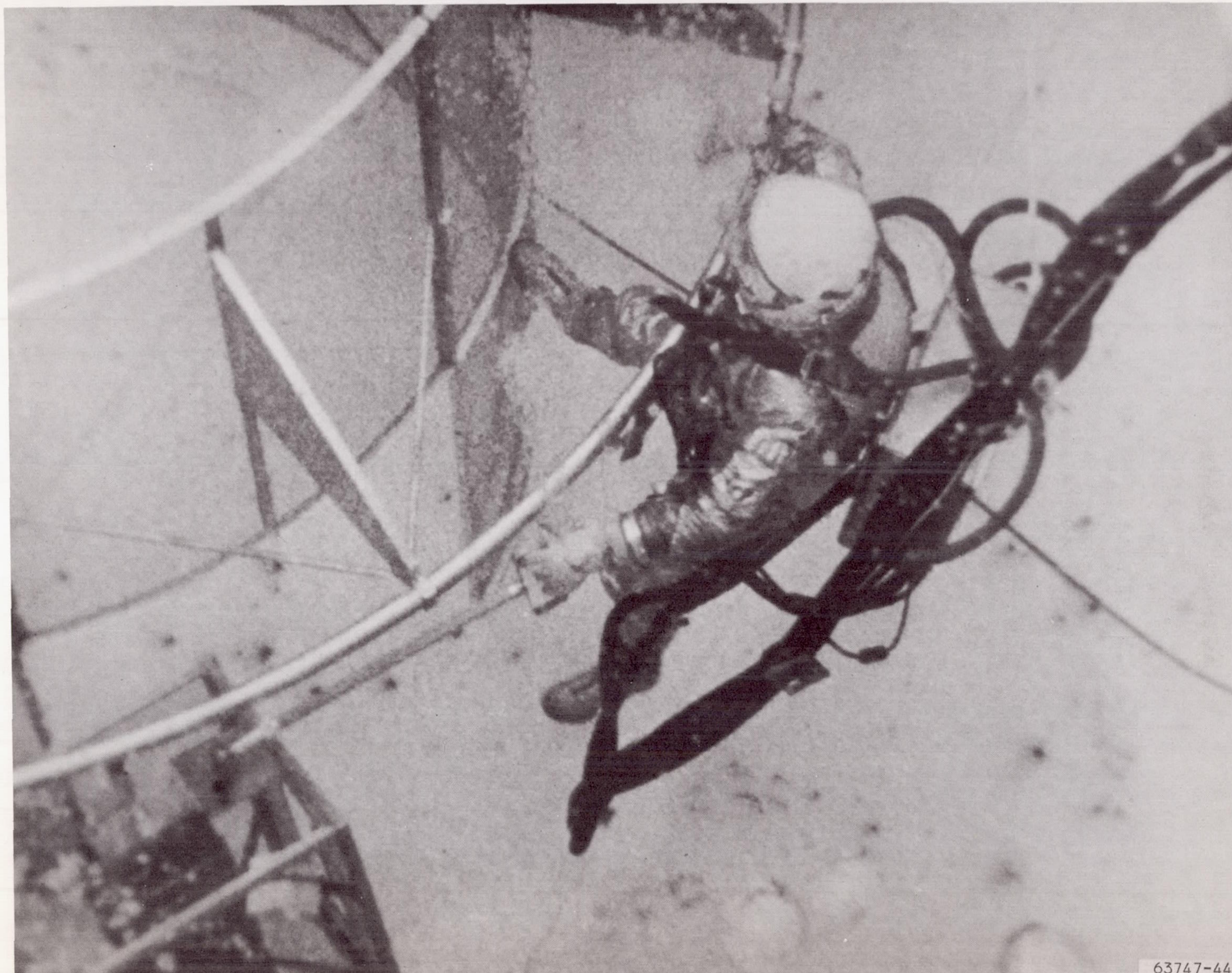


Figure 4-67. Last Photograph in Sequence, Depicting Use of Extended Handle on Cargo Module

- Pilot run with an 8-cu-ft volume and 1-slug mass package

- Exploratory runs with the following packages:

  8-cu-ft volume and 1-slug mass

  40-cu-ft volume and 5-slug mass

2. Observations.--Trolley truck assemblies that functioned at 1 g were not applicable to moving neutrally buoyant cargo packages. Apparently, the lack of constant tension on the truck wheels allowed enough "play" to cause them to bind in the rail. Teflon slides were substituted for the trolley trucks; although usable, they could not provide as free a flow of objects along the rail as was desired. Unfortunately, little can be said about the success or failure of the concept without the use of functional hardware in the observation which leads directly to the recommendation of hardware design, even in exploratory programs.

Moving cargo in space by trolley truck and rail would provide the necessary control that is lacking when the subject manually grasps cargo packages. A double rail system should provide essentially all the control necessary for both the astronaut and the cargo; it is strongly recommended that this concept be considered in future studies.

Test series 5

1. Conditions.--The subject was connected by a strap restraint to the trolley truck in the rail. A rigid trolley assembly is on the cargo, and the cargo module is pushed by the subject. A pilot test run was performed with an 8-cu-ft volume and 1-slug-mass package.

2. Observations.--So much difficulty was encountered in attempting to push the modules around the rail that no further tests were conducted in this test mode. Pushing the module on a highly functional trolley system might prove more feasible but may be undesirable. Control becomes a problem when force is applied at the rear of a free or semi-free cargo module. It appears that the numerous restrictions associated with the pressure suit also hamper the subject when pushing as compared to the same work when pulling.

Test series 6

1. Conditions.--The subject is connected by a strap restraint to the trolley truck in the rail. The cargo module is attached to the subject's back with a special backpack harness.

No pilot test runs were conducted in this test series. The exploratory tests performed used the following packages:

8-cu-ft volume and 1-slug mass

8-cu-ft volume and 5-slug mass

8-cu-ft volume and 15-slug mass

40-cu-ft volume and 1-slug mass

40-cu-ft volume and 5-slug mass

2. Observations.--Attaching the cargo modules to the backpack was the most functional mode of transporting the cargo modules. The success of this mode is attributed mainly to two factors: (1) the subject had both hands available to use for traversing, and (2) the subject had only one mass to control because, with the module attached to his back, the subject and the module are essentially one unit. (See Figures 4-68 through 4-71.)

The subject encountered difficulty with the module striking the railing, the underwater platform, and the drag effect of the screen wire modules. It was noted that the subject had a successful run with the 8-cu-ft, 15-slug package which was as effective as the 8-cu-ft, 1-slug package and better than either of the two 40-cu-ft volumes tested. Tentatively, it appears that for this mode the increased size of the cargo package was more of a hindrance than an increase in mass.

The most obvious fault of the technique used in the tests is the lack of size perception which resulted in the subject running into other objects with his back-mounted cargo. Traversing when contacts were not made with other items in the tank constituted the best runs of the entire set of cargo transport tests.

An obvious problem with the backpack is the difficulty that the astronaut would have in making his connection or disconnection with the module in an EVA condition. Underwater simulation has demonstrated that the worker must be able to see his work to accomplish it effectively. The lack of appropriate spatial awareness makes the use of backpacks a limited concept for EVA cargo transport.

Test series 7

1. Conditions.--The subject is connected by a strap restraint to the trolley truck in the rail. A flush-mounted handle in combination with a forearm handle is mounted to the cargo module. The subject pulls the module.

No pilot test runs were performed. The exploratory runs were conducted using the following packages:

8-cu-ft volume and 5-slug mass

8-cu-ft volume and 15-slug mass

40-cu-ft volume and 1-slug mass

40-cu-ft volume and 5-slug mass

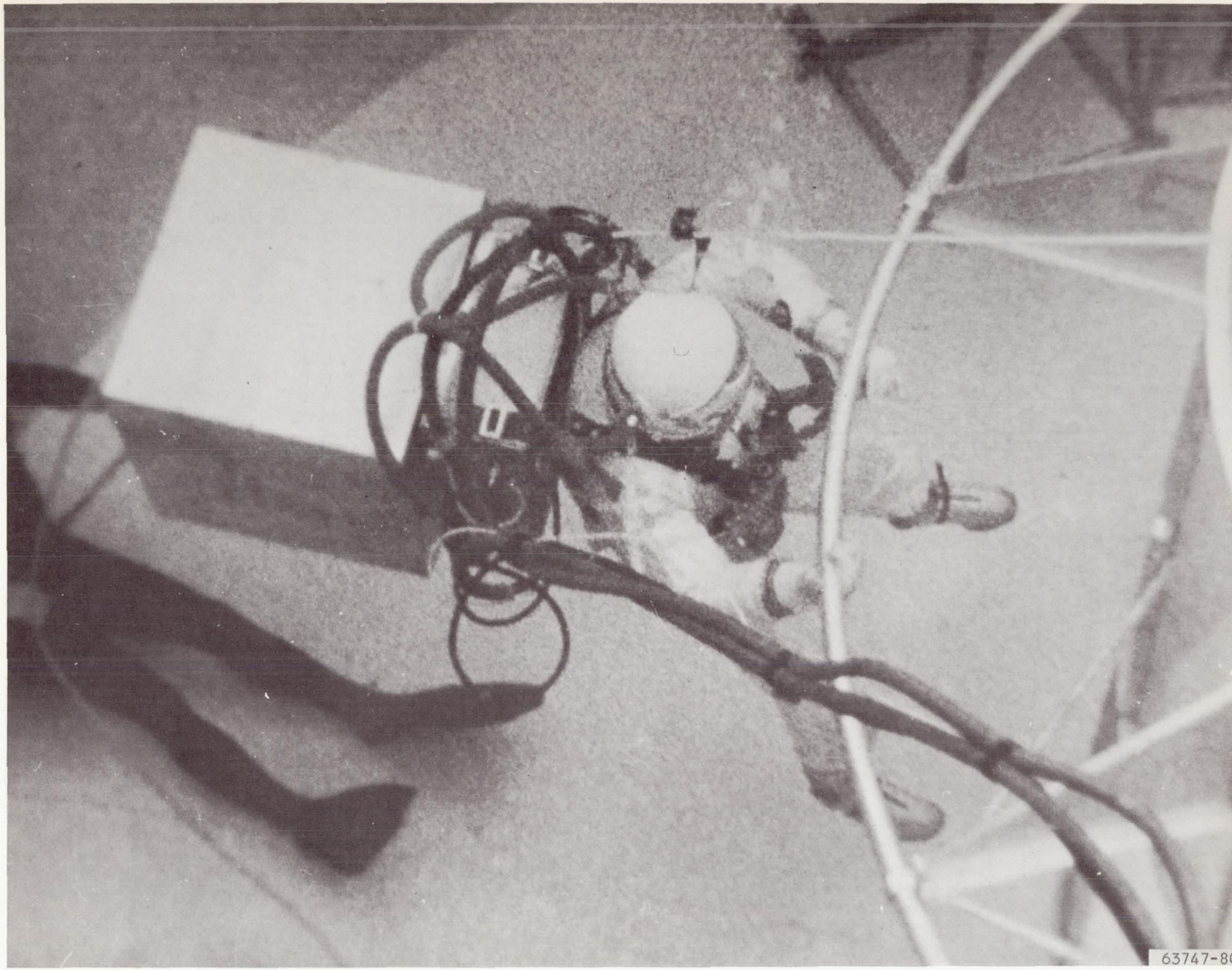


Figure 4-68. Subject Traversing with 8-cu-ft Volume and 15-Slug Mass Attached to Back

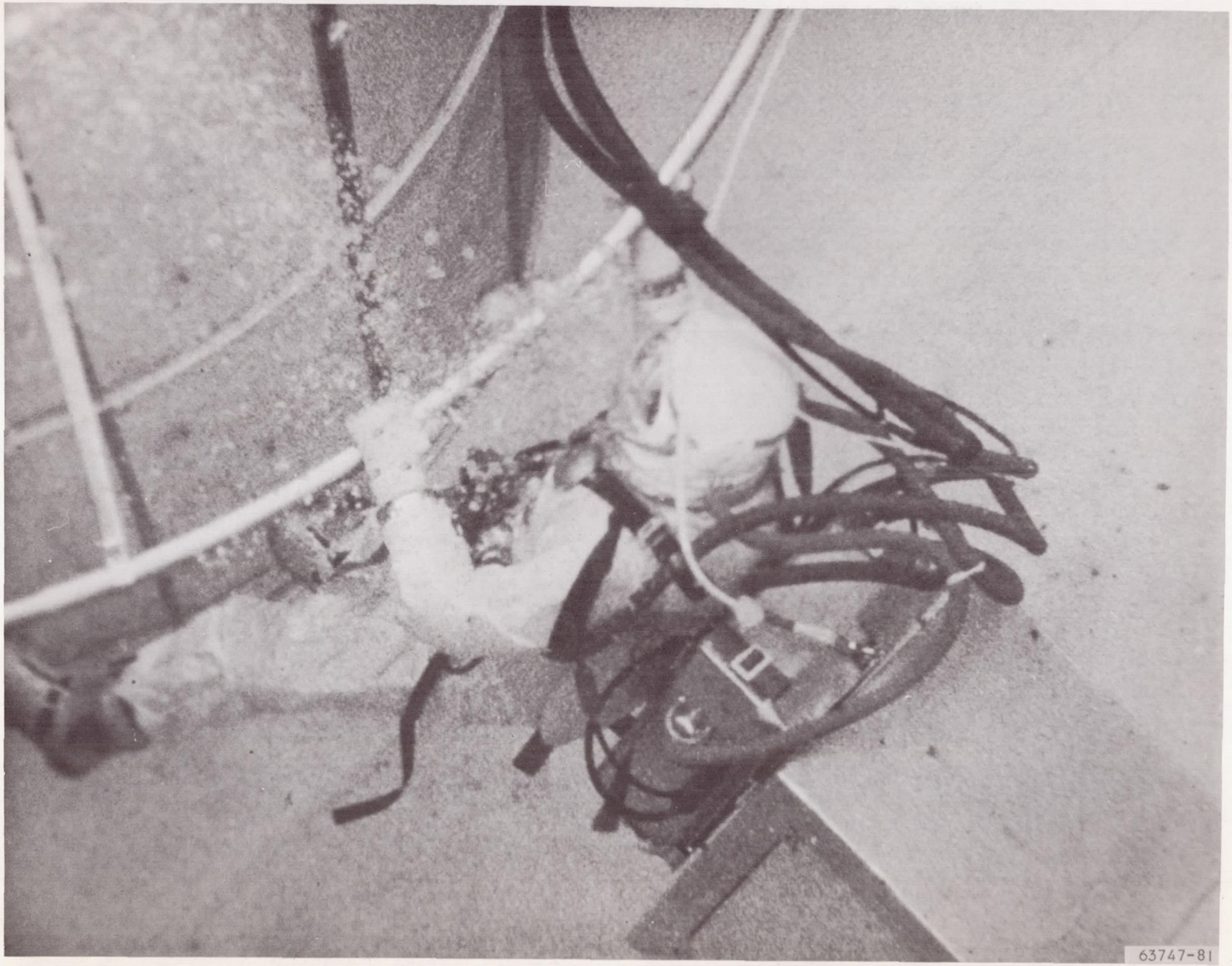


Figure 4-69 Subject Traversing with Cargo Attached to Back, Illustrates the Use of Both Hands for Traversing

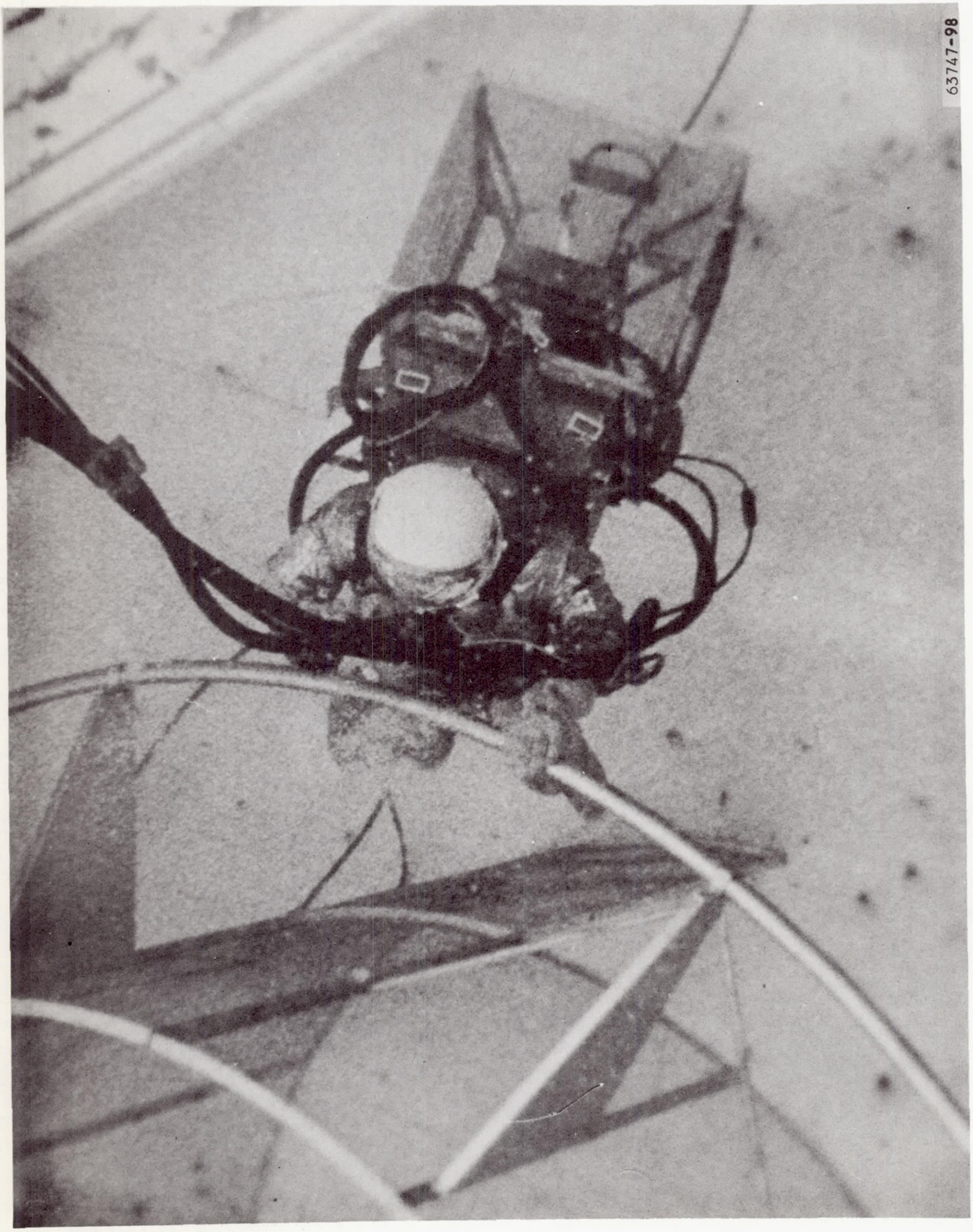


Figure 4-70. Subject with 8-cu-ft and 1-Slug Mass on Back, Using Both Hands on Rail

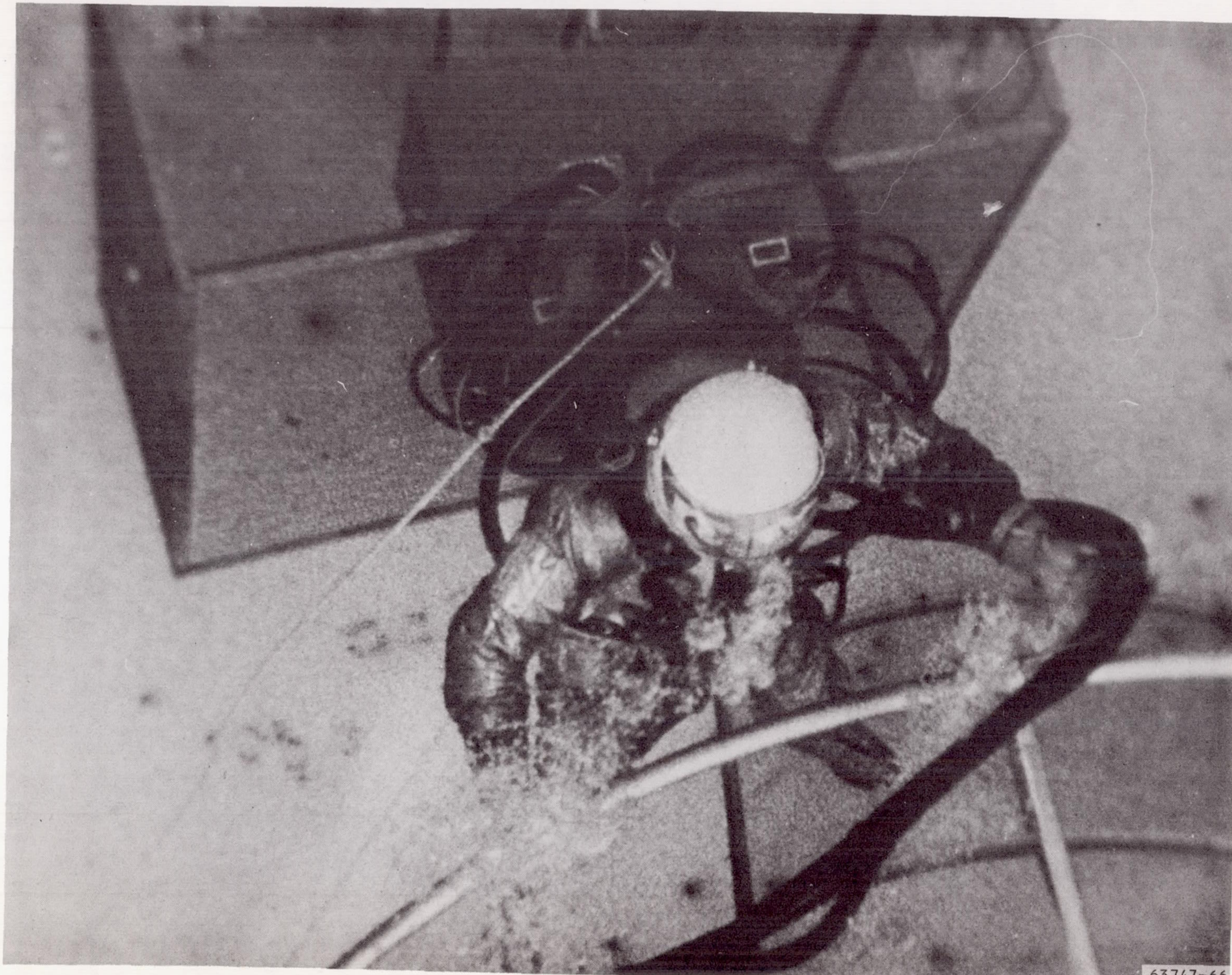


Figure 4-71. Subject with 40-cu-ft Volume and 5-Slug Mass on Back

2. Observations.--Generally, the forearm loop used with the simple handle demonstrated no important advantage over the simple handle used alone. For the task of replacing the cargo package in the holding jig, the subjects preferred the single handle. It is possible that this preference is an accessibility problem and that under other conditions, such as a more restrained position, the two-handle concept would be advantageous. This two-handle configuration tends to restrict the positioning envelope during the transport task. Under the test conditions, the cargo frequently snagged on the rail and mockup. Recovery appeared to be faster than with one handle.

Test series 8

1. Conditions.--The subject is connected by a strap restraint to the trolley truck in the rail. A flush simple handle and forearm handle is mounted to the cargo module. The subject pushes the cargo module ahead of him.

No pilot test runs were performed. Exploratory runs were with a 40-cu-ft volume and a 5-slug mass.

2. Observations.--This test was terminated because the subject had so much difficulty trying to traverse and control the cargo module at the same time that he made no progress and was "fighting" the task. As noted previously, pushing the module, while it is not rigidly restrained, is not a functional means of transporting cargo in underwater simulation.

Conclusions of Exploratory Tests on Cargo Transport

During the pilot tests, it was readily apparent that transport and manipulation of the larger modules did not simulate a weightless state even though the modules were neutrally buoyant. The tests illustrated difficulties in generalization due to the effect of drag in the water environment. Caution must be used in applying the results of the neutral-buoyant cargo transport to the actual conditions that the EVA worker will find in space.

It also appears that, to enable the astronauts to move and control cargo of various mass and size in the weightless conditions, special control measures must be taken to provide for securing, positioning, and transporting both the astronaut and the cargo. In the tests, simple track trolley systems with 1 deg of freedom controlled were not successful in providing this capability. A more functional system is needed, e.g., a multiple track trolley system or a single astronaut/cargo mass.

When the subjects maintained an acceptable amount of control over the module and themselves during the traversing mode of the tests, the basic conditions mentioned above existed. These occurred when the subject had the cargo module attached to his back and thus both hands were free to traverse and maintain control. In this case, the subject and cargo module were effectively one mass, which reduced the coupling aspects of the control problem.

As previously mentioned, the largest package (120-cu-ft) could not be transported effectively underwater. The drag was so great that the module deformed as the subject pulled it through the water. Observers could actually see the ends of the module bulge and the sides collapse with each pulling motion. This same effect existed for each of the other two volumes but to a lesser degree, and structural change in the modules was not observable.

The pilot tests illustrated the subjects' difficulty in pushing the modules ahead of them while traversing the locomotion rail; it was assumed that this difficulty was a product of the resistance of the water. This difficulty existed for the 8-cu-ft module as well as for the larger volumes. It is not reasonable to assume that EVA workers will encounter control problems with similar dynamics in free space. Following the control problem encountered in pushing the cargo packages during the pilot tests, other tests were conducted with the subject pushing the module during the traverse. In both of these cases, the results were less efficient than pulling the packages.

From the earliest pilot test throughout the cargo transport tests, it was evident that the primary problem for module transport was one of astronaut control of the package. Although a considerable portion of the control problem observed must be attributed to the drag effect of the water on the packages, other control factors separate from the drag effect existed which can be extrapolated to EVA. It was noted that the subject must have both hands free to perform work effectively. The very nature of moving cargo modules by hand is counter to conclusions of prior research. The results of the cargo transport exploratory tests further substantiate the earlier observations that (1) the weightless man needs firm and rigid support to perform meaningful work, and (2) one-handed tasks should be avoided whenever possible. These observations imply that the need for special hardware and equipment development will be identified for specific EVA tasks as a result of simulation.

The use of special handles for transporting and manipulating modules tends to imply that the successful performance of the task depends on the selection of the best handle. The tests conducted indicate, however, that, for manual control, cargo modules must be handled with two hands to maintain adequate control over the module. These same tests and prior tests also indicate that the astronaut required two hands to traverse along simple locomotion aids. Thus, the problem is to enable the astronaut to control the cargo while transporting it but at the same time to leave his hands free to traverse with or separately from the cargo module. The former is provided by attaching the cargo package to the subject's back. The backpack concept has serious limitations as mentioned in the observations of that test. This implies that a traversing/cargo transport hardware system is required. If the subject had only to control the forward motion of the cargo and could use both hands in traversing and imparting motion to the cargo, he would, it is believed, have a functional EVA cargo transport system.

The physiologic data for the exploratory cargo transport experiments are shown in Figures 4-72 through 4-80. Metabolic rates in kilocalories per minute are shown in the upper graph; corresponding cardiac rates in beats per minute are seen in the second trace; expired ventilatory volume expressed as liters per minute at body temperature, pressure, and saturated with water vapor are shown

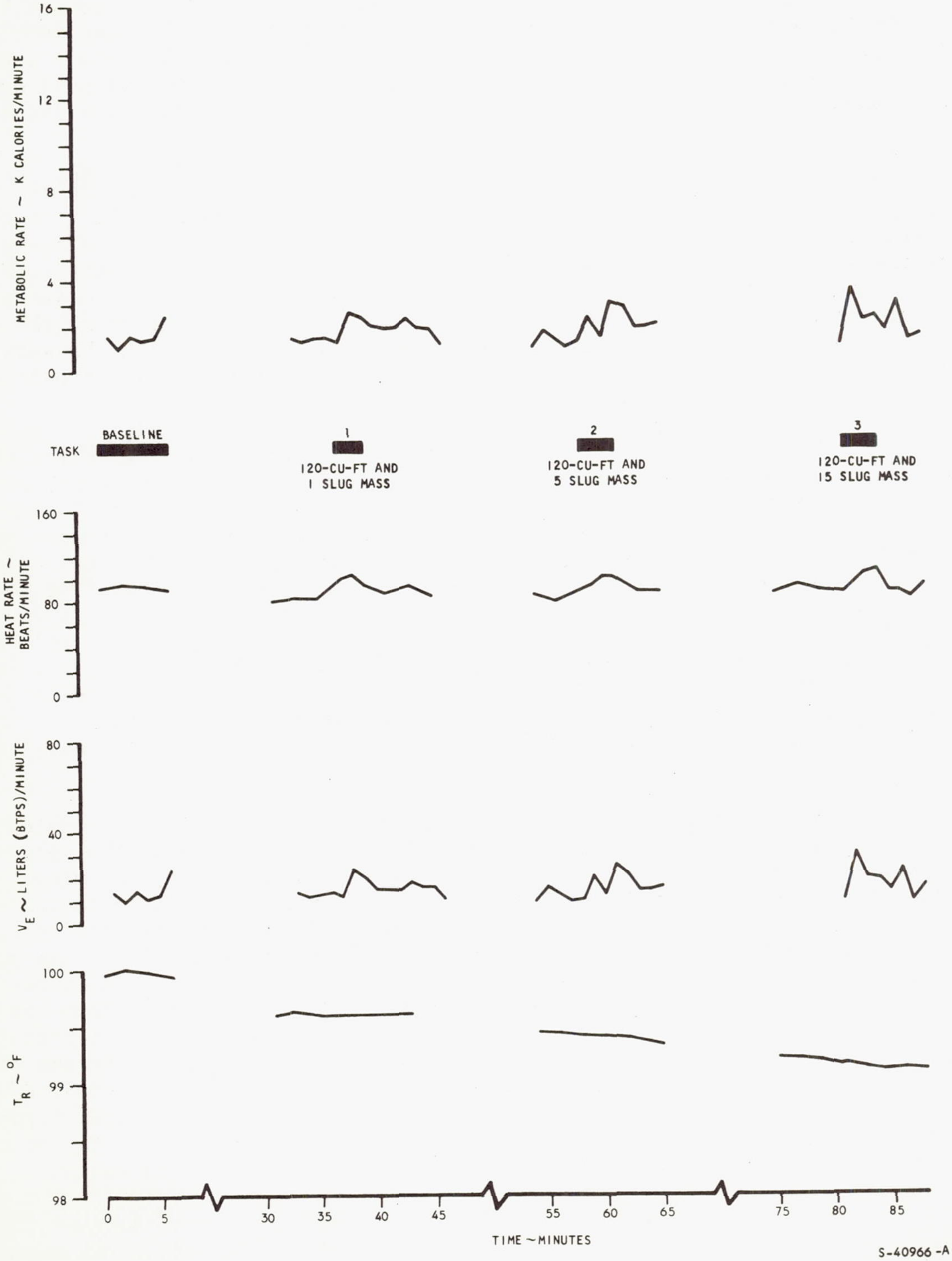


Figure 4-72. Physiologic Data for Cargo Transport Pilot Test 901

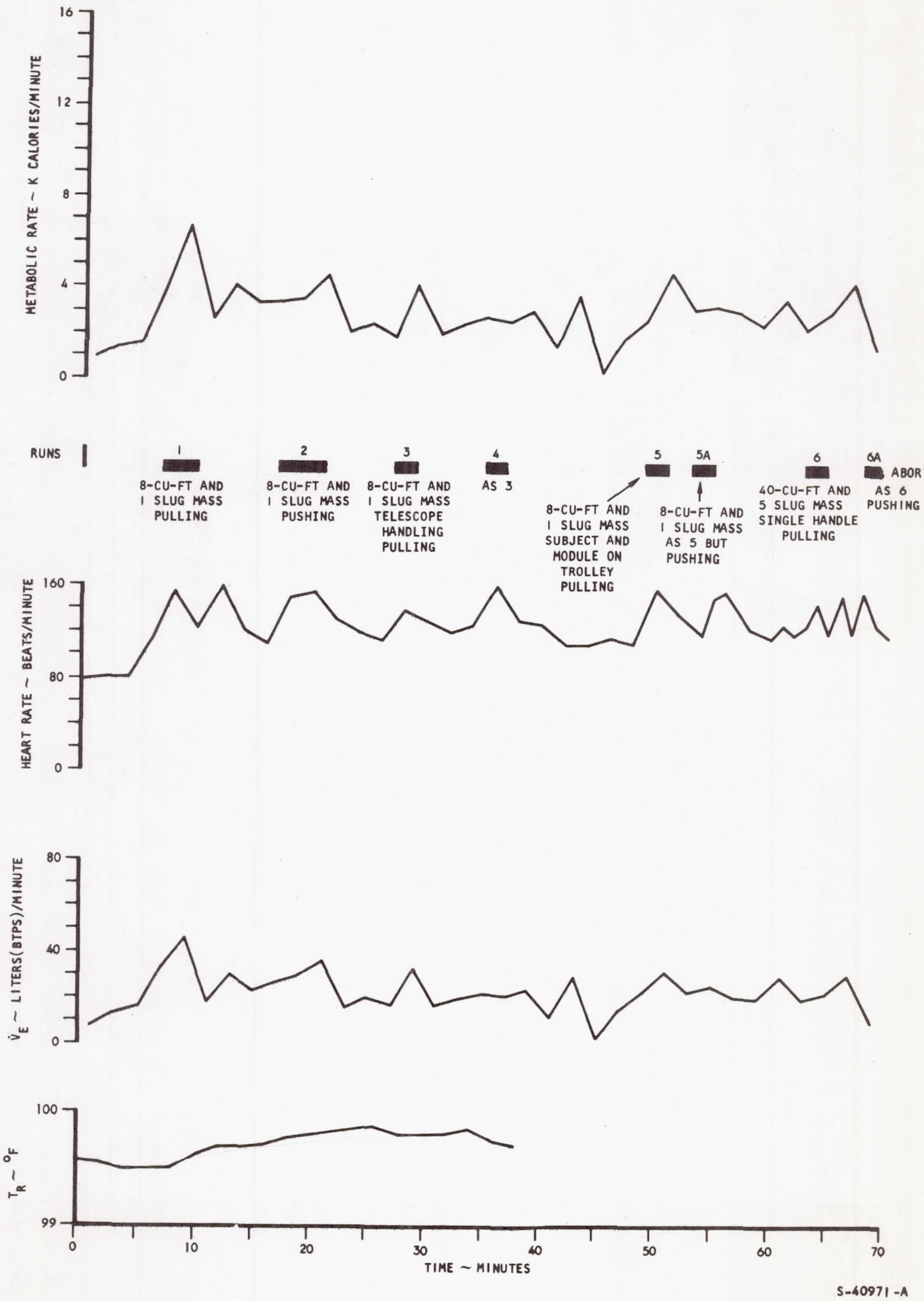


Figure 4-73. Physiologic Data for Cargo Transport and Formal Test 901

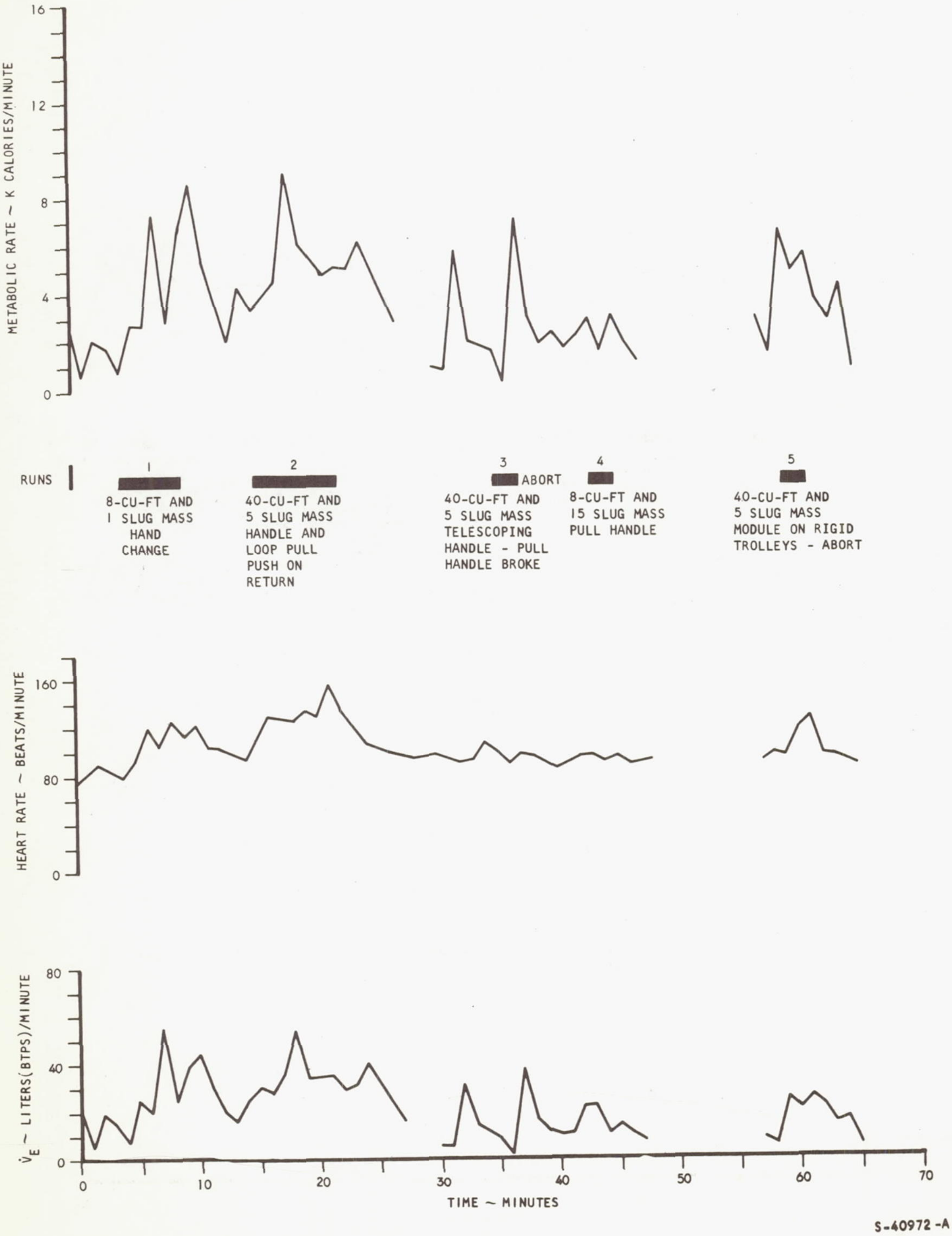


Figure 4-74. Time Course Physiologic Data for Cargo Transport Test 902

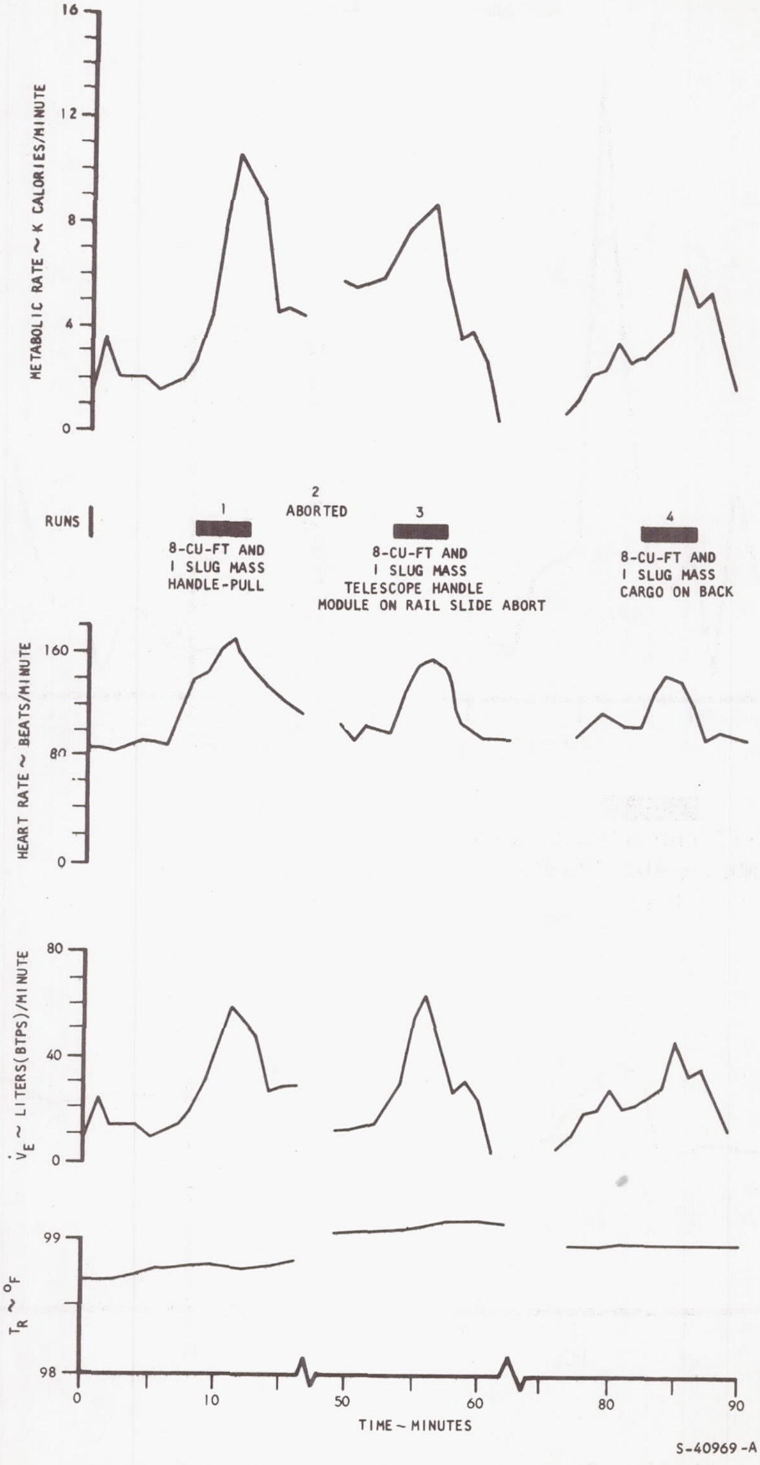


Figure 4-75. Physiologic Data for Cargo Transport Test 904

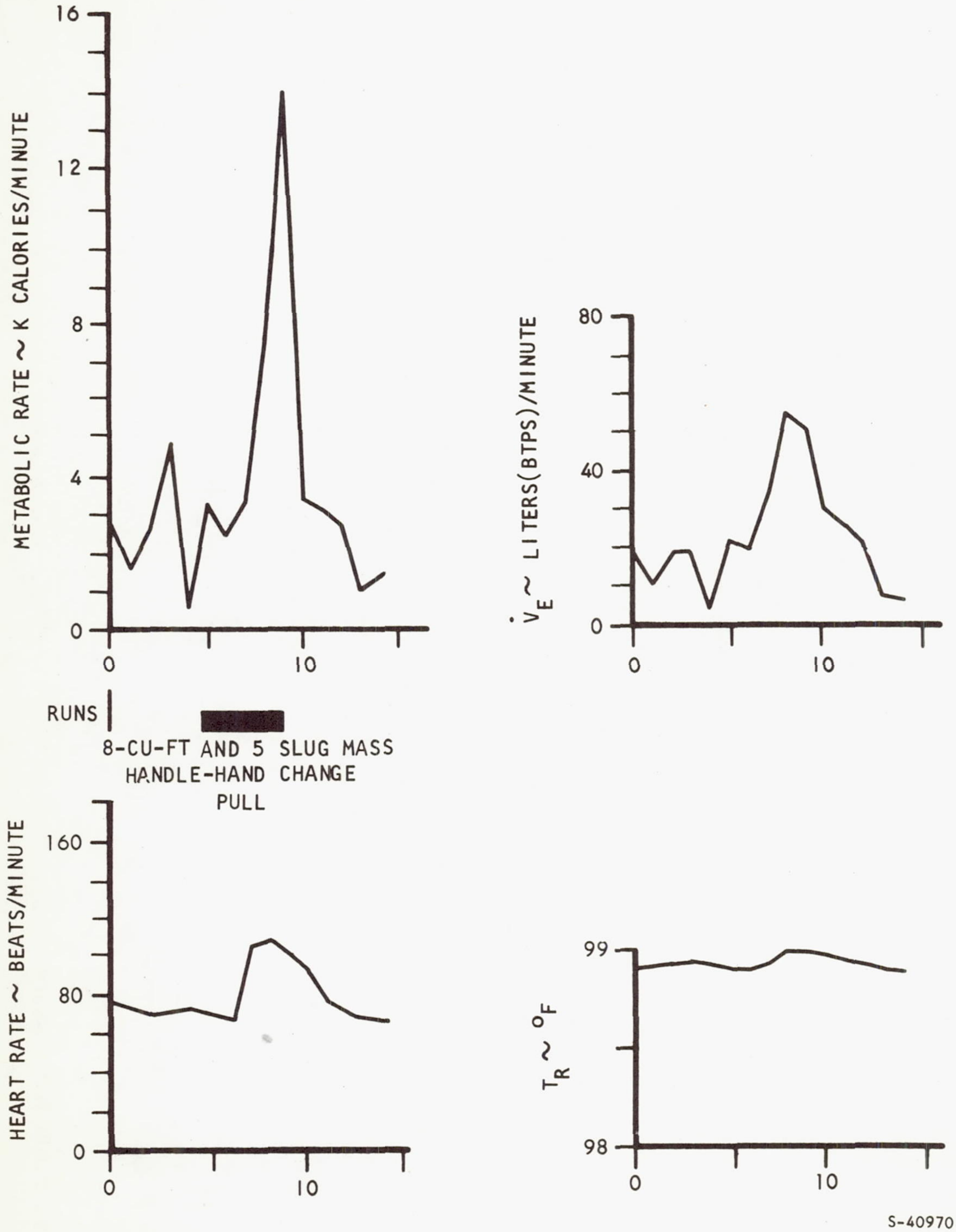


Figure 4-76. Physiologic Data for Cargo Transport Test 906

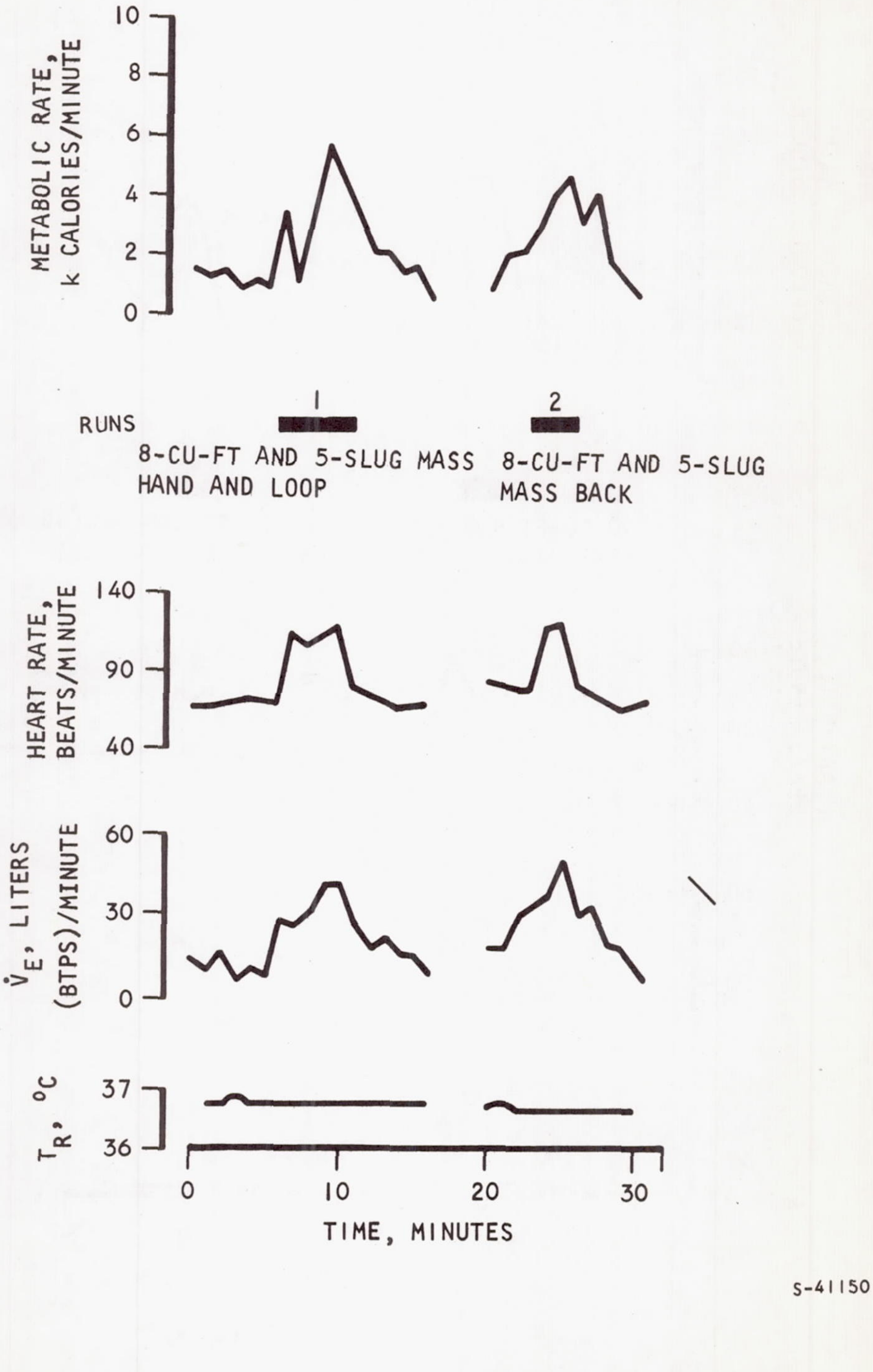


Figure 4-77. Physiologic Data for Cargo Transport

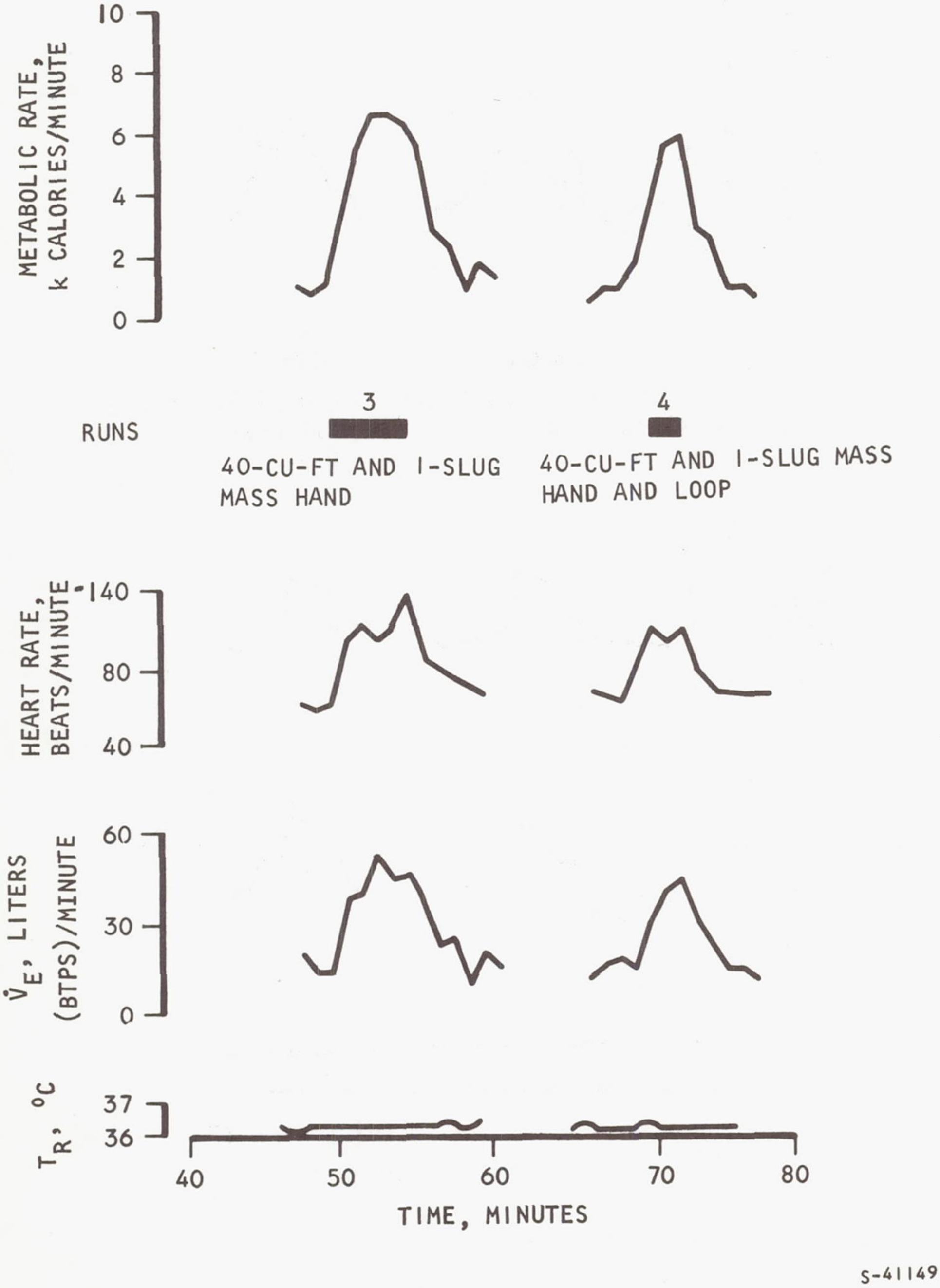


Figure 4-78. Physiologic Data for Cargo Transport

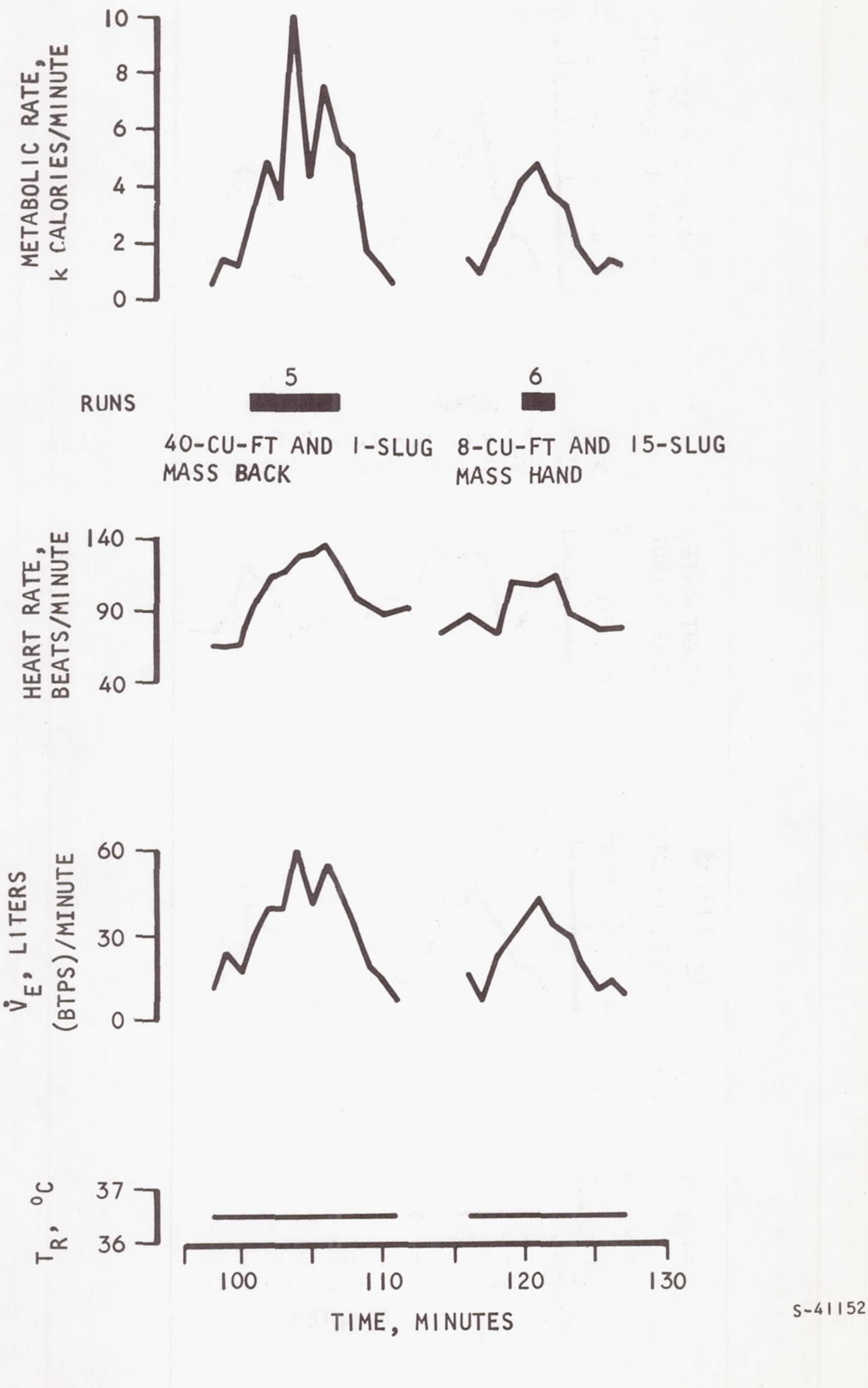


Figure 4-79. Physiologic Data for Cargo Transport

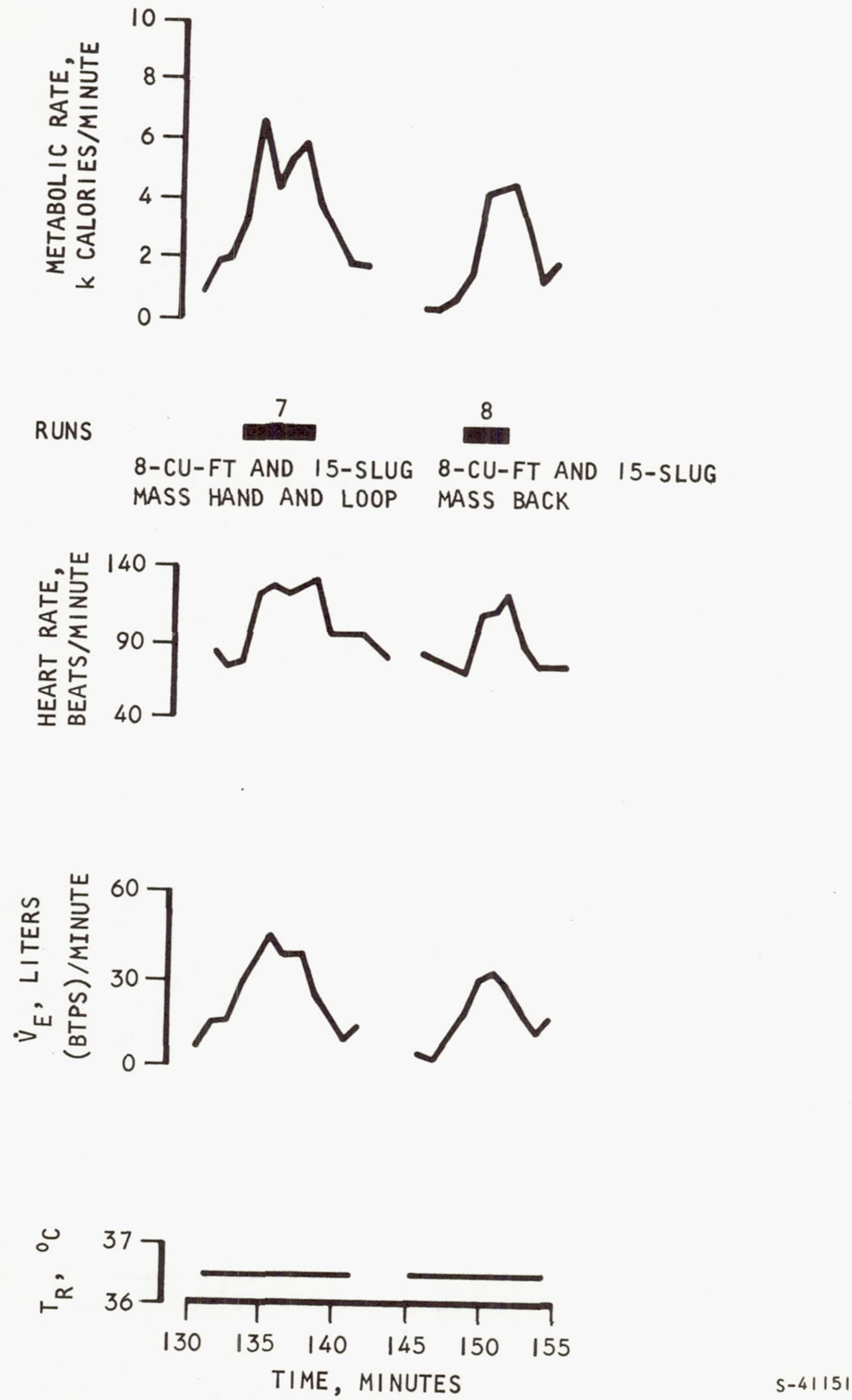


Figure 4-80. Physiologic Data for Cargo Transport

in the third trace; and rectal temperatures in ^{0}F are given in the bottom trace for each figure.

A cursory examination of these graphs shows a sharp contrast to the data reported under NASA Contract NAS I-5875. In that effort, metabolic rates never exceeded 2000 Btu per hr (8.4 kcal per min), and heart rates were never higher than 140 beats per min. During these tests, metabolic rates reached as high as 14 kcal per min (3325 Btu per hr), and heart rates of 160 beats per min were often noted. However, these data tend to follow those noted in the previous study. The subjects generally paced their work effort so that their energy requirements were generally less than 6.5 kcal per min (1500 Btu per hr) and operated at heart rates of 140 beats per min or less. It is apparent that man strives to work at a light-moderate to moderate work load in neutral buoyancy just as in 1-g conditions. Levels higher than these cannot be maintained for a long period of time.

The ventilatory data show little of interest. As expected, the ventilatory response is a reflection of metabolic rate, and the changes noted were necessary to handle the volume of carbon dioxide produced. It should be noted that the subjects achieved rates of as high as 65 l per min during one test and did not report any problem with respiratory resistance, indicating the acceptability of the metabolic rate measuring system.

In general, rectal temperatures showed a very slight trend downward, indicating the subjects were cooling during each test. It is very doubtful that the amount of cooling noted would affect the metabolic rates even though rapid heat loss must be compensated for metabolic heat. The actual effect of thermal transfer on metabolic rates during pressure-suited underwater simulations should be completely evaluated to account for any possible effects on the total energy cost of work.

EXPLORATORY TESTS OF CREW RESCUE

The exploratory orientation of the crew rescue tests was to identify the problems associated with securing, moving, and manipulating passive subjects. The tests were conducted around the basic task of recovery, transporting, and securing the passive subject. The rescue concepts were different procedural approaches to recovering the passive subject. Each pre-established concept was conducted, and procedural changes were made on the spot to improve the basic aspects of recovery, transporting, or securing the subject. The changes made were based on insights gained during the test due to either task failure, long-task-performance time, or subject and team member inputs.

Procedures and Test Apparatus

It was not possible to use a human passive subject for rescue in a full-pressure-suited condition since the current ECS can accommodate only one-suited subject at a time. Furthermore, it was questionable from a safety point of view whether it was advisable to have two pressure-suited subjects in the tank at the same time since the capability to rescue two subjects simultaneously did not exist. The decision was made to use a G-2C suit pressurized to 3.5 psi with water for the passive subject. Small weight additions were required to make the dummy neutrally buoyant.

Since the crew rescue tests were conducted following a week of actual rescue procedural development, required as a safety measure for the program, the subjects were all familiar with the elementary tasks of rescue. Although in these prior runs, the rescuers were skin divers, the practice taught them much about the force requirements and the movements of the subject being rescued. Therefore, rather than develop a series of specific tasks for the subjects to perform, it was believed that a general procedural instruction narrative would more accord with the exploratory nature of the test. Six concepts were developed and used as general instructions for each test.

Observations

Rescue concept I

1. Conditions.--The test (see Figure 4-81) starts with the passive subject floating free and unrestrained; his umbilical runs out the hatch. The rescue subject starts the recovery procedure by moving slowly along the front of the mockup and along the pipe rail while holding the umbilical of the passive subject as he traverses. At the point closest to the passive subject from the pipe rail, the rescuer slowly pulls the passive subject to him. The passive subject is then attached with a strap tether in a ring on his suit. The passive subject is then allowed to float free, and the rescuer returns along the rail and mockup to the hatch. After attaching his strap restraint to the left side of the door, the rescuer then wedges his left leg or foot behind the hand rail on the mockup. This will place the rescuer in a prone position but will leave both hands free to manipulate the passive subject through the hatchway. If the rescuer finds it necessary to release the passive subject from himself during any part of this task, he will reconnect the passive subject's restraint to keep him captive and available for manipulation. Once the passive subject is through the hatch, the rescuer will follow him in. This completes the test.

2. Observations.--The umbilical for the rescue dummy was a 1/4-in. plastic tube supplying the water to maintain the 3.5 psi ΔP. This small diameter tube interfered with the subject's ability to maintain control while traversing. Actually, the subject was able to return to the mockup faster with the dummy in tow than he could traverse to the dummy while gathering the 1/4-in. umbilical to him as he went along. The difference, of course, was the freedom to use both hands for traversing on the return trip.

Attachment of snap connectors or strap tethers out of the field of vision of the EVA worker is an undesirable condition. Releasing the dummy from the rescuer was a fumbling and time-consuming task because of the location of the connecting point on the rescuer's chest.

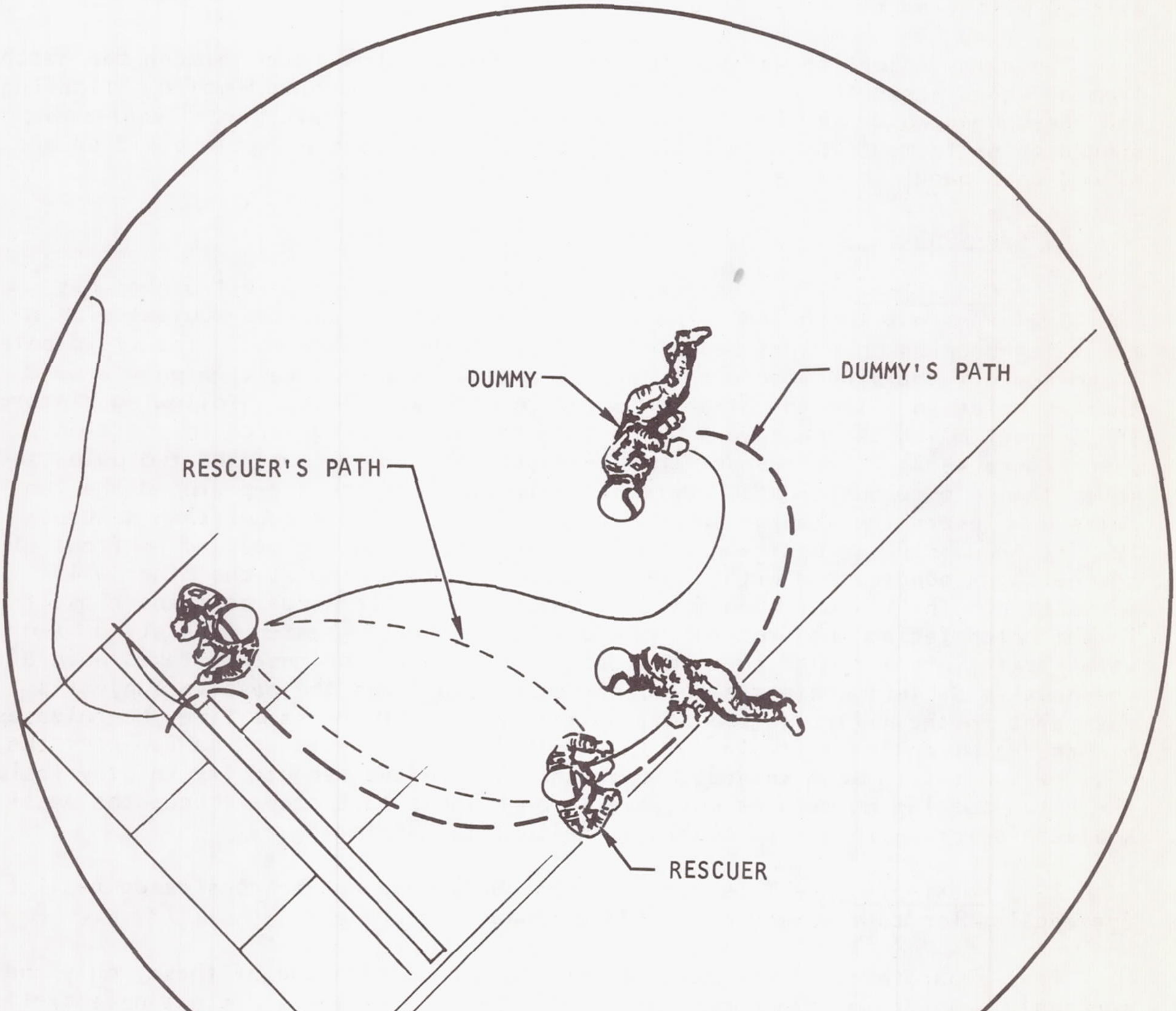


Figure 4-81. Concept I--Exploratory Crew Rescue

The attempt by the subject to place his foot behind the rail to give him a stable position from which to manipulate the dummy was not successful. The difficulty was twofold: (1) in that position, the subject was poorly placed for the task of putting the dummy through the hatch and (2) the position did not allow him to view the totality of the hatch and dummy.

The dummy insertion was accomplished by pushing the dummy through the hatch from an erect position in front of the hatch. There was much fumbling, floating, and one-handed work associated with the task. A task of this force requirement should be performed from a restraint system that provides a stable position and allows both hands to be used in the work (see Figure 4-82).

Rescue concept 2

1. Conditions.--The passive subject floats free and unrestrained; his umbilical runs out the hatch. The rescuer captures the passive subject with a rigid telescoping pole that has a slip/noose on the forward end. The rigid pole is worked off the pipe locomotion rail by a strap that may be tightened around the two poles to allow the "fishing pole" to work as a lever. Following capture, the subject moves the passive subject through the levering force to position 1 (see Figure 4-83). The rescuer then releases the strap around the two poles and moves the pole to position 2. Here he again tightens the strap around the two poles and levers the passive subject to position 3. The rescuer then secures the "fishing pole" at position 4 to hold the passive subject secure in front of the hatch; a bungee cord with a hook at one end and a ring at the other will serve here. The rescuer then moves to the hatch opening and restrains himself in the hatch facing out from the mockup. The restraint system consists of two strap restraints attached to both sides of the door. The rescuer takes hold of the passive subject, releases the loop/noose, and snaps the passive subject's restraint in the lift-side eye bolt of the hatch. At the same time, he releases his restraint on the left side of the hatch and then pivots and manipulates the passive subject through the hatch opening. The rescuer should try to stay inside the hatch opening as much as possible through these last steps. Once the passive subject is inside the hatch opening, the test is completed.

2. Observations.--This rescue technique should not be considered realistic for application to recovery of an EVA astronaut.

Five separate runs were made of this test condition and of these, only one successful capture of the dummy was made. The four failures are not necessarily a product of the impossibility of the task, but of the failure of the task within a given time limit. The dummy was allowed to flow free approximately 10 ft from the pipe rail. When placed in this position, the dummy would begin to slowly float away. This free floating was quite random, and the dummy changed direction periodically. Thus, the dummy provided a slow-moving target for the subject. The dummy was available for capture only about 30 to 45 sec, and then it was out of range. If not captured while in range, the run was considered a failure.

The difficulty of the capture task is attributed to the lack of control over the torso and legs when the subject is manipulating the pole from the pipe rail. The technique of pole manipulation from the pipe rail was to have one arm over

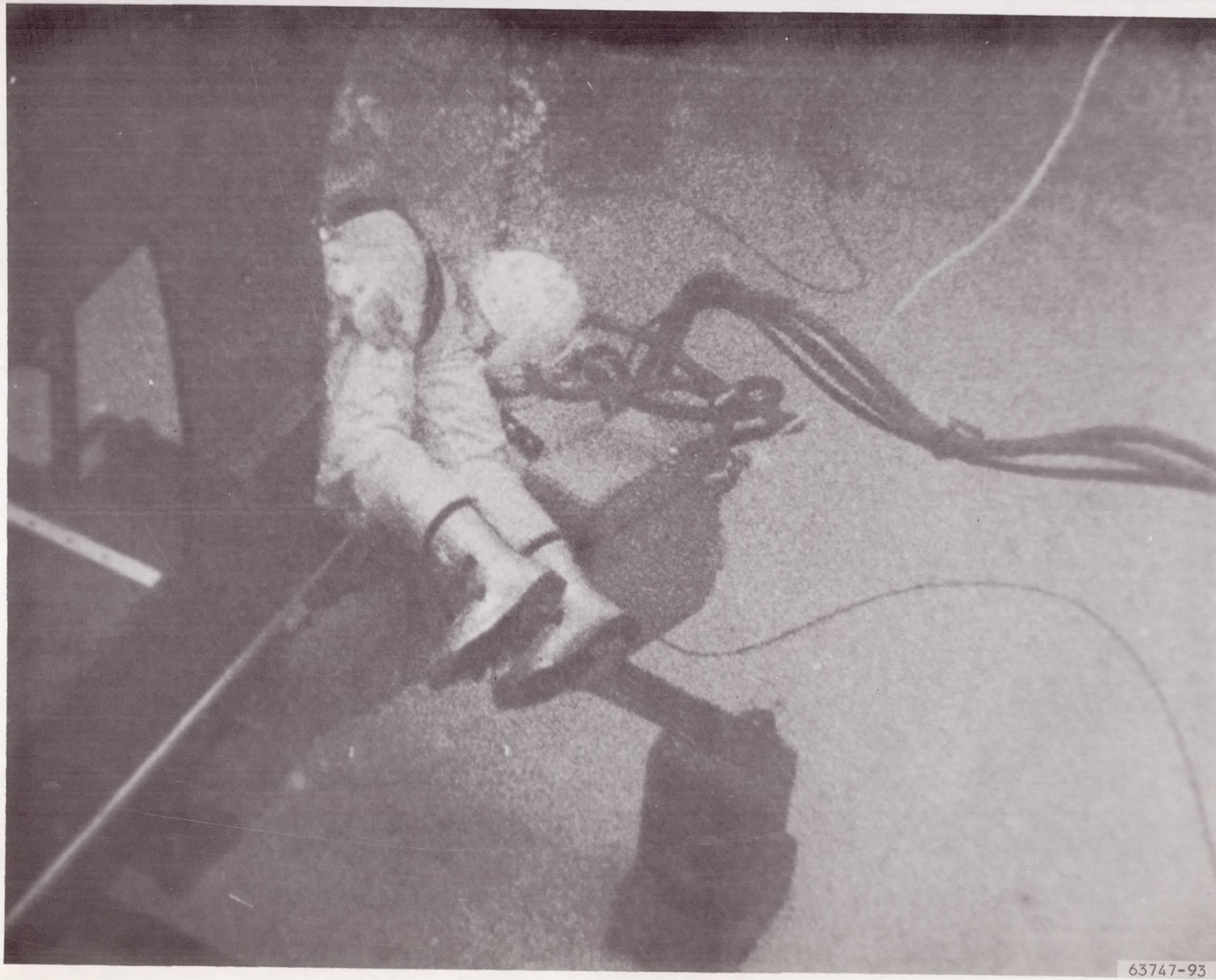


Figure 4-82. Subject Placing Dummy Through Hatch of Mockup

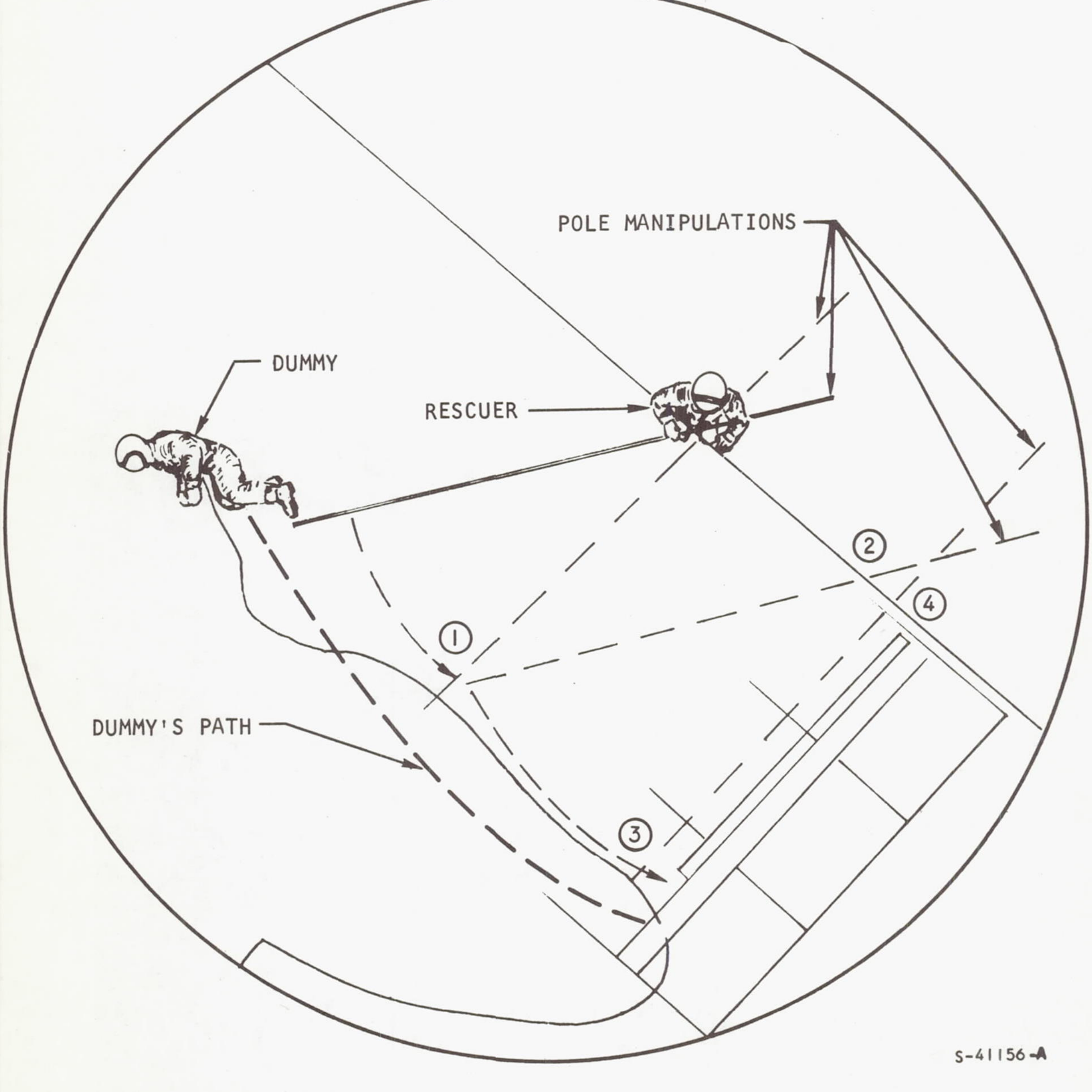


Figure 4-83. Concept 2--Exploratory Crew Rescue

and one arm under the rail, with the capture pole resting on the pipe railing (see Figure 4-84). This allowed the subject to simultaneously keep himself close to and attached to the pipe rail and manipulate the capture pole. Any movement of the subject to position the pole would be reflected, as expected, in his legs and lower torso to counteract the forces being applied in the shoulder and arm area. The forces, in turn, were a body control problem for the subject, necessitating repositioning and a loss of productive task time (see Figures 4-85 and 4-86). To provide adequate control to perform tasks requiring more than minimum force, restraint capability must be provided for the legs and/or feet of the EVA worker.

Rescue concept 3

1. Conditions.--In this test (see Figure 4-87), the passive subject is tethered on a strap restraint attached to a ring on the pipe locomotion aid. The rescue subject leaves the hatch of the mockup, taking with him the free end of a rope attached to the inside of the mockup. The rescuer traverses past the passive subject to the ladder on the far side of the pool where he pulls the rope as taut as possible before tying it off. The subject then returns to the passive subject and moves him to the ladder where he transfers him to the rope. A short line is then attached to the passive subject and to the rescuer who proceeds to pull the passive subject along the rope and through the hatch opening to end the test. Care must be taken by the rescuer to keep both himself and the passive subject captive and restrained in some manner throughout the test.

2. Observations.--The test consisted basically of traversing and flexible restraint manipulation. The traversing was performed with both hands free and went successfully for the rescue subject. The restraint manipulation for the dummy and the subject was performed between the pipe rail and the taut rope at the ladder. Here the subject could fix a foot behind the ladder rung and provide stability for his position. Under these circumstances, the manipulation of restraints and transfer from the pipe rail to the taut rope were successfully completed in the task. The total task concept as performed was accomplished in 2-1/2 min.

Rescue concept 4

1. Conditions.--The passive subject is tethered on a strap restraint attached to a ring on the pipe locomotion aid (Figure 4-88). The rope from hatch to ladder used in Concept 3 is left in place. The rescuer leaves the hatch, taking with him several bungee ties and a special wide strap for securing the passive subject to the rescuer's back. The rescuer moves the passive subject to the ladder where he secures him with the bungee ties in a position against the ladder and between the pipe and rope. The rescuer then places himself in front of the passive subject and restrains himself to the ladder. He passes the large wide strap about the passive subject and himself and fastens it loosely above his restraint so that it will not slip down. The rescuer then releases his restraint and leans forward to clear his backpack of the subject as he turns and places his back to the passive subject. When the subject is positioned well with his back to the passive subject, the restraint (a single connection seems advisable for this purpose) is connected to the rope. At this time, the rescuer

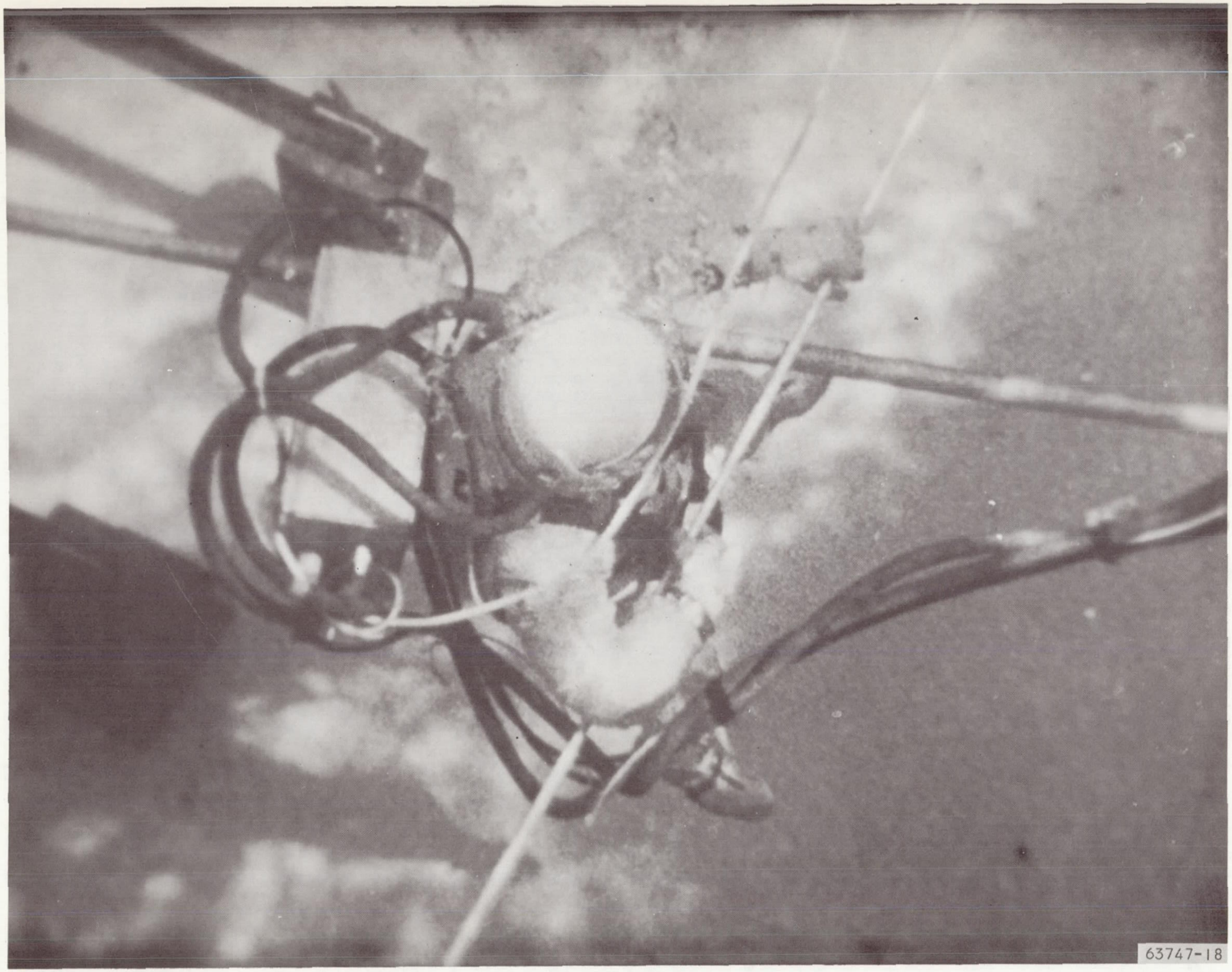


Figure 4-84. Photographs 4-84, 4-85, and 4-86 Depict the Subject "Fishing" for the Dummy with a Catch-Pole and Illustrate the Control Problem Resulting from Unrestrained Feet and Legs

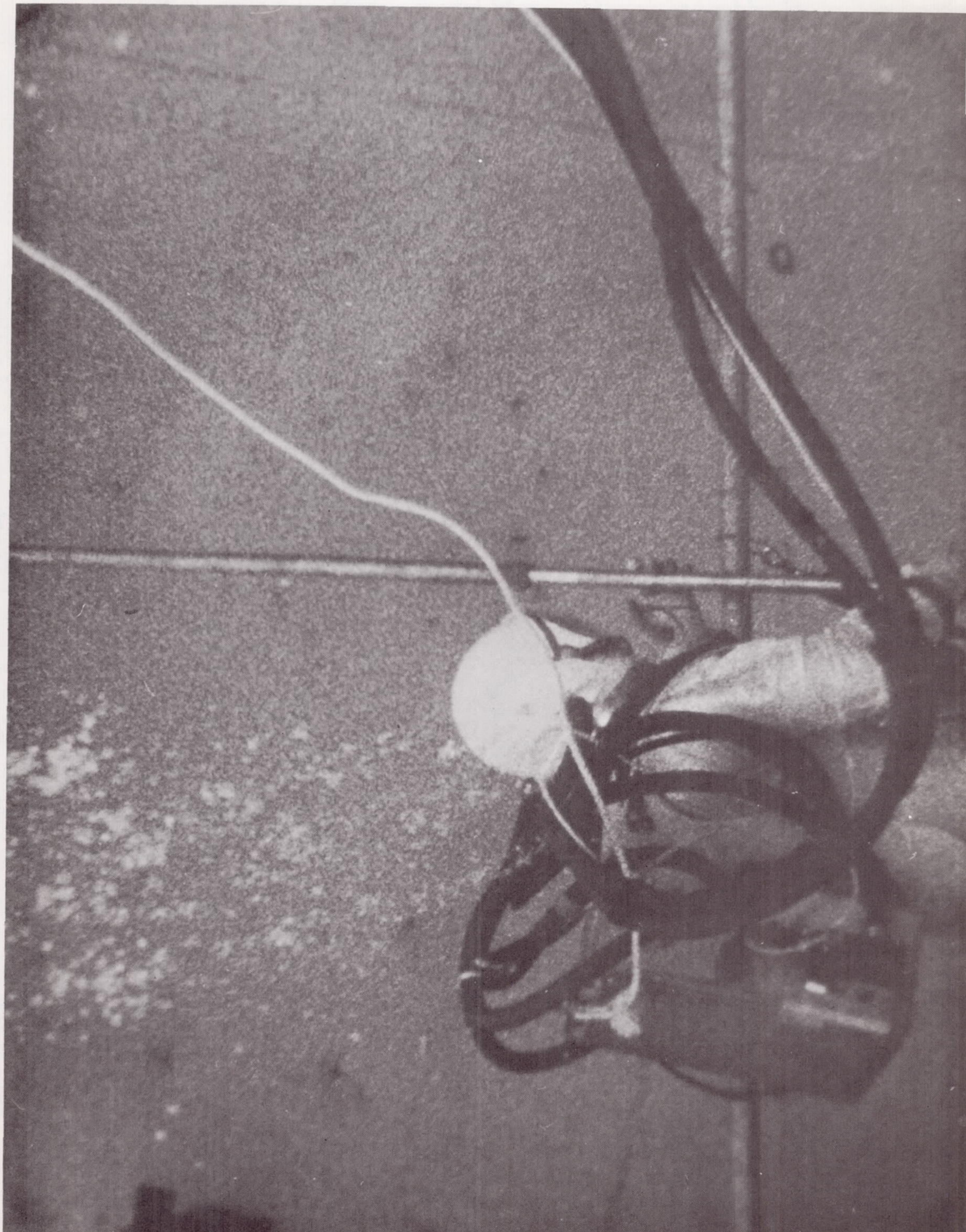


Figure 4-85. Second Photograph of Sequence of Pole Rescue

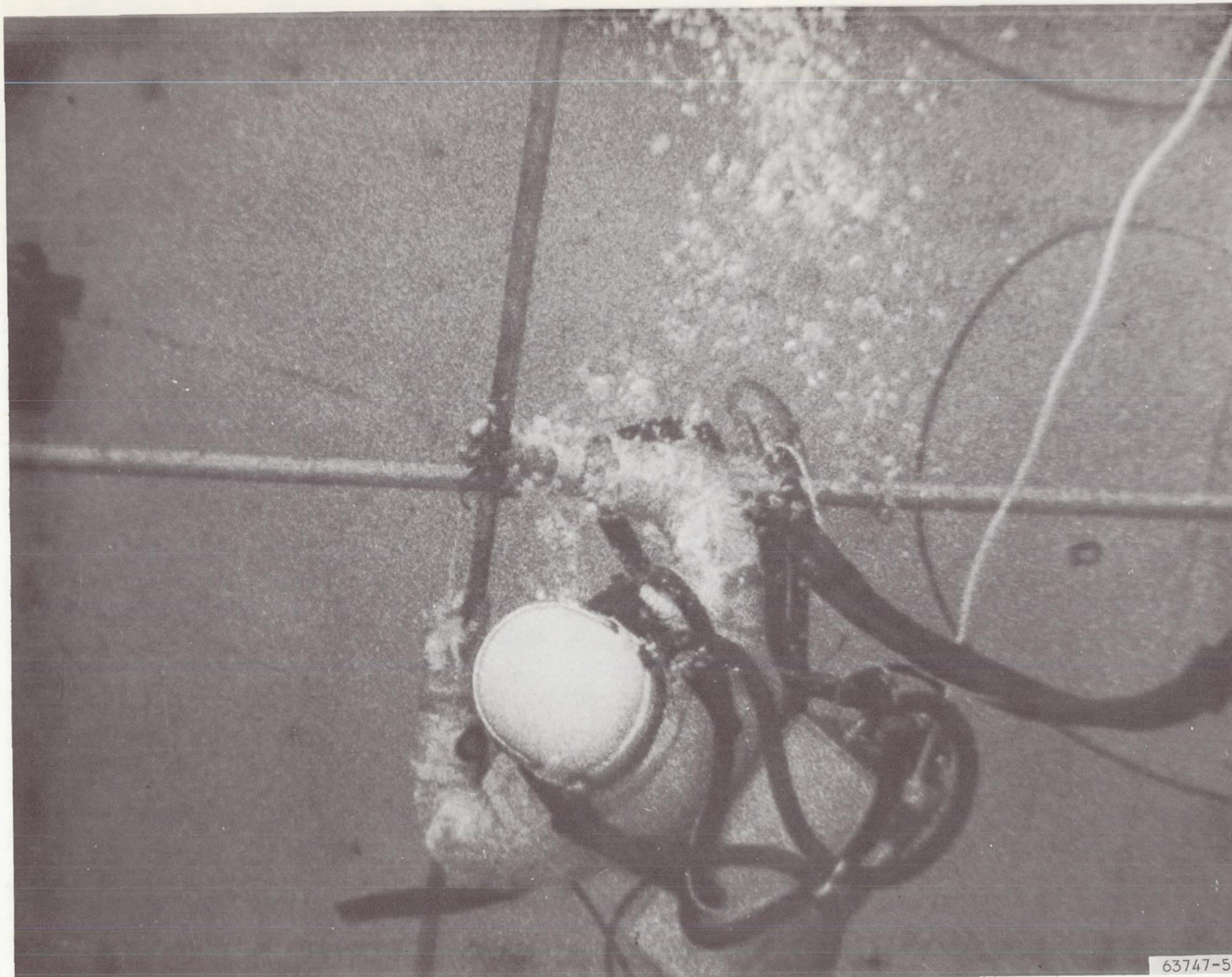


Figure 4-86. Third Photograph of Sequence; Subject Falling Out of Control from Position on Rail

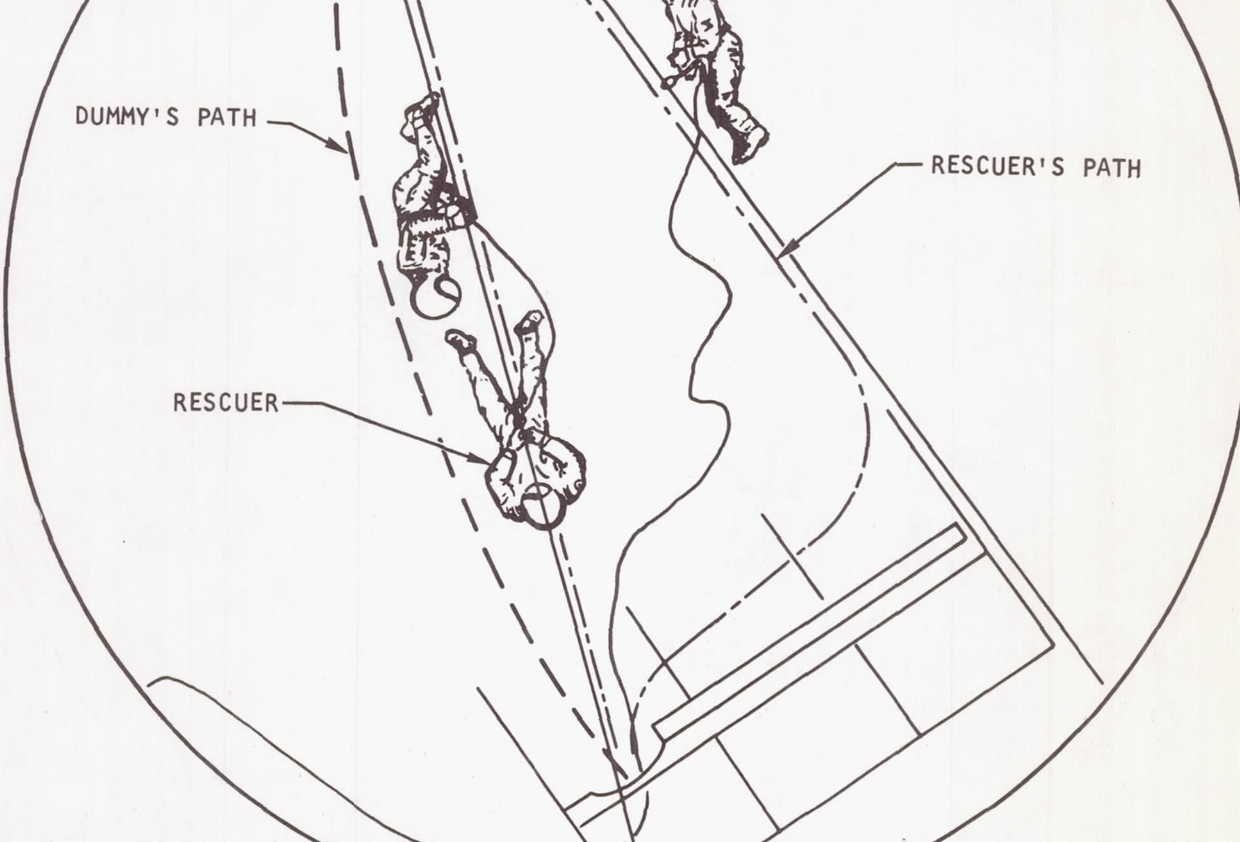


Figure 4-87. Concept 3--Exploratory Crew Rescue

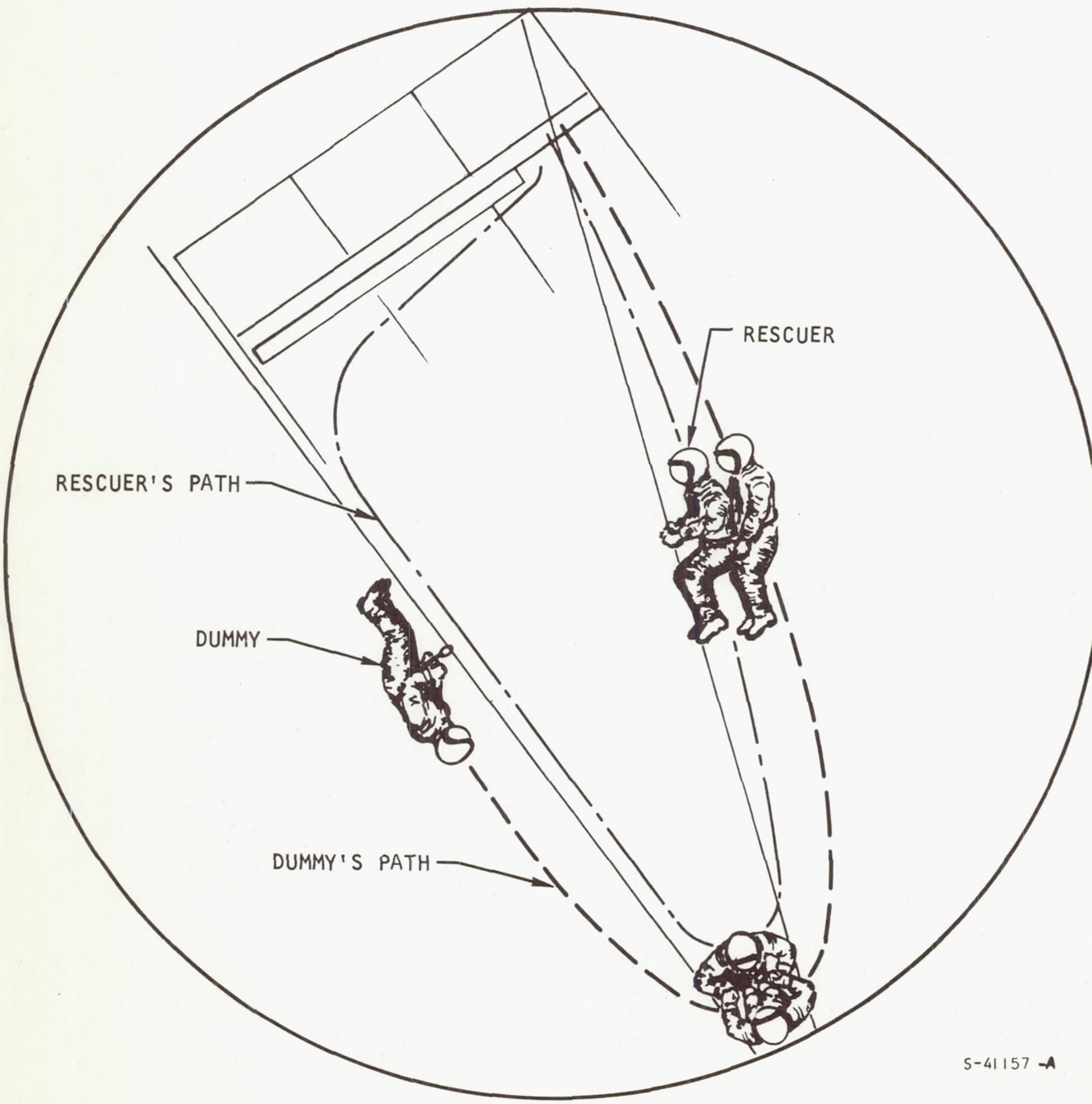


Figure 4-88. Concept 4--Exploratory Crew Rescue

cinches up the special strap as tight as possible and then traverses with the passive subject on his back through the hatch. This ends the test.

2. Observations.--Two attempts were made to perform this rescue concept. The first attempt closely followed the procedures, and the second was made with numerous innovations to accomplish the rescue. Both attempts were terminated during the task of attaching the dummy to the back of the rescuer. In the second trial, the cage restraint was attached firmly to the ladder to provide a work place for the rescuer to position and secure the dummy to his back (see Figure 4-89).

In both tests, failure to complete the attachment of the dummy was attributed to (1) the subject's inability to see the exact position of the dummy when he positioned his own back to it and (2) the inability to manipulate the strap when he was positioning (see Figures 4-90 through 4-92). The rescuers in both trials were sure that they were about to complete the task many times. The difficulty here could be very similar to the difficulty during the Gemini flights when the astronaut attempted to back into the AMU and had to eventually terminate the task.

The difficulty experienced in the "blind" work of this task surprised only the subjects; from numerous observations previously made, even the most elementary tasks ended in failure because the subject could not see his work, i.e., disconnecting a restraint snap on the chest. In both test efforts, the rescuer was allowed to pursue the connecting task for approximately 10 min before the tests were stopped.

Rescue concept 5

1. Conditions.--The passive subject is placed on the surface of the mockup, attached to the rail by a tether with a snap-ring connection (Figure 4-93). The rescuer traverses out the hatch and moves the passive subject along the rail and through the hatch opening. Care is taken to keep both the passive subject and the rescuer connected and restrained at all times. Several different approaches are used to find the best way for the rescuer to manipulate the passive subject.

2. Observations.--This procedure was to explore the various ways of manipulating the subject through the hatchway to determine the best approach. It was impossible for the rescuer to go through the hatch first or to follow the dummy through the hatch because the backpack configuration was too large to allow the passage. In the trials, a pushing procedure was required to place the dummy through the hatch. This prevented observations of the optimum procedure since pulling of objects appears to work better than pushing.

The subject puts the dummy (1) through the hatch with the rescuer's restraint connected to the right of the hatch (Figure 4-82), (2) through the hatch with the restraint connected to the left of the hatch, (3) through the access opening rather than through the hatch (Figure 4-94), (4) across the front of the rescuer, and (5) behind the rescuer.

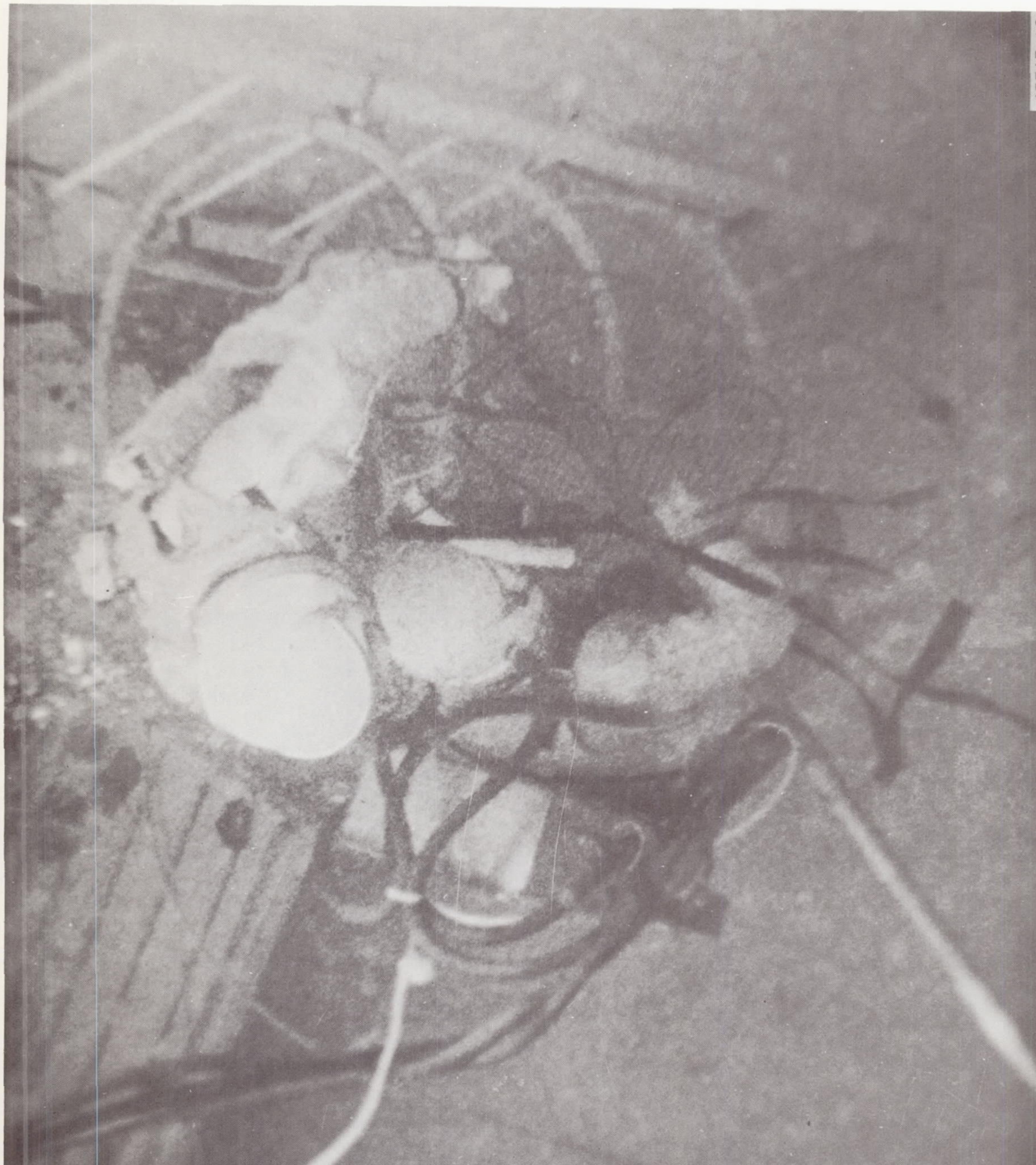


Figure 4-89. Subject Placing Dummy in Cage for Manipulative Control

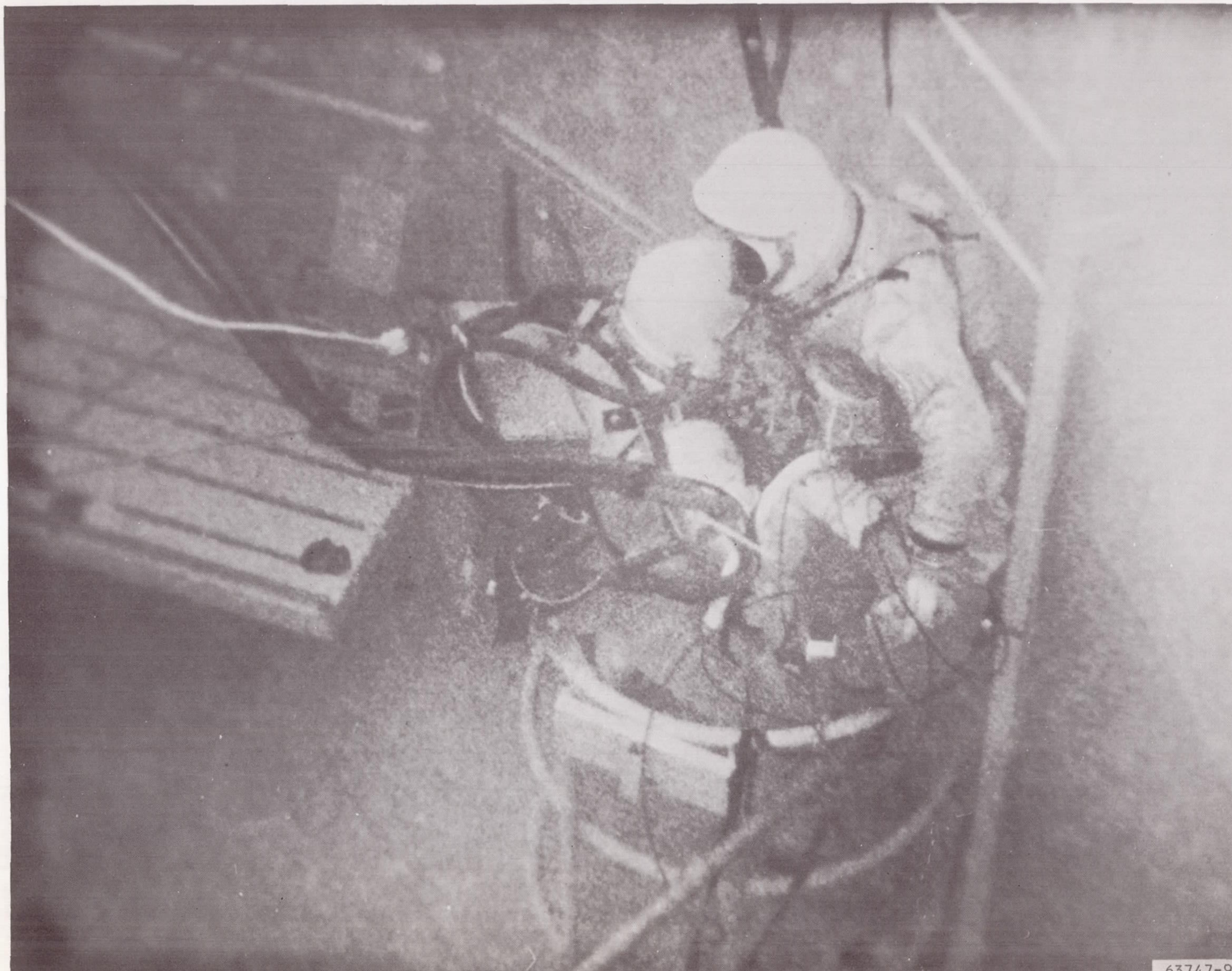


Figure 4-90. Subject Manipulating Dummy in Cage in Attempt to Strap Dummy on His Back

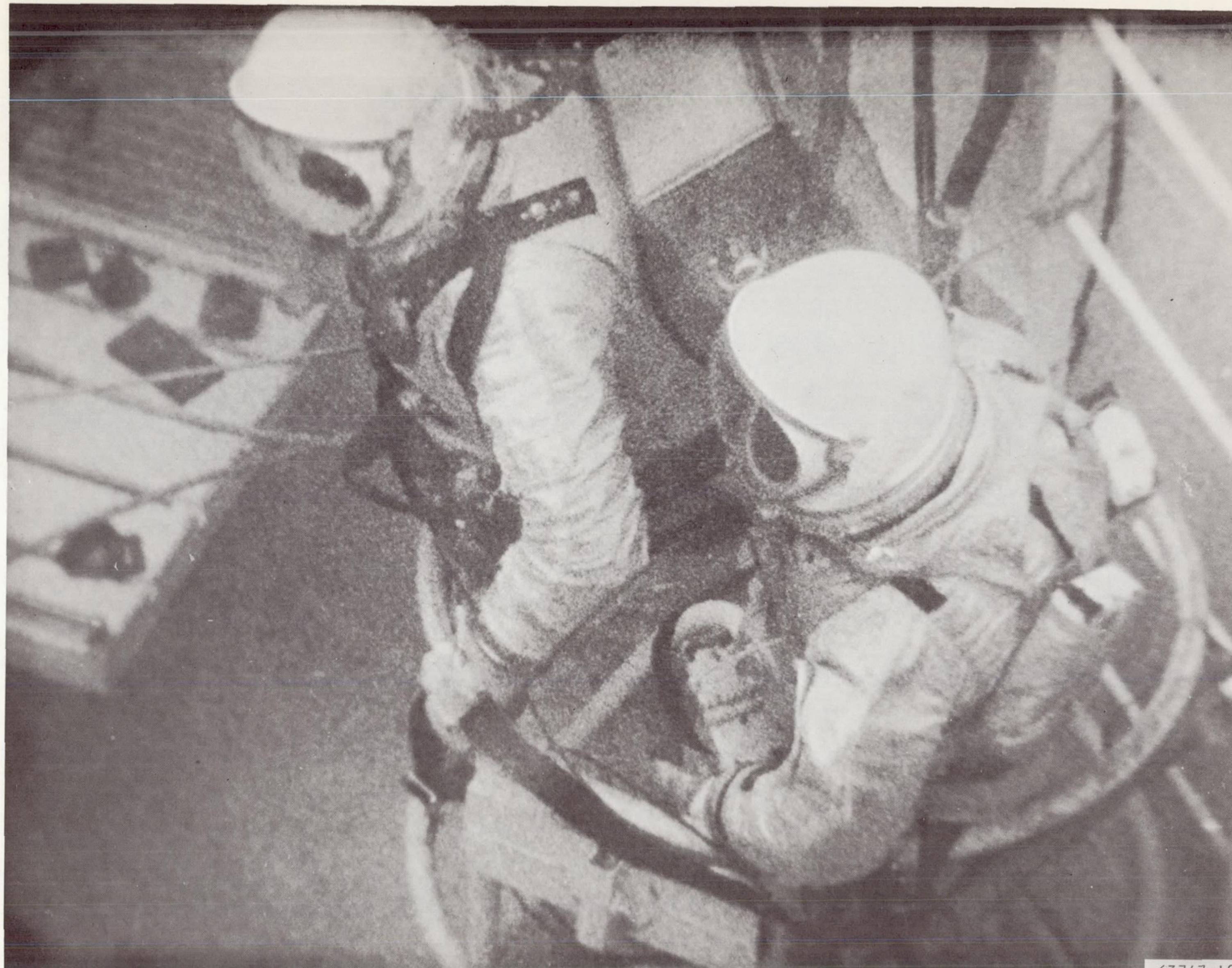


Figure 4-91. Subject Attempting to Position Dummy to His Back; Note Backpack Interference

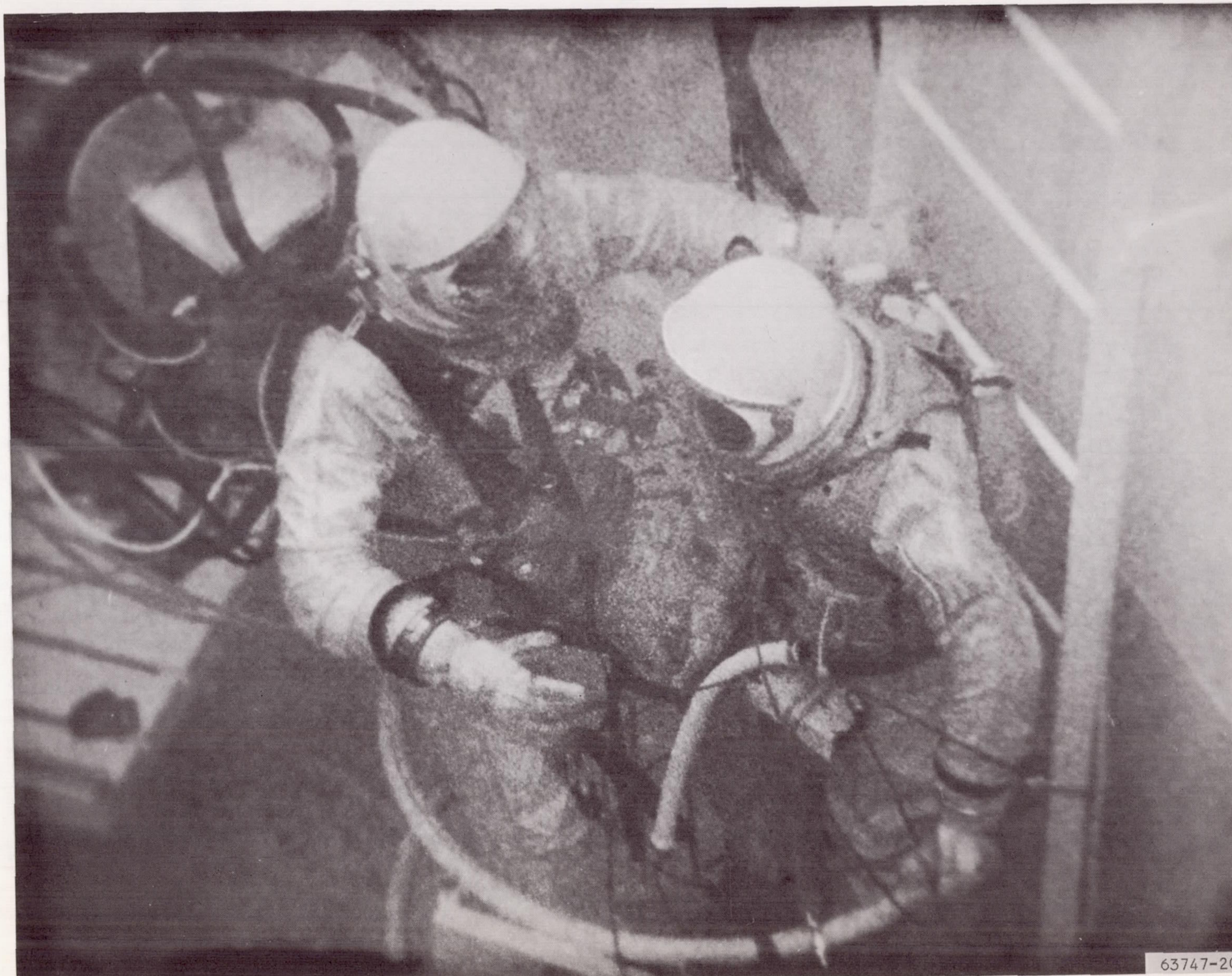


Figure 4-92. Subject Attaching Dummy to Ladder in Attempt to Gain More Control Over Dummy

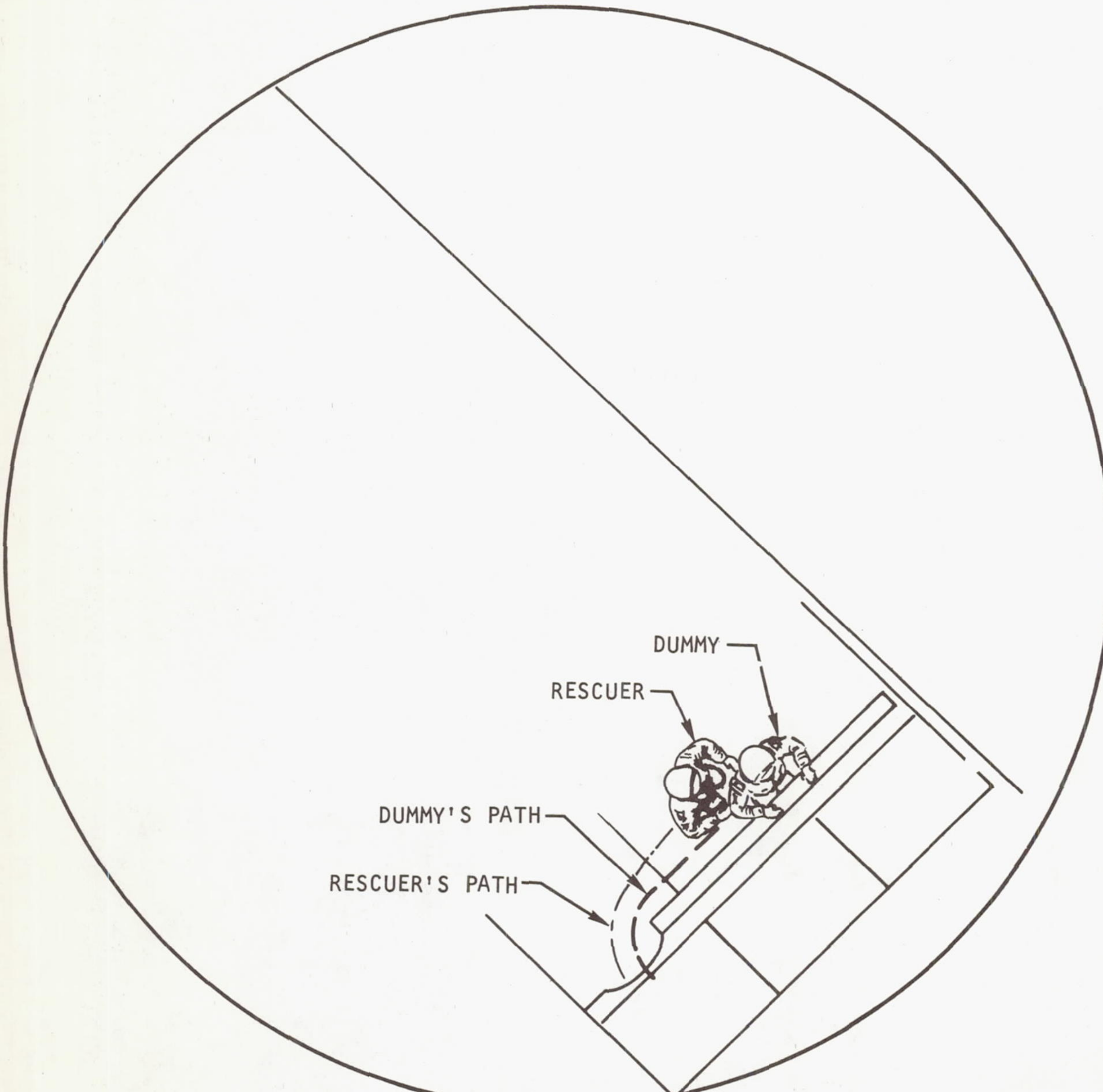


Figure 4-93. Concept 5--Exploratory Crew Rescue

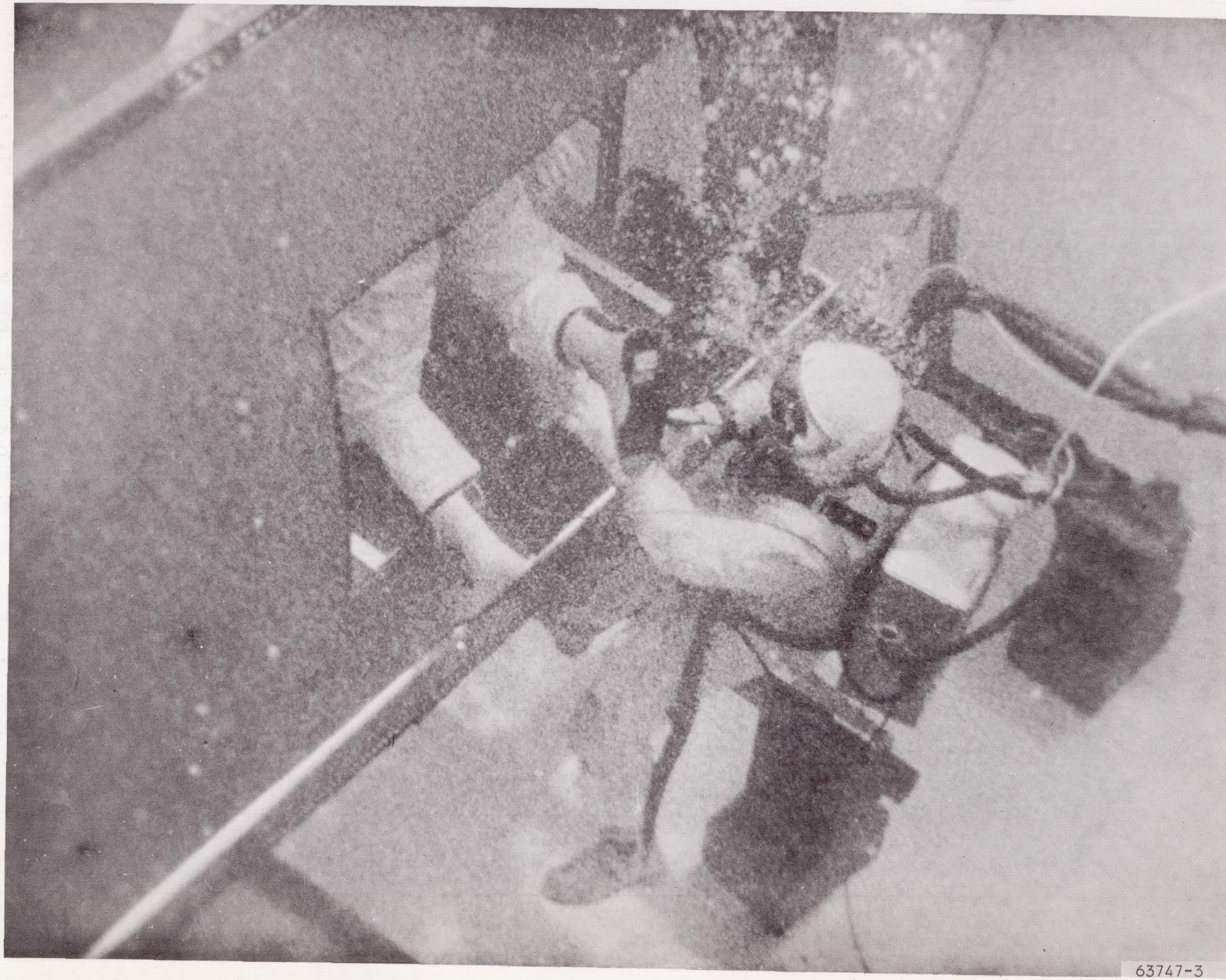


Figure 4-94. Subject Placing Dummy in Mockup Through Access Opening

Actually the procedural difference in the above tasks did not appear to alter the task of pushing the dummy through the hatch. This task was basically the same each time. The differences were mainly the individual steps used in recovering the dummy; locating, connecting, and disconnecting the restraints; locating the rescuer's restraint so that it did not interfere with the task of pushing the subject through the access opening.

Each of these trials produced the same difficulties in getting the subject through the hatch:

Push-off effect due to the flexibility of the strap restraints and the lack of adequate supports

Absence of stability of positions and the consequential loss of position (e.g., no support for torso, legs, or feet), see Figures 4-95 and 4-96

Maintaining of position by holding on with one hand and performing the task with the other hand which resulted in long task times and poor task performance, see Figures 4-97 and 4-98

Limited vision (e.g., not noticing dummy's foot or feet being caught on the lower edge of the hatch opening)

Conclusions

Considerable similarity existed between the crew rescue and the cargo transport tests. The types of problems observed in one series were also observed in the other series. The differences were mainly those of degree rather than of kind. For example, in the moving of a large object by pulling or pushing it along a locomotion aid, the subject performed better when he had both hands free (see Figure 4-99).

Traversing with the dummy in tow on a strap tether appeared rather effortless (see Figure 4-100). Once the dummy was started in motion, it continued in a smooth flow with only the slightest pull or push from the subject. Drag, of course, stopped the motion if the subject did not keep the dummy moving.

Although the water drag effect seemed less with the rescue dummy than with the cargo modules, it is uncertain to what extent the movements of large masses and large volumes in neutral buoyant simulation is a realistic simulation technique. The simulation technique is more appropriate for the subject alone at very low velocities (see Figures 4-101 and 4-102). When large objects are attached firmly to the subject, the simulation also appears good, i.e., the backpack transport. Objects separated from the subject for manipulation appear to introduce new conditions which are probably mass-to-mass coupling problems that tend to compromise the simulation technique.

Since the only restraint provided for the subject was a single strap tether, he had considerable difficulty in getting appropriate positions from which to work

Figure 4-95. Subject Pulling Dummy Along Rail Locomotion Aid

Figure 4-96. Subject Manipulating Dummy Attached to Rail with Strap Tether

Figure 4-97. Subject Pulling Dummy Along Front of Mockup Toward Hatch

Figure 4-98. Subject Manipulating Rescue Tether During Rescue Test

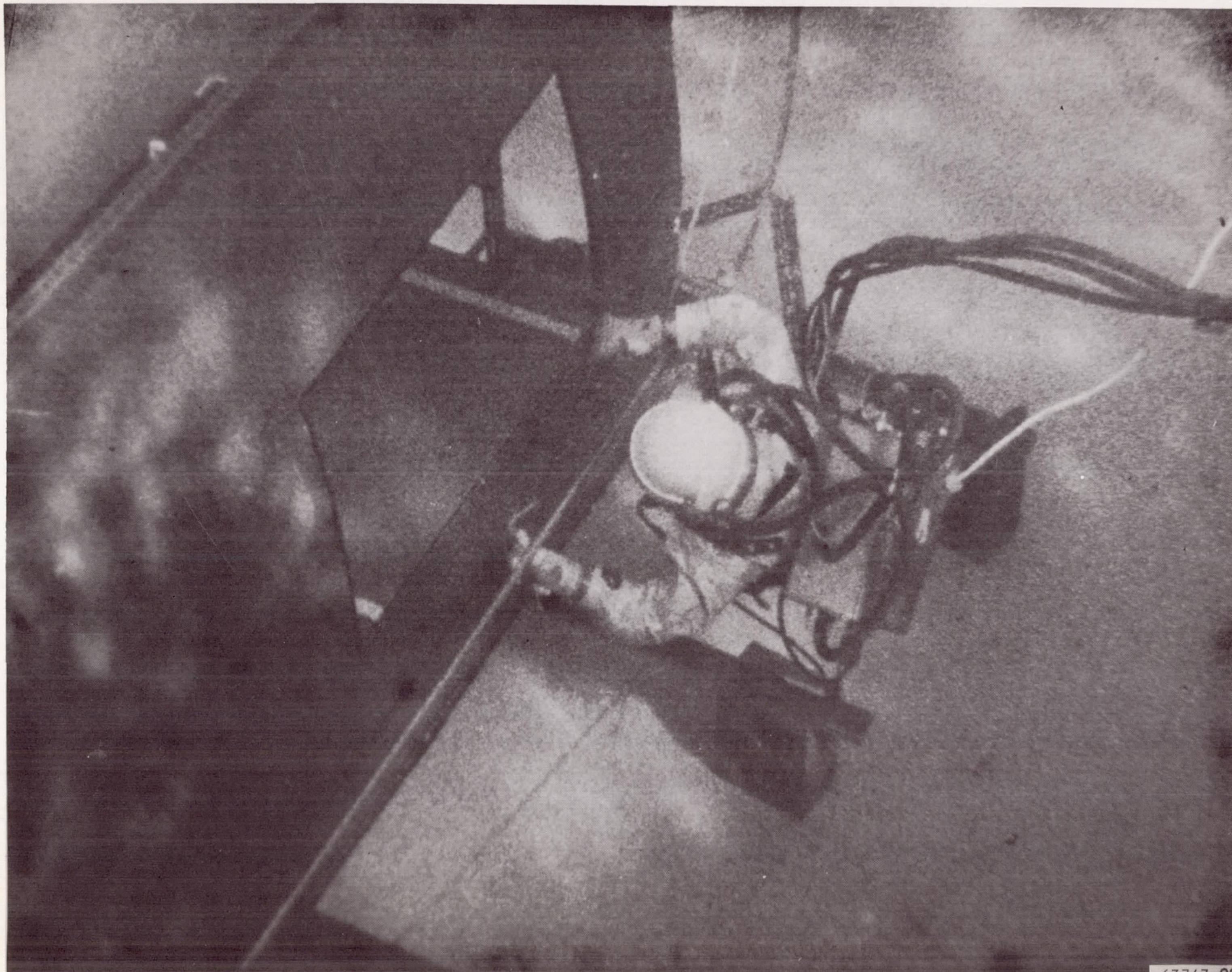


Figure 4-99. Subject Moving Along Front of Mockup to Pick Up Dummy During Rescue Test

Figure 4-100. Subject Pulling Himself with Dummy in Tow to Mockup

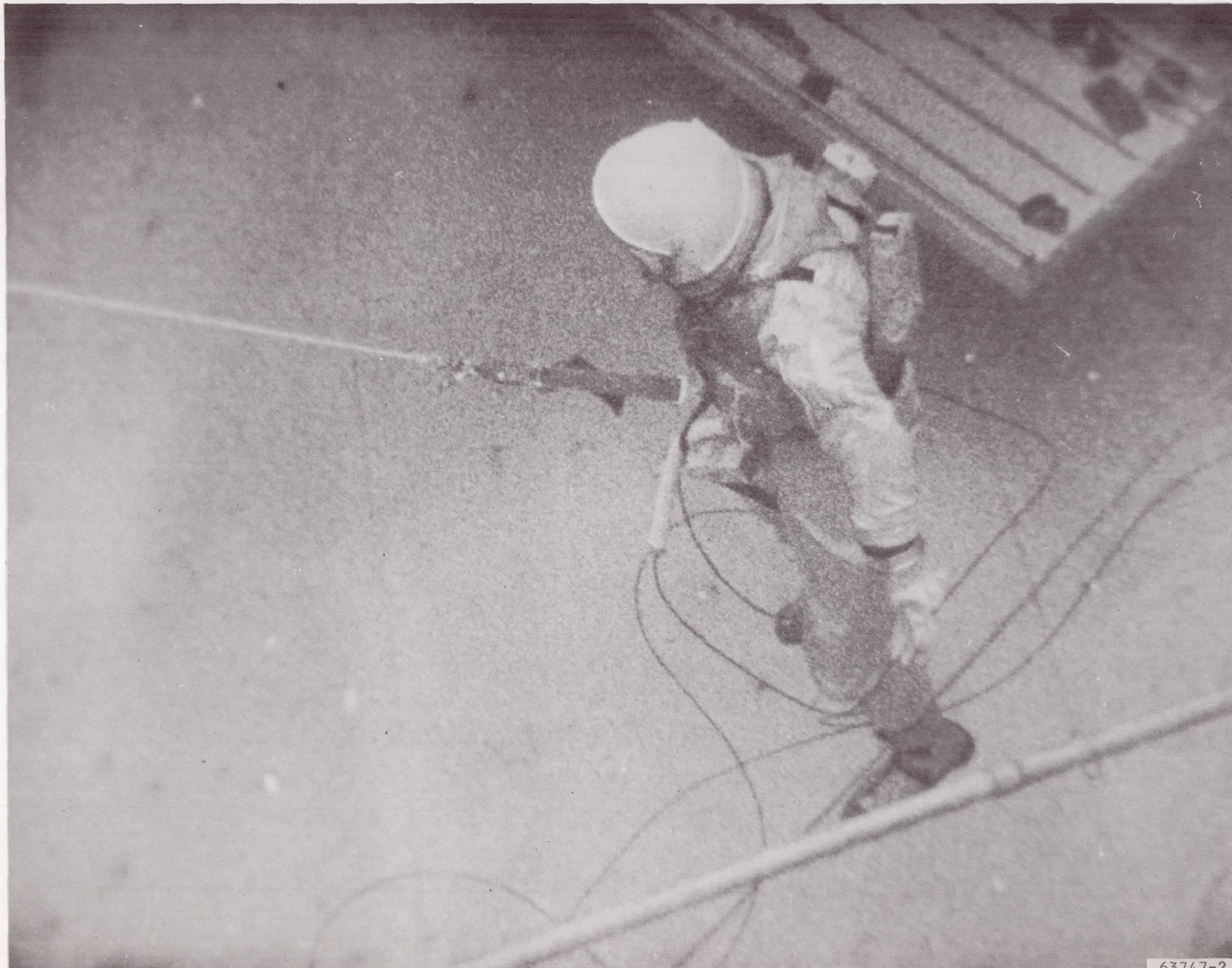


Figure 4-101. Dummy Being Pulled to Mockup by Subject During Rescue Test

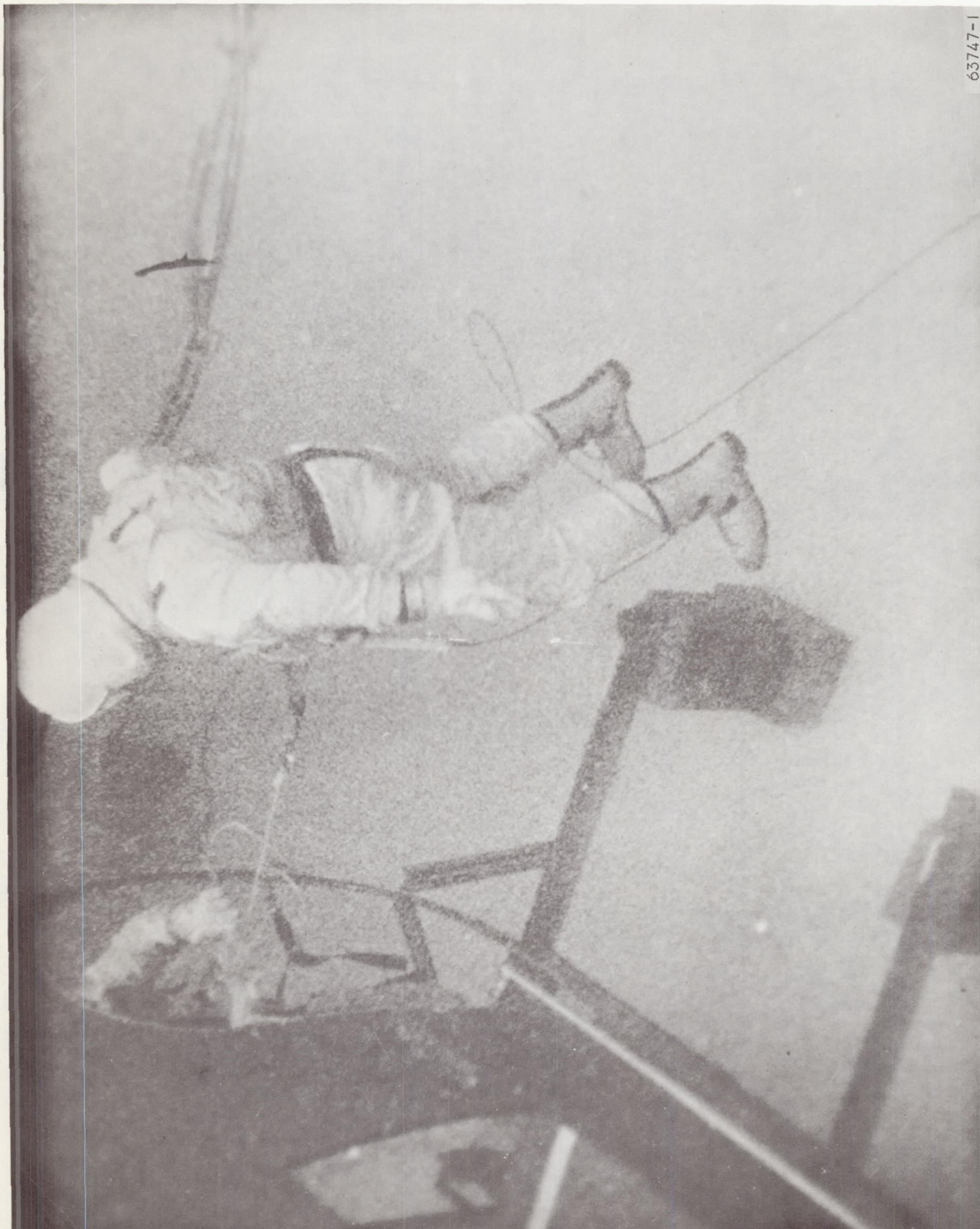


Figure 4-102. Subject Pulling Dummy Through Hatch During Rescue Test

and in maintaining the position throughout the specific task. The task of placing the rescued dummy through the hatch is an example of this problem. When the subject pushed on the dummy, the reactive force pushed him away from the dummy; consequently he would "float" away from the dummy and then be required to reposition himself and start the task again. When rigid support is not available to the subject, he spends the major part of the task completion time getting into position, falling, or losing position and then regaining position.

Hand holds are effective but are only adequate for tasks of relatively small force requirements; large force applications require securing the feet, legs, or torso. This latter capability did not exist at the mockup hatch. Getting the rescued dummy through the hatch was a difficult task since it was essentially a one-hand operation under the circumstances.

The outstanding single time-consuming problem of the rescue tests was the time spent during the tasks with the subject "free floating" on the strap restraint after he had lost position and was reseeking position. This fault can be corrected with a functional restraint system that will enable the subject to contain his feet, legs, or lower torso.

This series of tests required frequent strap restraint manipulation. The release and connection of the end snaps were a constant source of difficulty for the subject especially when the subject could not see the connector. An additional problem exists when the subject is trying to locate his strap restraint out of his visual field. A considerable portion of the total test time was wasted by the subject working inefficiently with his restraints. It is recommended that strap restraints be semirigid and that design consideration be given to the end connectors to make them compatible with pressurized gloves.

RESTRAINT EVALUATION EXPERIMENT

The restraint tests were structured to compare four different EVA restraint conditions. Six subjects performed identical task sequences with each restraint to identify the advantages and disadvantages of each restraint configuration. In addition, the task performance interface was moved away from the subject to further identify the work envelope of the subject, relative to each restraint. Figure 4-103 illustrates the experimental design and the 72 individual test modes.

PROCEDURES AND TEST APPARATUS

To test the restraint devices, 72 individual test modes were performed by each subject on a task box designed for this purpose. These modes were a sequence of elementary maintenance tasks. The task modes and task elements were kept simple with clear-cut, observable beginnings and ends to provide accurate time data points. Simplicity of tasks and task equipment was required to obtain data points for loads translated from the subject to the equipment in performing the tasks.

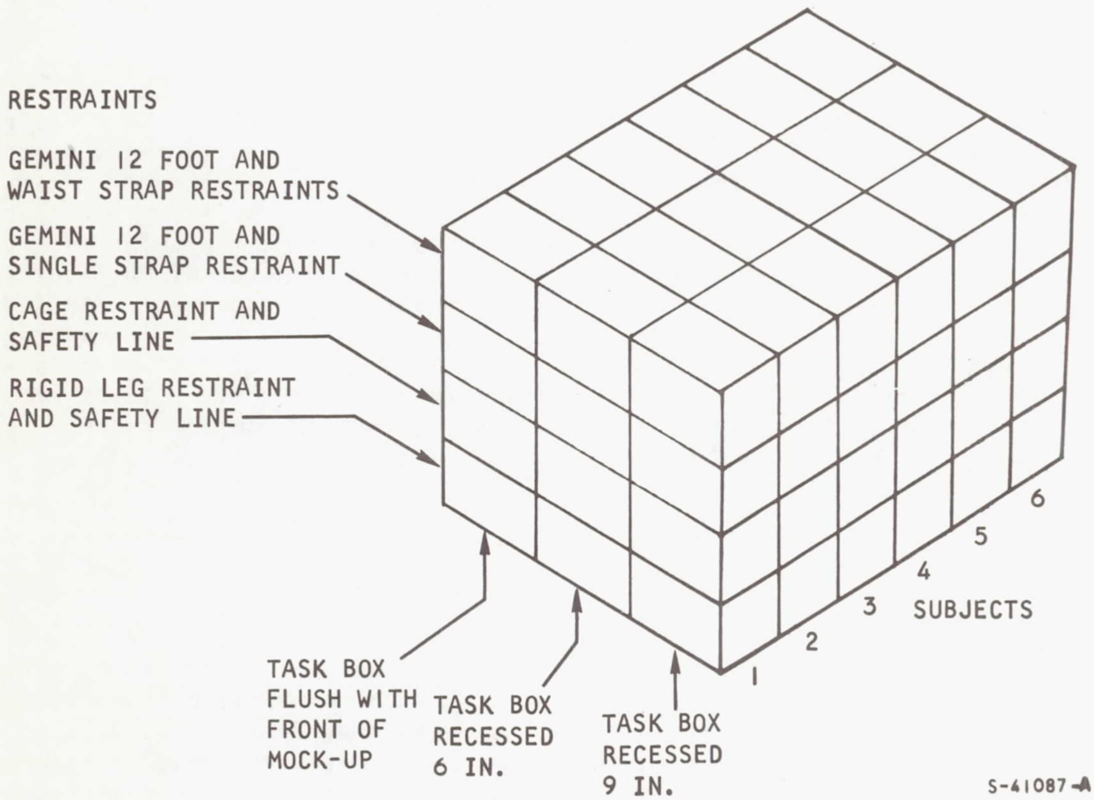


Figure 4-103. Experimental Design for Restraint Testing

The four restraint conditions are as follows:

(a) Gemini 12 foot restraints used with two adjustable waist strap restraints

(b) Gemini 12 foot restraints used with a single adjustable strap restraint connected to the subject's chest

(c) A cage restraint, adjustable in depth and diameter

(d) A single, rigid-leg restraint connected centrally to the subject's shell. This restraint included a lockable universal at each end to provide a pivoting capability

Each restraint configuration was instrumented to measure the loads imparted to it by the subject during the task performance.

Figure 4-104 depicts the task sequencing used for the restraint tests. Prior to formal testing, the sequence was subjected to pilot tests to correct deficiencies of timing points, procedure, and sequence. Each of the six subjects used the final procedures shown for each of the four restraints at three distances from the task box. The discrete tasks within the task sequence for the formal restraint test were selected to represent a wide variety of typical maintenance acts. In addition, several large muscular force tasks were included.

For the restraint tests, the key data were performance time for the specific tasks associated with the task box. The learning associated with the task sequence required each subject to perform the sequence correctly from memory. Learning was considered adequate when the subject performed the sequence without fumbling while blindfolded. It was believed that training to this level demonstrated an adequate task performance level and that individual differences in the skill required to perform the task sequence would be minimized.

The task box used for the restraint tests is illustrated in Figure 4-105. The maintenance tasks represent removal and replacement of components in keeping with the current space maintenance concepts. Additional tasks of fine adjustment and manipulation were included along with large torque tasks associated with the level and hand wheel.

The task box was positioned in an access opening of the mockup. The access opening is 30 in. high and 40 in. wide. Three positions were used to increase the depth of reach for the subject. The first position of the task box is flush with the front edge of the access opening, the second position is 6 in. back from the front edge, and the last condition is 9 in. back from the front edge of the access opening.

Figure 4-106 depicts the configuration of the spacecraft mockup section. The task box was located in the 30 in. by 46 in. hatchway. Figure 4-107 depicts the location of the astronaut/subject in the cage restraint with respect to the spacecraft mockup, the task box, and the location of the load cell. Figure 4-108 presents the same information for the utilization of the Gemini "dutch shoe"

TEST NO.		DATE	SUBJECT	OBSERVER
Task No.	Task Time		Task Sequence	Equipment
1			Release housing over gage. Release locking screw on gage and set gage to read "10." Reset locking screw. Remove gage and attach to tool kit. ◄——— Hand free of gage	Tool kit secured in position prior to starting test
2			Procure replacement gage from tool kit and install on task box. Replace housing and secure fasteners. ◄——— Hand free of housing	Replacement gage
3			Remove flexible tubing from task box, attach to tool kit. Procure replacement and attach to task box. ◄——— Hand free of tubing	
4			Remove housing No. 2 and attach to tool kit. Exchange quick disconnects and replace housing cover. ◄——— Hand free of housing	
5			Install lever and align RED arrow. With left hand pull twice and push twice. DISCRETE ACTS. ◄——— Hand off lever	
6			Place right hand on lever and pull twice and push twice. DISCRETE ACTS. Remove lever and place in holder. ◄——— Hand free of lever	
7			Procure "T" wrench and place lanyard on wrist. Open door. Loosen terminal nuts and wires. Loosen captive nuts. Remove box and turn 180 degrees. ◄——— Turning of box	
8			Reposition box, position wires and tighten terminals. Finger tighten captive bolts, wrench tight, close door and latch. Return wrench to kit. ◄——— Hand off wrench	
9			Turn hand wheel. Clockwise Clockwise Counter clockwise Counter clockwise } Discrete acts ◄——— Hand on wrench	
10			Procure wrench. Torque two top right hand bolts to maximum. Break top two left hand bolts loose ◄——— Wrench touching front bolt	3.4 in. open end wrench on lanyard
11			Torque two front right hand bolts to maximum. Break two front left hand bolts loose. Replace wrench in tool kit. ◄——— Hand free of wrench	

Figure 4-104. Restraint Test Task Sequencing

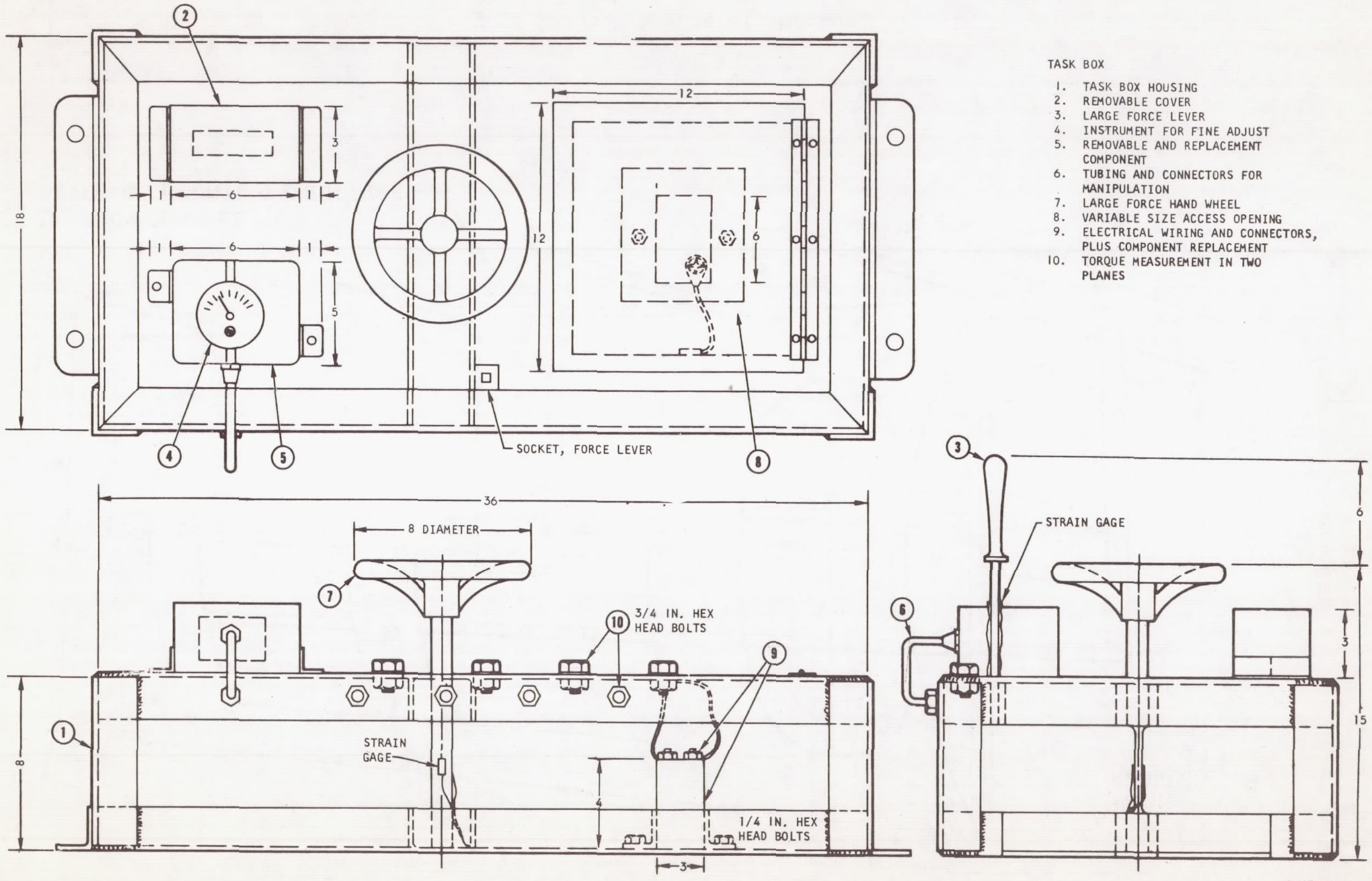


Figure 4-105 Task Box

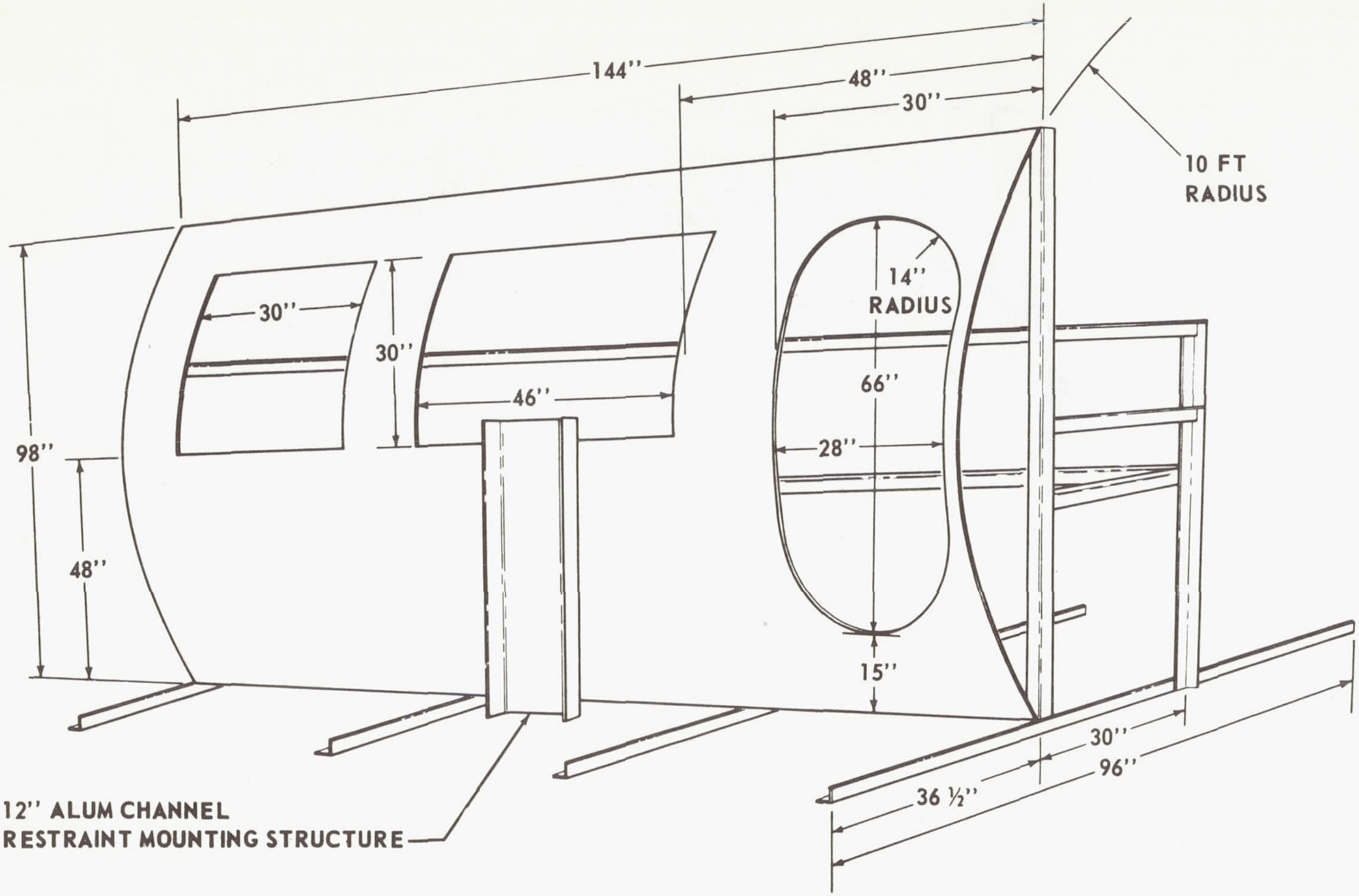


Figure 4-106. Spacecraft Mockup

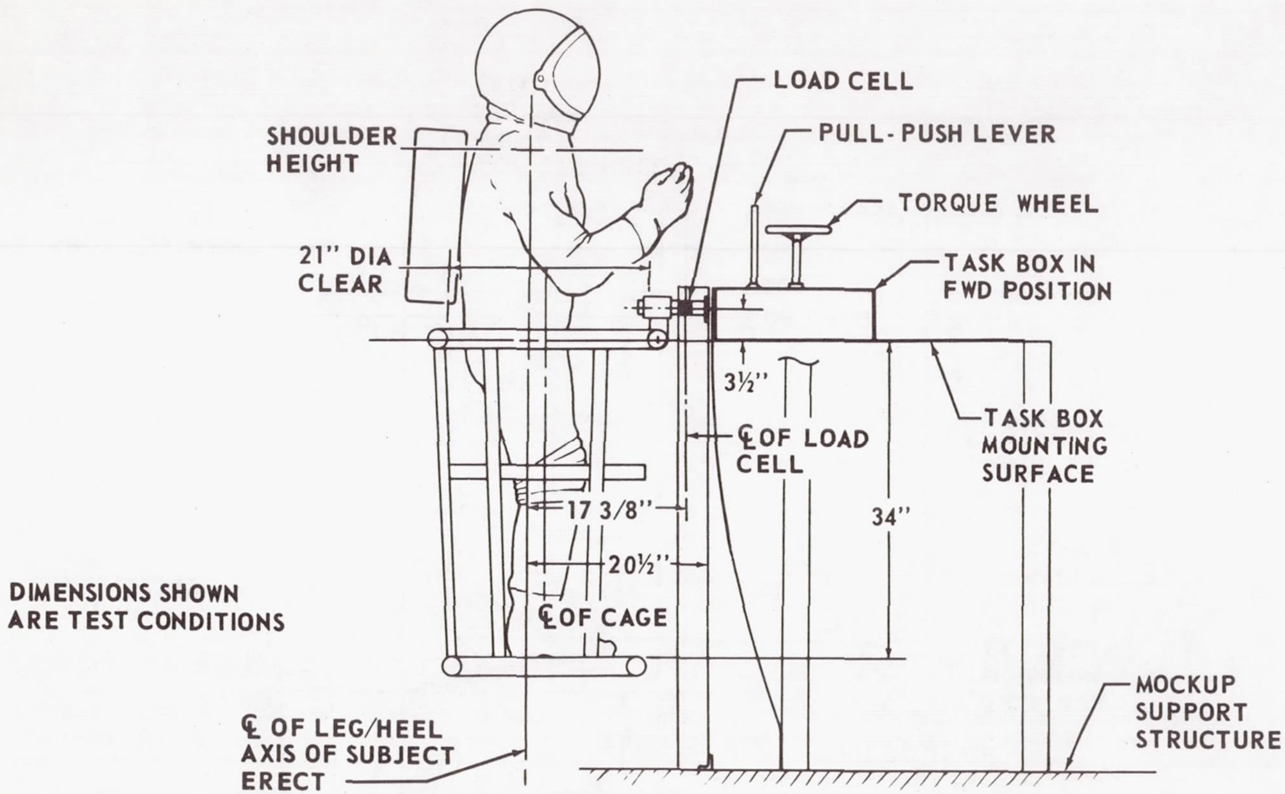


Figure 4-107. Cage Restraint Geometry

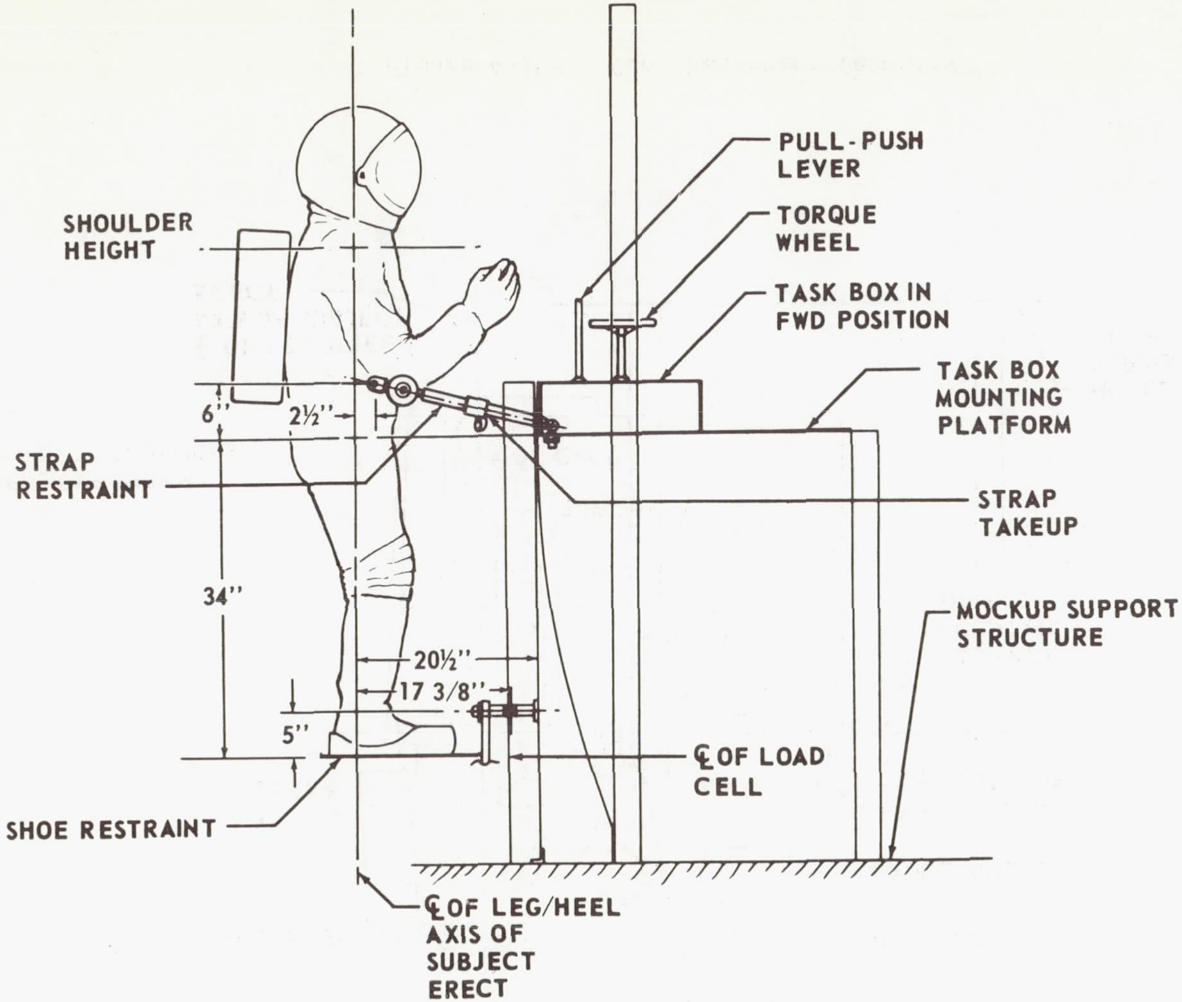


Figure 4-108. Foot Restraint and Strap Geometry

restraints. Figure 4-109 presents the geometry of the dutch shoe foot restraint with respect to the load cell.

The variables manipulated during the restraint tests are summarized in Table 4-5. This table also identifies the test identification code numbers entered in the test log, the task sequence timing sheets, the various recording data tools, and the film record. Thus, test number 1-2-3 identifies:

1 = the Gemini foot restraints combined with two adjustable waist straps; 2 = the task box positioned 6 in. back from the front edge of the mockup; 3 = the subject (Clegg)

TABLE 4-5

RESTRAINT TEST IDENTIFICATION NUMBERS

First Digit 1-4 Restraint Devices	Second Digit 1-3 Distance of Task Box from Front of Mockup	Third Digit 1-8 Subject Identification Number
1 Gemini 12 foot and waist strap restraints	1 Flush with front edge of mockup	1 Barnes
2 Gemini 12 foot and single strap restraint	2 Recessed 6 in. from front edge of mockup	2 Blacker
3 Rigid leg restraint and safety line	3 Recessed 9 in. from front edge of mockup	3 Clegg
4 Cage restraint and safety line		4 Lockwood
		5 Paige
		6 Perry
		7 Romero
		8 Whitney

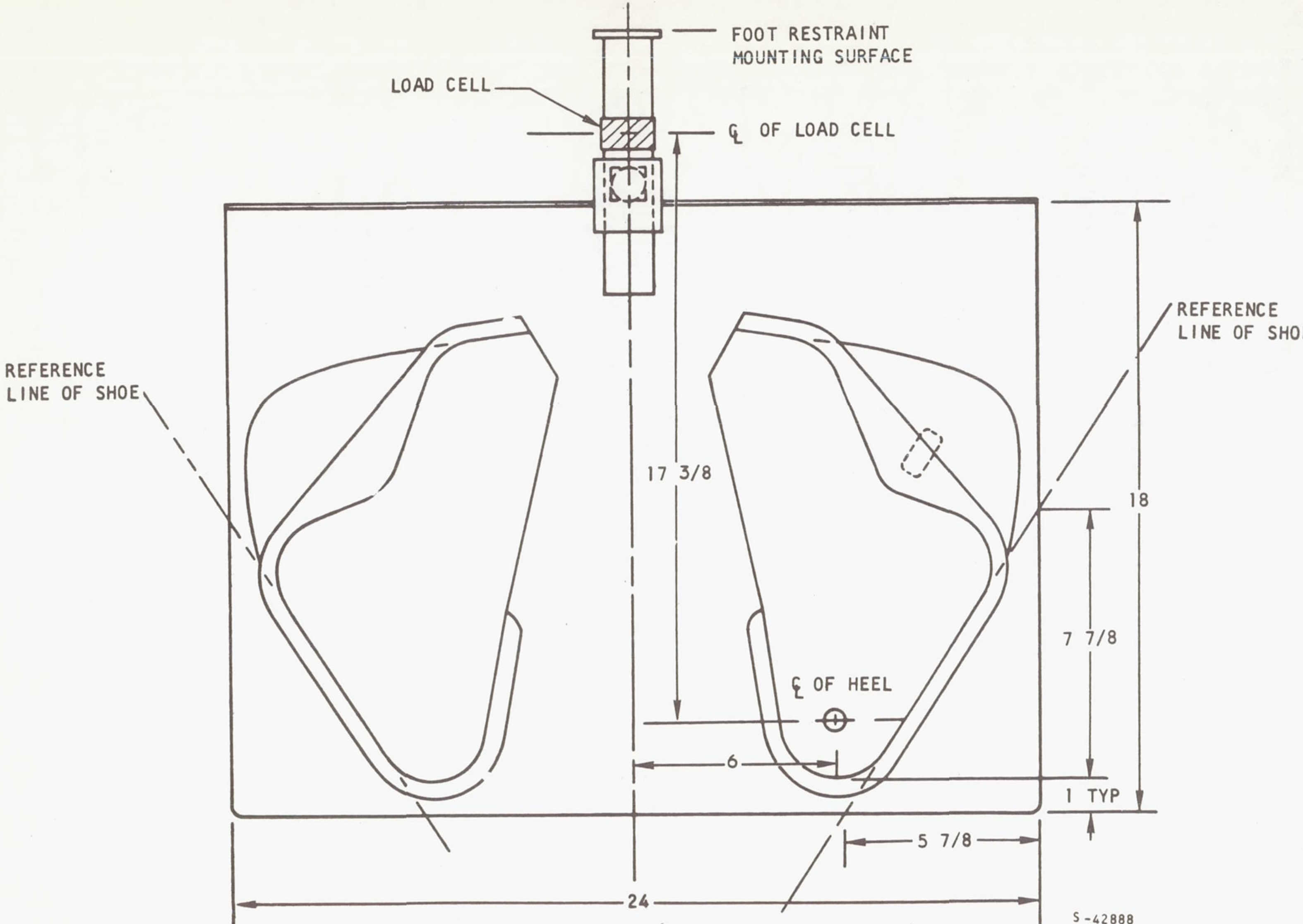


Figure 4-109. Foot Restraint - Plan Geometry

Performance Data

The bar graphs (Figures 4-110 through 4-116) depict the mean time for all subjects to complete each task element. The last bar graph (Figure 4-116) depicts the mean total time for all subjects to accomplish the complete task sequence (11 task elements) on the task box. The bar graphs compare the three restraint types: dutch shoes and tethers; dutch shoes and strap; and the cage restraint labeled A, B, and C, respectively. The bar graphs also compare the effect of the depth of the task box at 0, 6, and 9 in. from the front surface of the vehicle mockup. The results of the analysis of variance of the time data are tabulated directly below each set of bar graphs.

In reviewing these data, it is apparent that statistically the types of restraint employed for almost every one of the task elements differed significantly. The general order was B, C, A; dutch shoes and strap; cage; and dutch shoes and tethers, respectively. The depth of the task box significantly affected performance time in only one case (task element 6, push and pull of the lever). The box depth was not affected in the other cases because the subjects using either configuration of the dutch shoes repeatedly left the shoes to perform the deep tasks. They could perform the deep tasks only because of the peculiarities of the test situation which allowed them to wedge themselves into the opening and to react against the top or side of the access hole. The basic criterion for the test of task performance from the restraint was that only the cage restraint was usable under all test conditions.

Figures 4-117 and 4-118 plot the mean torque values obtained for all subjects torquing the bolts on the front and top of the task box, respectively. Significantly lighter torque values were obtained on the front bolts utilizing the cage and on the top bolts using the dutch shoe and strap configuration. The torque achieved with the top bolts is substantially higher than that with the front location which is the reverse of what would be observed at earth gravity conditions.

Physiologic Data

The total energy above the resting values was determined for all subjects across each restraint system tested by the technique described earlier in this section. Data were not obtained for the rigid leg restraint for the reasons noted under the human engineering observations. The total energy used to perform work in each of the other three restraint systems is shown in Table 4-6 and graphically in Figure 4-119. A statistical analysis of these data ranked the restraints with the cage having a higher metabolic cost to perform the task than either of the other two restraints ($p < 0.01$). The use of the two dutch shoe configurations did not produce different data statistically. The higher metabolic costs noted with the cage restraint were due to higher energy cost of using the restraint system, i.e., mobility within the restraint. Also, the subjects could develop a greater force field while using this restraint. Therefore, even though the energy costs were higher, the subject was able to perform more work efiiciently. The cage restraint is considered the best all-around restraint system tested even though each restraint system has specific attributes which allowed certain tasks to be performed easier and more efficiently.

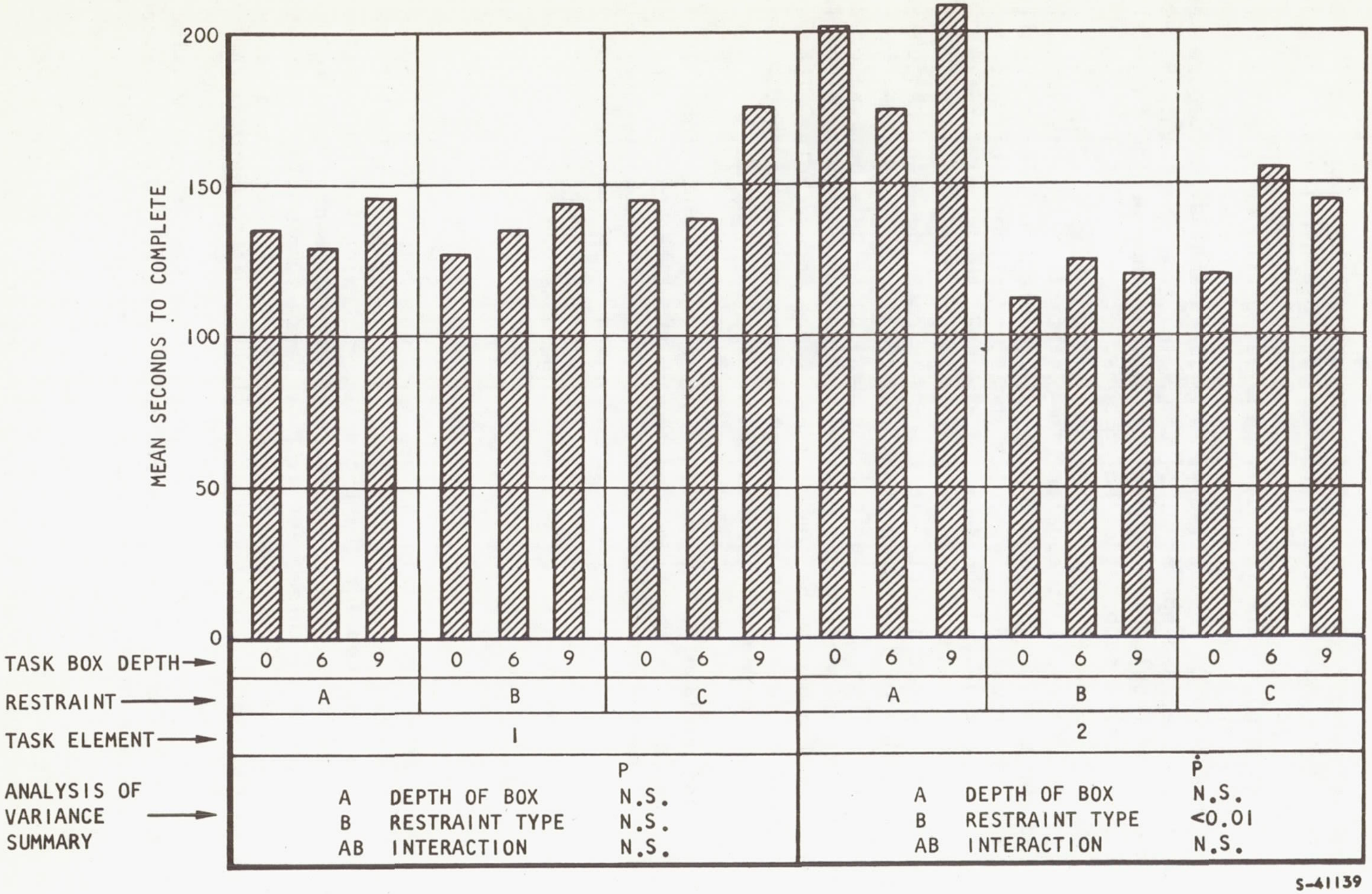


Figure 4-110. Subject Mean Time for Task Element

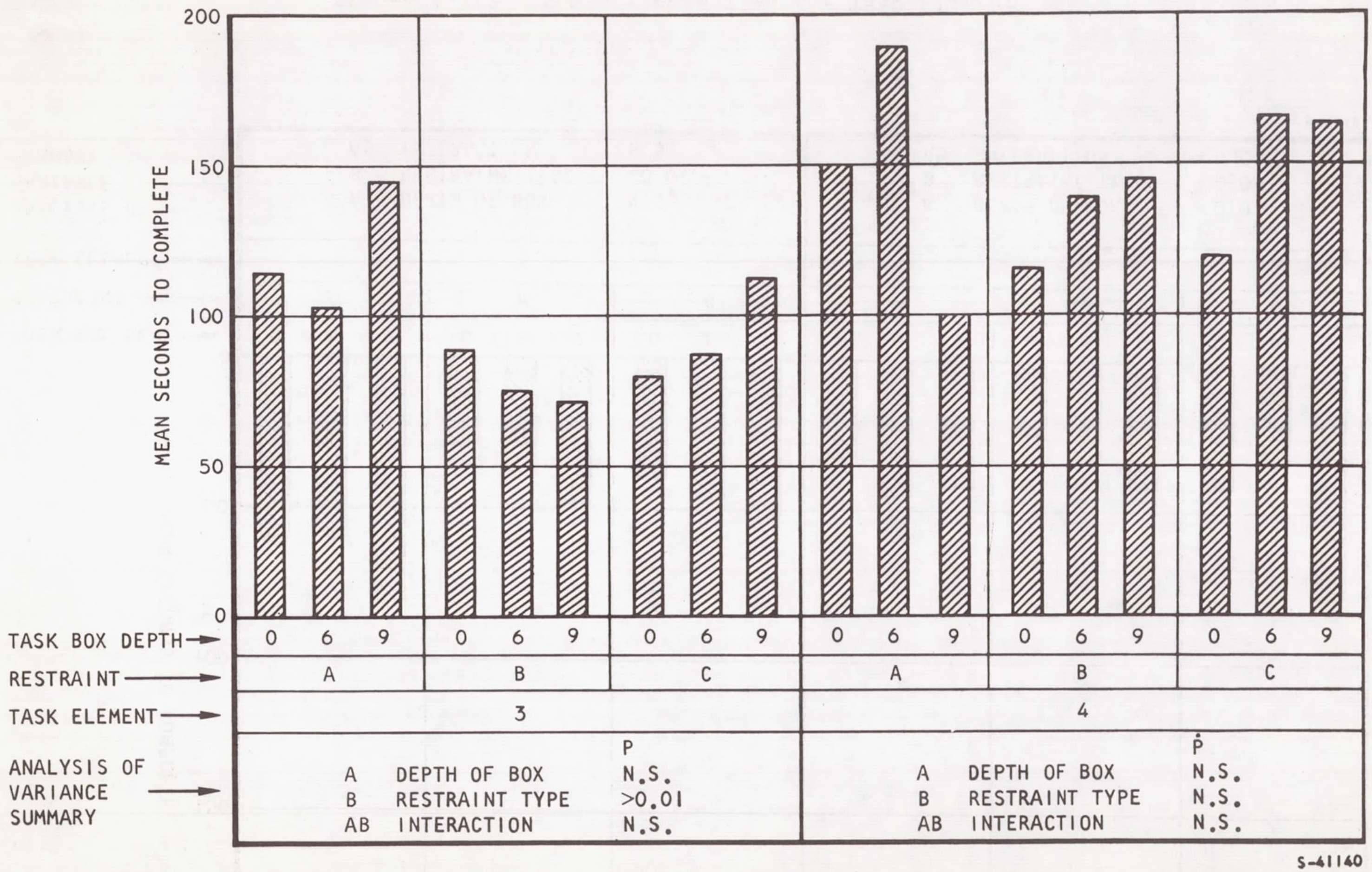


Figure 4-111. Subject Mean Time for Task Element

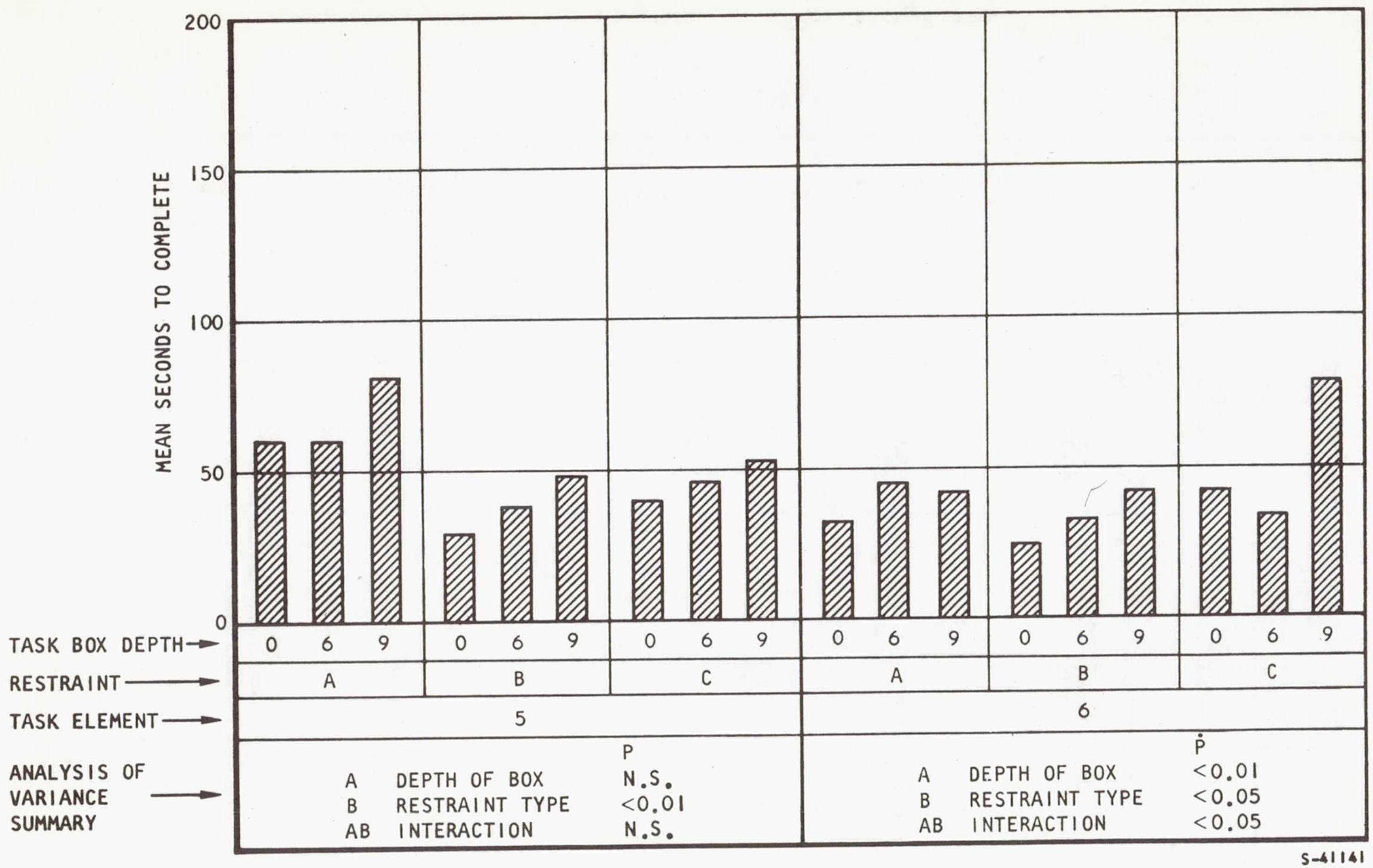


Figure 4-112. Subject Mean Time for Task Element

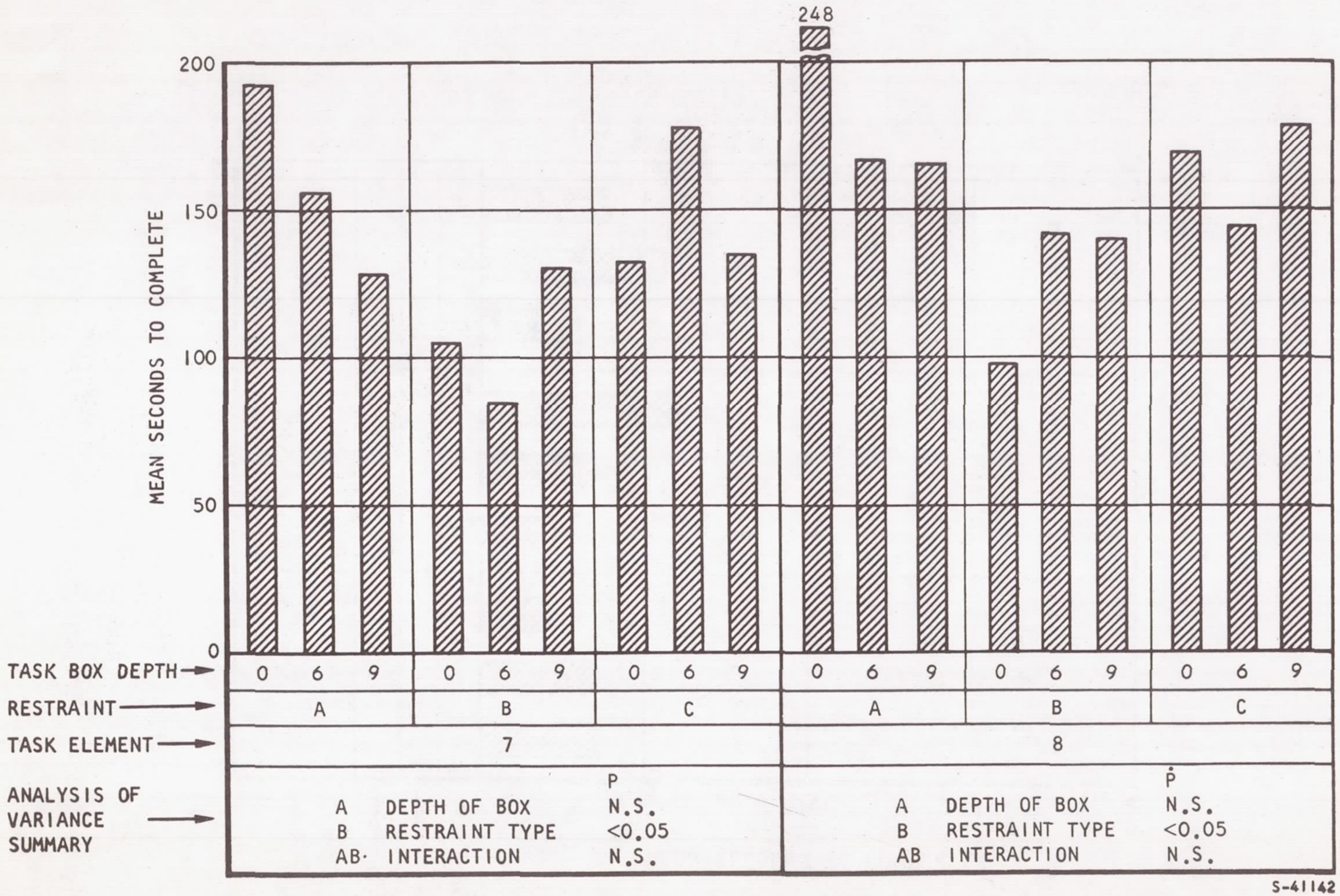


Figure 4-113. Subject Mean Time for Task Element

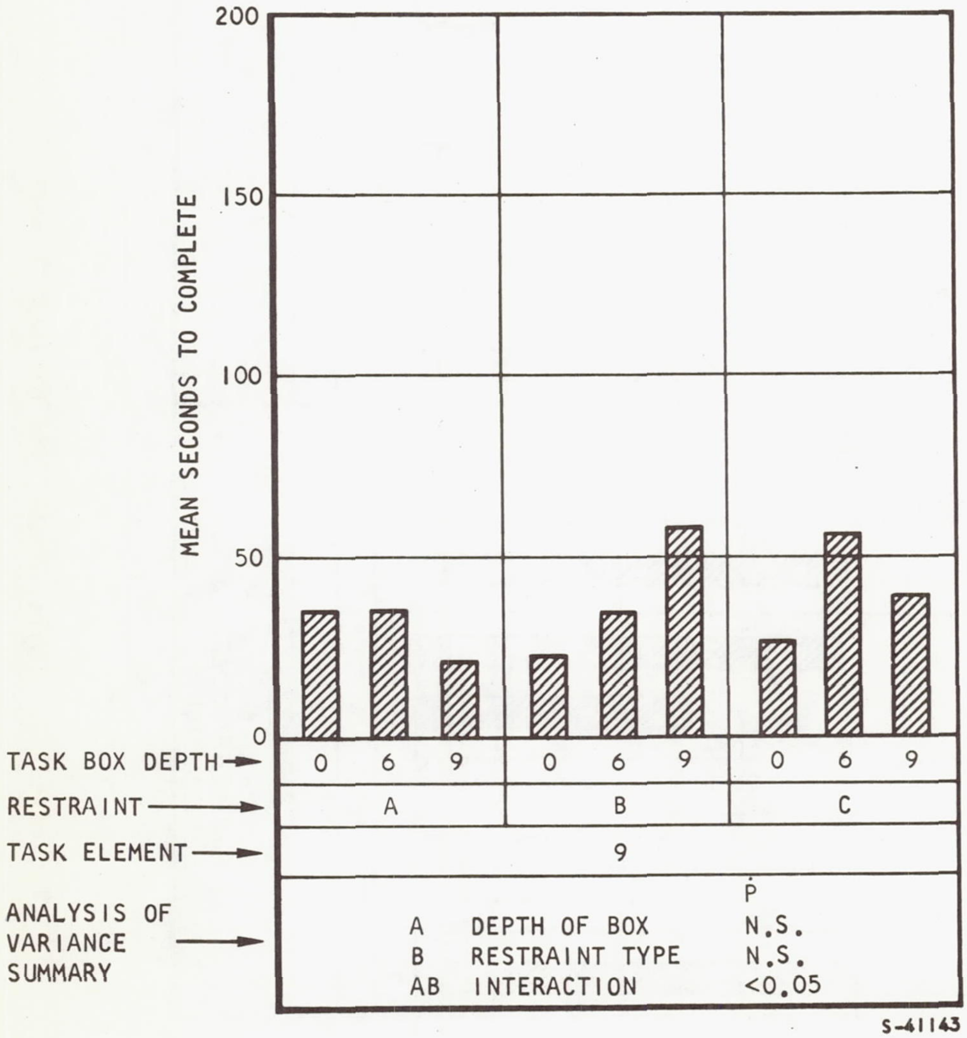


Figure 4-114. Subject Mean Time for Task Element

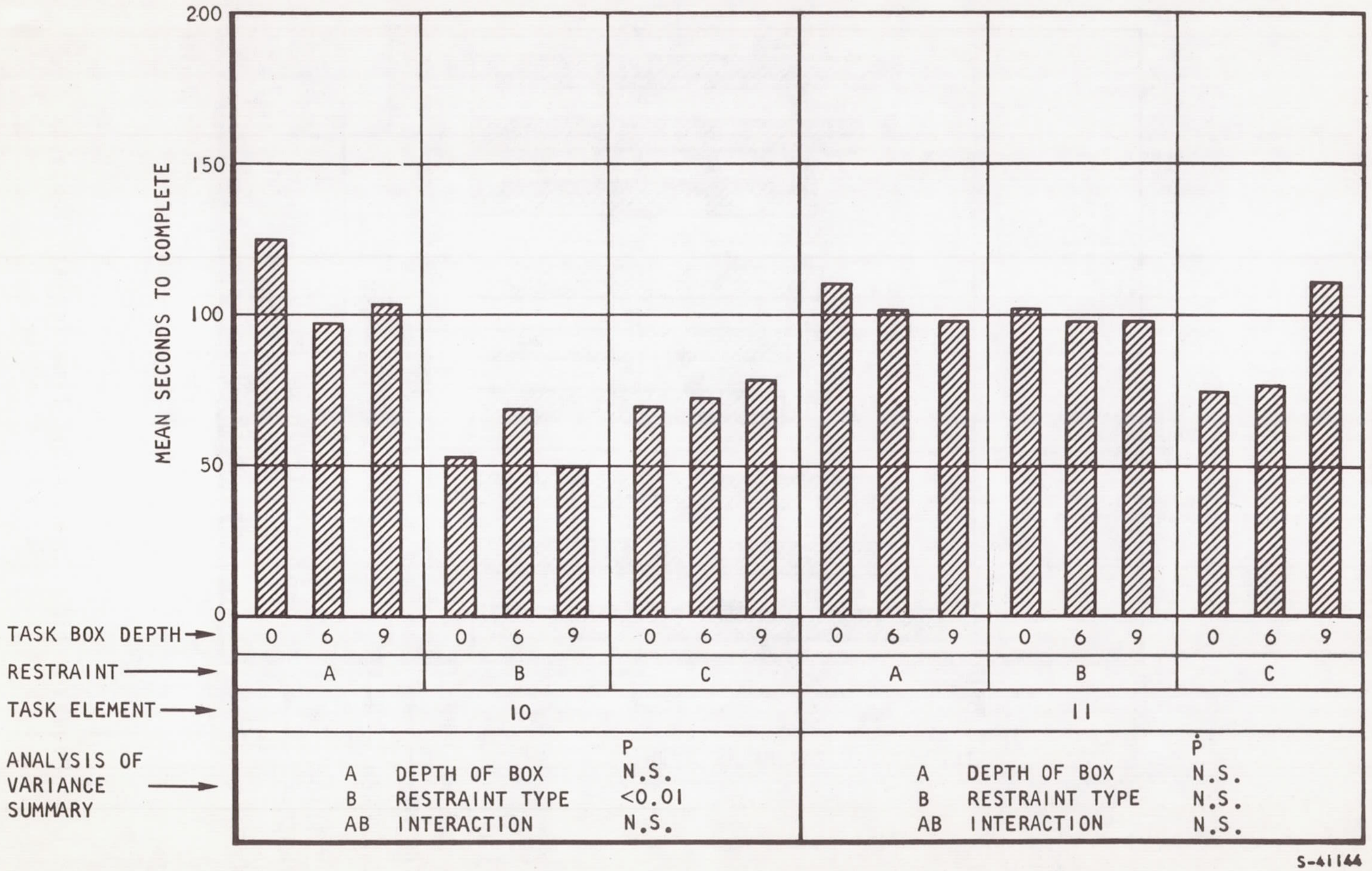


Figure 4-115. Subject Mean Time for Task Element

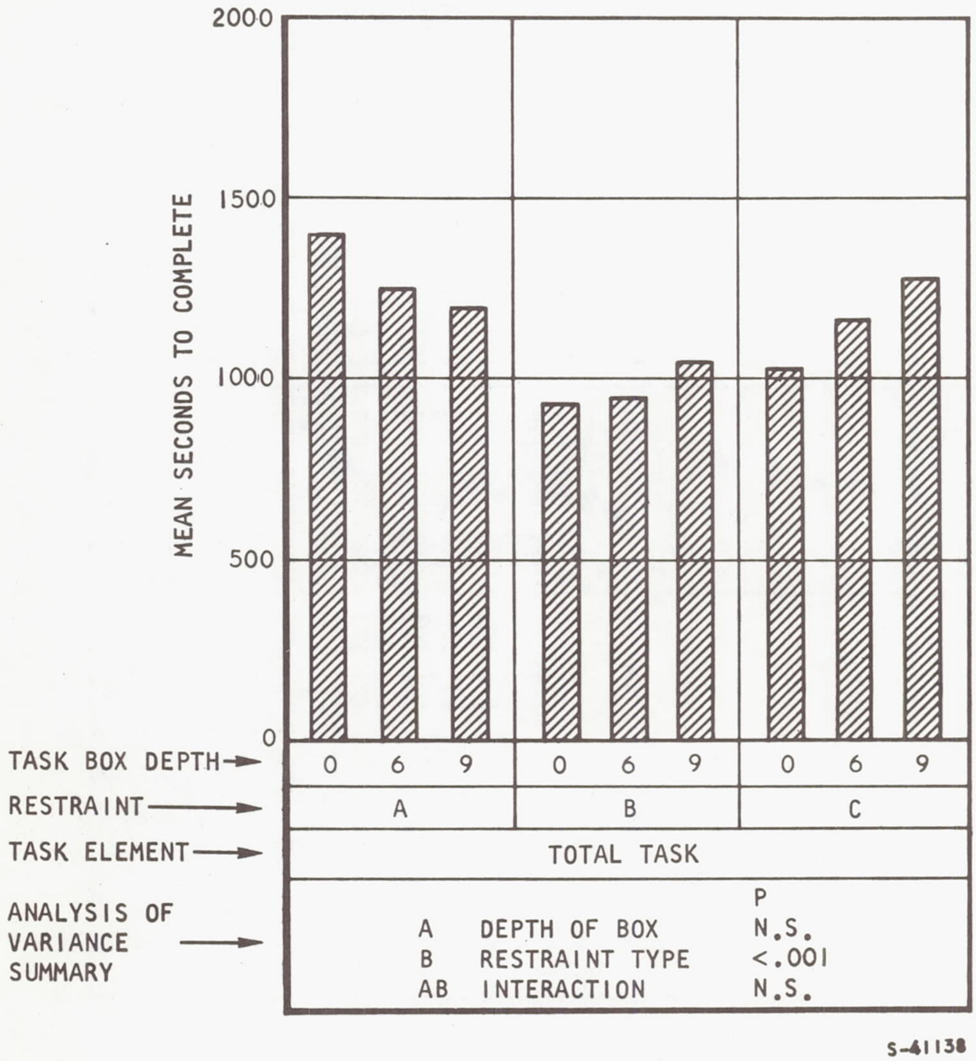
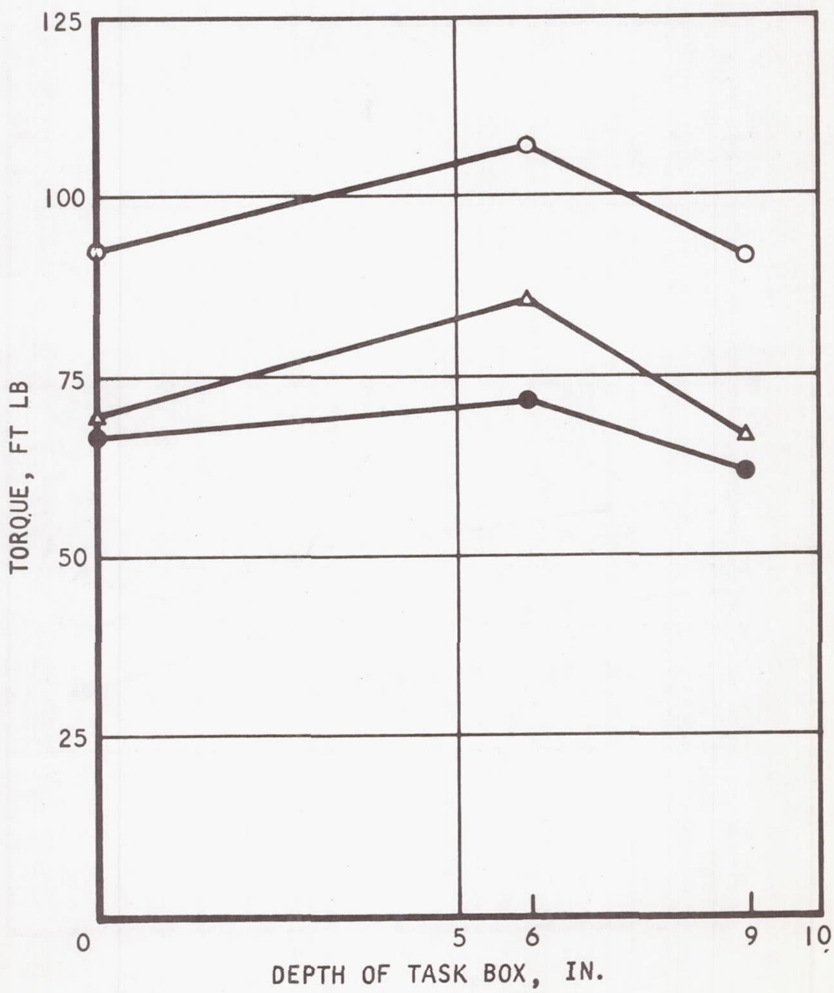


Figure 4-116. Mean Total Time for All Subjects for Task Element

RESTRAINT TYPES
LEGEND

● A
○ B
△ C

	VARIABLE	P
ANALYSIS OF VARIANCE SUMMARY	DEPTH OF BOX	N.S.
	RESTRAINT TYPE	<0.01
	INTERACTION	N.S.



S-41148

Figure 4-117. Mean Torque Values

RESTRAINT TYPES
LEGEND

● A
○ B
△ C

ANALYSIS OF VARIANCE SUMMARY	VARIABLE	P
	DEPTH OF BOX	N.S.
	RESTRAINT TYPE	<0.01
	INTERACTION	N.S.

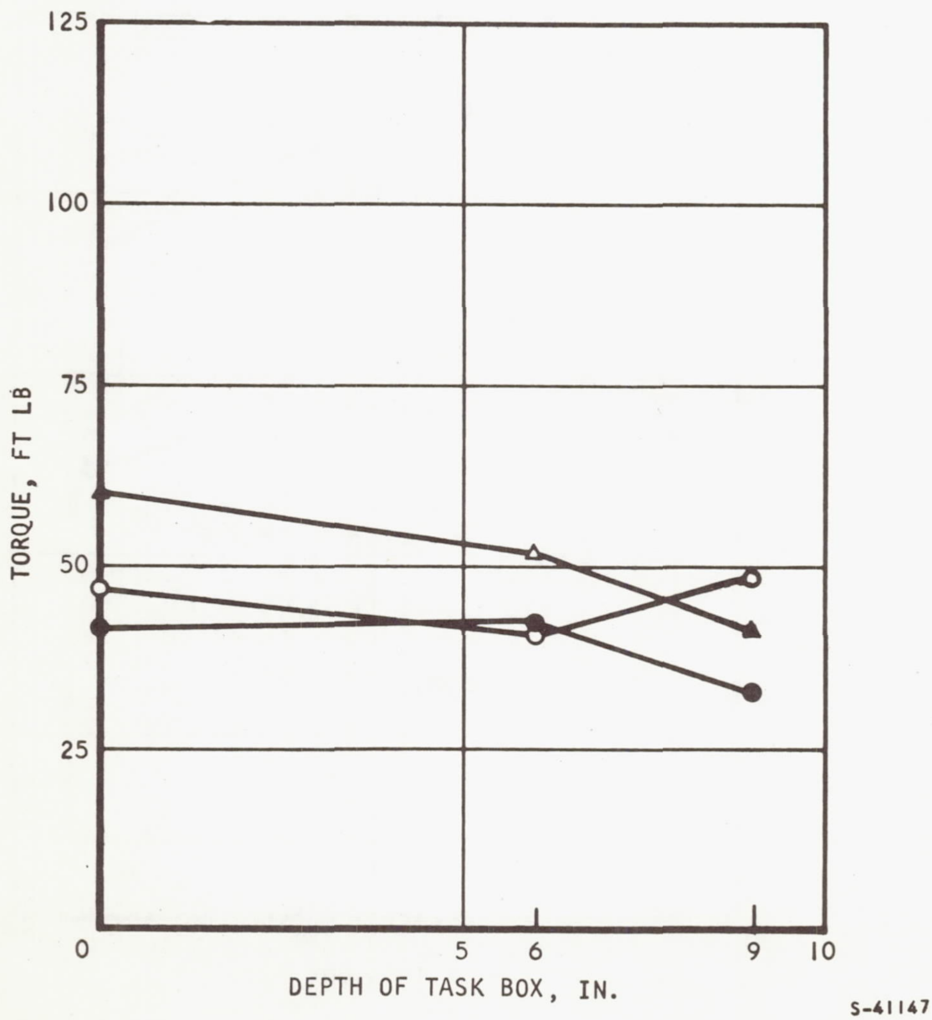


Figure 4-118. Mean Torque Values

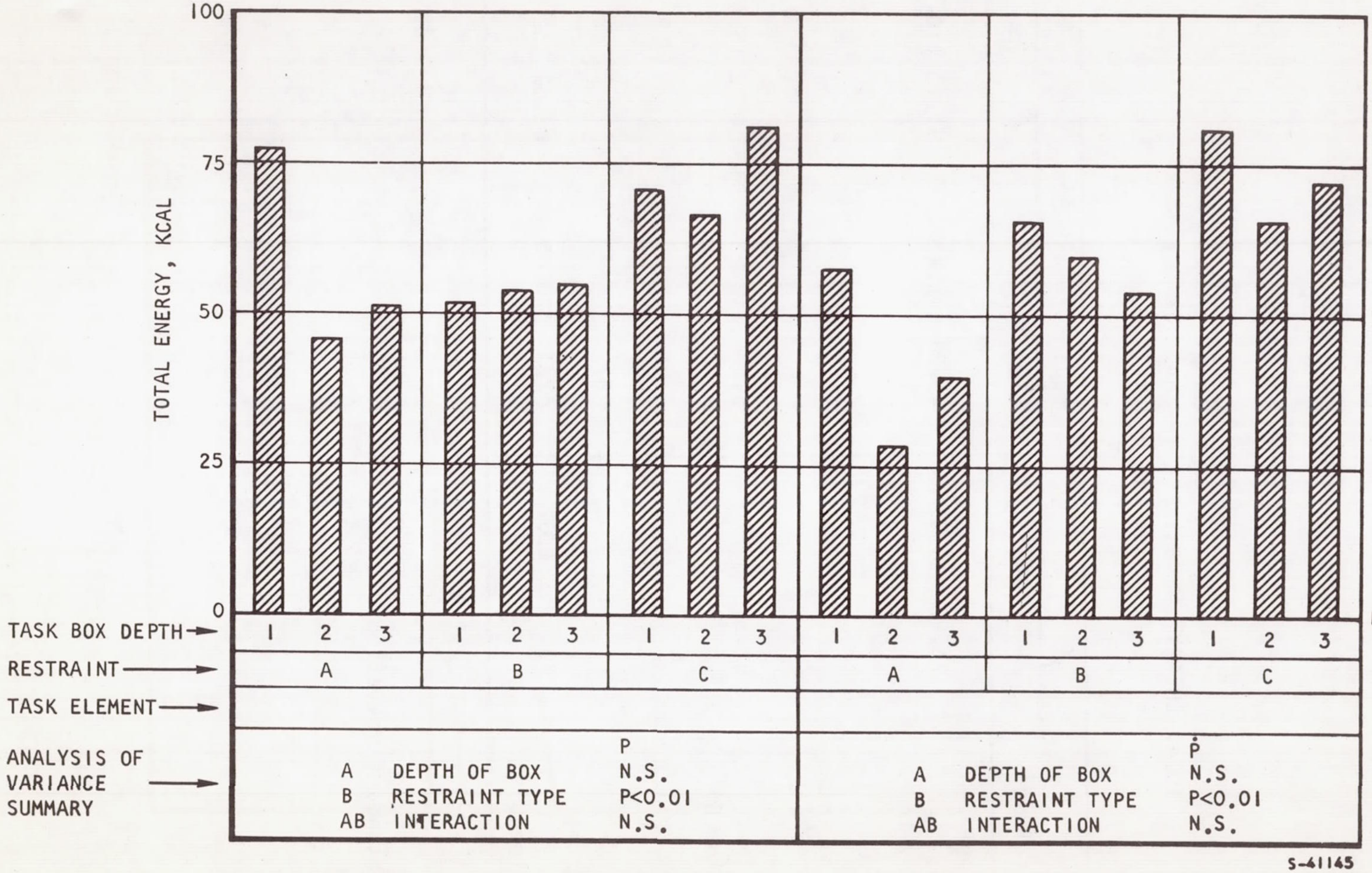


Figure 4-119. Total Energy for the Maintenance Task for the Six Subjects

TABLE 4-6

TOTAL ENERGY IN KCal FOR THE MAINTENANCE TASK
FOR THE SIX SUBJECTS

Restraint Types	Depth of Task Box		
	Flush	6 in.	9 in.
Gemini Foot and Straps (A)	76.95 ±14.39	45.78 ±14.43	51.13 ±10.21
Gemini Foot and Safety Line(B)	51.67 ±6.71	54.04 ±12.22	54.82 ±5.47
Cage and Safety Line(C)	70.19 ±14.07	67.39 ±20.65	82.68 ±32.84

Mean ±1 standard deviation

The depth positions of the task box did not differ significantly within any restraint system because the subjects left the dutch restraint systems to reach the deep tasks. If the subjects had been restricted in their mobility within these restraints, differences undoubtedly would have been noted.

Table 4-7 presents the resting data for the six subjects for each test mode; in addition, the average energy costs above resting for each mode are given. These averaged values were determined by dividing the total energy for the task shown in Table 4-6 by the total time of work for each subject. The sum of the resting values and the average values above rest shown in this table provides an index of the average metabolic rates during the work task. The summation shows that, on the average, the subjects paced their work efforts and maintained a light-moderate to moderate work level over the entire task.

Heart rates during rest and while performing the maintenance tasks are presented in Table 4-8. A cursory look at the rates noted for resting shows at least four instances where some anxiety existed. The other resting data are typical of individuals standing at 1 g. However, no statistical differences existed between any resting values over all the modes. The working heart rates are generally lower than expected for the metabolic rates measured. Working mode heart rates were not significantly different.

Expired ventilatory volumes are shown in Table 4-9. Resting ventilatory values are in the range expected with several of the values in the upper limits of the normal range indicating a trend forward to the hyperventilation of anxiety. These slightly increased volumes correspond to the slightly increased resting heart rates noted above. Ventilatory volumes were not significantly different for any test mode during work. However, the higher mean ventilatory rates measured during tests with the cage restraint system correspond to the higher metabolic rates noted above for this system.

Reactive Loads Analysis

The loads induced by the subject and reacted by the restraint devices were evaluated; they indicate that the restraint attachment to the primary structure must be designed to withstand the maximum possible load that has to be reacted from an astronaut performing specific tasks.

The maximum loads measured were obtained for a short duration of time. These are impulsive loads, and the duration of application from start-to-peak-to-zero is approximately 0.1 to 0.3 of a second. Sustained loads are very small and insignificant in the design of a restraint system. The sustained loads occur when the subject braces himself within the restraint system to maintain a particular position while working. The longest sustained load was approximately 55 sec (Test No. 418) and was apparently due to a position desired for accomplishing tasks 1 and 2 which required very little force. The value of this sustained force was 20 to 27 lb during the period of time.

TABLE 4-7

AVERAGE ENERGY COST IN KCal/Min FOR THE MAINTENANCE TASK FOR THE SIX SUBJECTS

Restraint Type		Depth of Task Box		
		Flush	6 in.	9 in.
Gemini Foot and Straps	Rest	0.80 ±0.09	1.68 ±0.69	1.22 ±0.16
	Work	3.34 ±0.55	2.19 ±0.62	2.60 ±0.48
Gemini Foot and Safety Line	Rest	1.07 ±0.37	1.12 ±0.19	1.18 ±0.30
	Work	3.62 ±0.87	3.40 ±0.89	3.18 ±0.23
Cage and Safety Line	Rest	1.03 ±0.20	1.01 ±0.14	1.52 ±0.80
	Work	4.24 ±1.15	3.66 ±1.39	3.90 ±1.56

Mean ±1 standard deviation

TABLE 4-8

HEART RATES (BEATS/MIN) FOR
PERFORMING THE MAINTENANCE TASKS

Restraint Types		Depth of Task Box		
		Flush	6 in.	9 in.
Gemini Foot and Straps	Rest	70 ±17.1	73.8 ±22.2	94 ±6
	Work	103.3 ±11.5	106 ±11.1	121 ±5
Gemini Foot and Safety Line	Rest	83.2 ±12.6	91 ±15.6	94.4 ±18.2
	Work	114 ±14.5	116 ±17.3	119.2 ±19.0
Cage and Safety Line	Rest	74.7 ±7.0	75.2 ±11.9	77 ±19.2
	Work	111.3 ±7.5	107.5 ±12.8	113.4 ±17.6

TABLE 4-9

EXPIRED VENTILATION (LITERS/MIN BTPS)
WHILE PERFORMING THE MAINTENANCE TASKS

Restraint Types		Depth of Task Box		
		Flush	6 in.	9 in.
Gemini Foot and Straps	Rest	8.42 ±1.74	10.08 ±0.73	10.3 ±0.47
	Work	26.83 ±2.91	23.16 ±3.93	25 ±5.09
Gemini Foot and Safety Line	Rest	10.83 ±2.91	11.16 ±1.57	11.2 ±1.72
	Work	28.66 ±3.64	30.16 ±3.13	29.8 ±1.94
Cage and Safety Line	Rest	8.83 ±1.86	9.33 ±0.94	11.4 ±4.63
	Work	32 ±3.36	30.33 ±3.64	32.2 ±5.74

The restraint load cells registered loads imparted to the structure from the start of the test throughout the test. Restraint loads are generally insignificant for tasks 1, 2, 3, 4, 7, and 8 in which the subject obtained tools and did light work when compared with the other tasks which required larger forces to perform the work. Generally the largest loads were induced into the structure during tasks 10 and 11 when torquing the bolts to maximum. The next largest loads were induced during tasks 5 and 6 when pushing and pulling the lever. The loads induced during task 9, turning the hand wheel, were only about 30 percent of the maximum task loads observed. The restraint loads on the pull-push tasks (5 and 6) show that the subject usually uses additional support on the pull portion of the task and little additional support for the push portion.

The pull-push lever was also used as an additional restraint (hand-hold) shown by the fact that at the end of a push the subject used the lever as a hand hold to stop his body movement away from the work place. A good example of this was shown during Test 221 (foot restraint and single strap). The load cell trace is shown in Figure 4-120 which is a trace of task 6; the events with pertinent information are noted as 1, 2, 3, and 4 corresponding to push, push, pull, pull, respectively. The push loads imparted by the subject were considerably less than the pull loads, and the reaction loads were significantly greater for the push loads indicating that a convenient additional hand hold was not available or not used in the push portion of this task. Events 3 and 4 also show that there was a reversal of reactions after the action which indicates that the subject held onto the lever and helped stop his body inertial forces.

The apparent criteria for rating a restraint are the ease of positioning and the work for the task to be accomplished. The rigid leg restraint provided neither of these advantages as shown by the continuous change of loads, duration of the task, and the apparent failure to accomplish the tasks. The tasks with the foot and two-strap restraint were very similar to the foot restraint with a single strap. However, in several of the two-strap restraint configurations, the load data show considerable activity on the strap restraints. Usually one strap is used throughout the test; test 115 exemplifies the extensive use of the straps. This test took longer than the average to accomplish. Initial adjustments were made during the first tasks so that the straps did not hinder the subject's work and at the end, the straps were again used when grossly different positions were required to do the work. These factors indicate that two straps are not as good as one in combination with the foot restraint. Several times during the tests, there is no evidence of a load being applied through the foot restraint. The only account for this is that the subject removed his feet entirely from the restraint and found other methods to restrain himself, which again illustrates that other methods than the restraints provided were used for holding his position.

The mean values of the moments induced on the spacecraft mockup are listed in Table 4-10. The bending moments in the vertical plane (M_V), the lateral plane (M_l), the torsional moment (T) at the point of attachment of the restraint system to the spacecraft are tabulated in this table. The values shown for

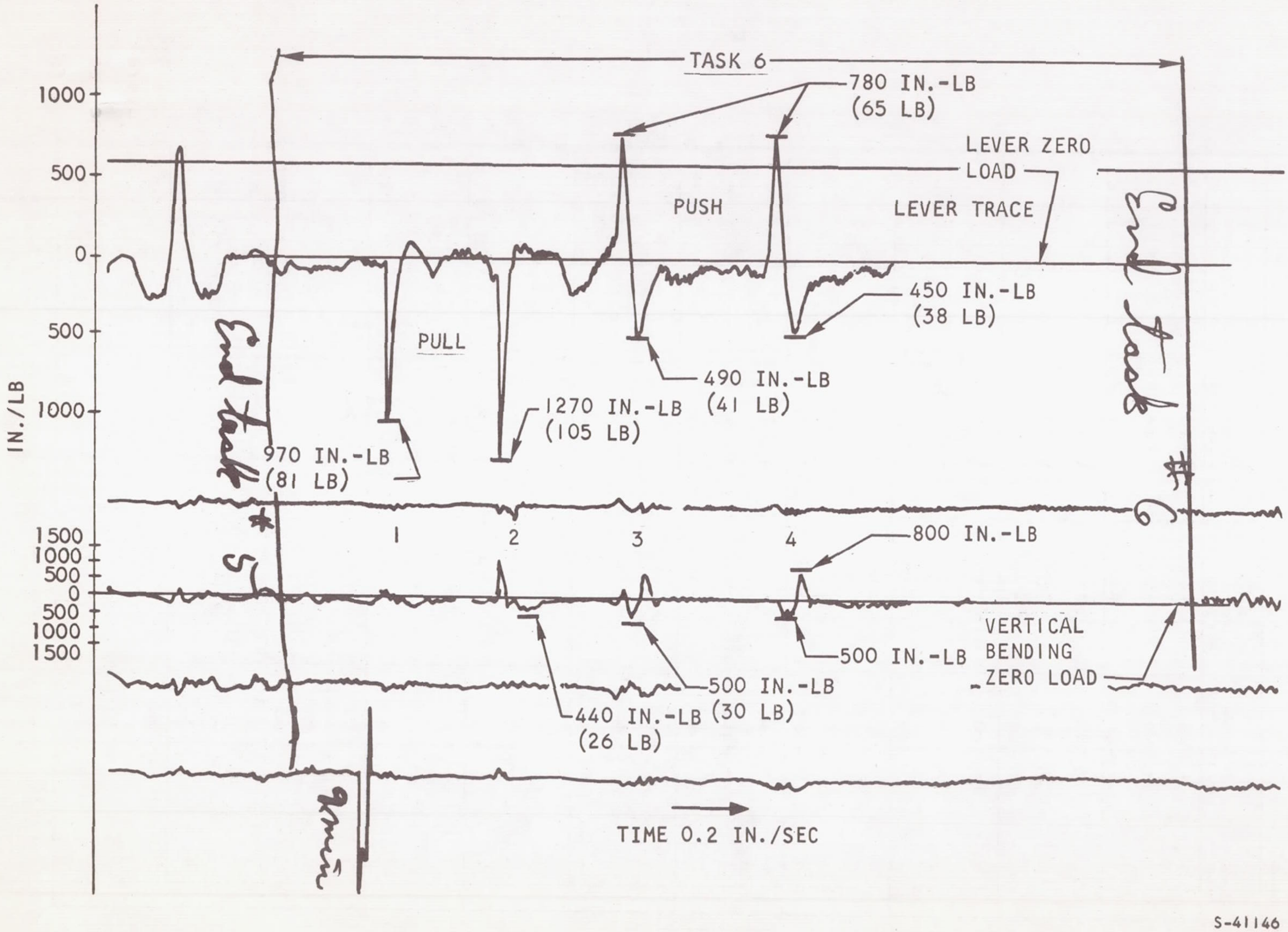


Figure 4-120. Load Cell Traces

TABLE 4-10

MEAN VALUES OF MOMENTS
INDUCED IN THE SPACECRAFT AT RESTRAINT ATTACH POINT

Column	1	2	3	Corresponding Task Loads	
Task Number	Gemini Strap and Foot, in-lb	Gemini Foot and Safety Line in-lb	Cage and Safety Line in-lb	Column	In.-lb
1	M_v = 650	M_v = 400	M_v = 200		
	M_l = 500	M_l = 200	M_l = 100		
	T = 460	T = 400	T = 150		
2	M_v = 400	M_v = 400	M_v = 200		
	M_l = 200	M_l = 200	M_l = 200		
	T = 400	T = 200	T = 150		
3	M_v = 440	M_v = 460	M_v = 200		
	M_l = 200	M_l = 200	M_l = 200		
	T = 400	F = 460	T = 250		
4	M_v = 400	M_v = 300	M_v = 150		
	M_l = 250	M_l = 100	M_l = 250		
	T = 300	T = 300	T = 200		
5	M_v = 1540	M_v = 1100	M_v = 880	1	900
	M_l = 1420	M_l = 960	M_l = 580	2	950
	T = 460	T = 460	T = 400	3	1080
6	M_v = 1500	M_v = 1320	M_v = 880	1	976
	M_l = 950	M_l = 760	M_l = 700	2	900
	T = 1150	T = 500	T = 200	3	1000
7	M_v = 400	M_v = 400	M_v = 400		
	M_l = 150	M_l = 200	M_l = 200		
	T = 200	T = 300	T = 100		
8	M_v = 200	M_v = 300	M_v = 150		
	M_l = 200	M_l = 200	M_l = 100		
	T = 200	T = 350	T = 200		
9	M_v = 220	M_v = 400.	M_v = 650	1	350
	M_l = 950	M_l = 900	M_l = 600	2	800
	T = 460	T = 460	T = 440	3	750
10	M_v = 700	M_v = 700	M_v = 450	1	66
	M_l = 950	M_l = 780	M_l = 1000	2	98
	T = 700	T = 400	T = 950	3	70
11	M_v = 900	M_v = 1350	M_v = 960	1	42
	M_l = 500	M_l = 200	M_l = 440	2	47
	T = 1060	T = 860	T = 1380	3	60

tasks 5, 6, 9, 10, and 11 are the mean values of the maximum loads induced for the specific high work element within these tasks.

The loads in Table 4-10 illustrate that, during the light work tasks, the Gemini foot and two-strap restraint differ little from the Gemini foot restraint with a single strap. The cage restraint loads during these tasks show substantially lower loads, which indicates that the subjects imparted lower loads to the spacecraft while performing the light work tasks than the other two restraints. During the push-pull tasks (5 and 6), the load measured in the lever was higher while using the cage restraint than the other restraints, and the loads induced in the structure were lower, indicating that the subject could work more efficiently using the cage. This is also true for the torsion lever task (9). The best summary of the loads is obtained by combining the vertical and lateral bending loads into one vector as in the following example:

$$\overline{M} = \sqrt{M_v^2 + M_l^2}$$

For task 10, foot restraint and single strap:

$$\overline{M} = \sqrt{\overline{700}^2 + \overline{780}^2} = 1050 \text{ } \overline{\text{in}}.\text{-lb}$$

For task 10, cage restraint:

$$\overline{M} = \sqrt{\overline{450}^2 + \overline{1000}^2} = 1100 \text{ } \overline{\text{in}}.\text{-lb}$$

For task 11, foot restraint and single strap:

$$\overline{M} = \sqrt{\overline{1350}^2 + \overline{200}^2} = 1365 \text{ in.-lb}$$

For task 11, cage restraint:

$$\overline{M} = \sqrt{\overline{960}^2 + \overline{440}^2} = 1050 \text{ in.-lb}$$

The ratio of work load to loads induced to the structure for the various tasks is the best indicator of the adequacy of the restraint system. This ratio is defined as follows:

$$R = \frac{\text{task load}}{\text{reacted load}}$$

and

$$R_{pp} = \frac{\text{push-pull load (in-lb)}}{\overline{M} \text{ (in.-lb)}}$$

$$R_T = \frac{\text{torsion lever load (in.-lb)}}{\overline{M}}$$

$$R_{BT} = \frac{\text{bolt torque load (in.-lb)}}{\overline{M}}$$

where $\overline{M}$ is the vector sum of the moments in the vertical and lateral planes.

This ratio for tasks 5, 6, 9, 10, and 11 is given in Table 4-11 which shows the cage as the generally most efficient restraint system.

TABLE 4-11

TASK RATIOS FOR RESTRAINT SYSTEMS

Task and Ratio	Restraint		
	Foot and Two Straps	Foot and One Strap	Cage
5 R_{PP}	0.43	0.65	1.02
6 R_{PP}	0.55	0.592	0.89
9 R_T	0.36	0.81	0.85
10 R_{BT}	0.67	1.12	0.76
11 R_{BT}	0.49	0.42	0.68

General Observations

Gemini 12 foot and two waist-strap restraints.--No new outstanding beneficial results were observed for the double strap/dutch shoe restraint combination. The major advantage of the strap restraints is the freedom of movement they provide for the subject's upper body. The subjects varied greatly in their ability to use the strap restraints to advantage. This is largely attributed to the subject's willingness to move the restraints to different connecting points as well as the necessity to lengthen and shorten them as the positioning and stability of the task required. It is essential for the subject's stability to load the strap restraints by exerting upward or backward pressure by the legs. To ensure this condition, the strap restraints must be constantly manipulated by lengthening and shortening them. Subjects generally started the task sequences with good stable position but as the test progressed, they failed at some point to make adjustments in the strap restraints and consequently lost contact with the dutch shoes. The subject then either floated free or fell to one side. At such times, productive task time was lost as the subject struggled to regain the original position with both feet firmly placed in the dutch shoes.

Many tasks were successfully performed with both feet firmly set within the dutch shoes and with the appropriate tension on the strap restraints. These cases, without exception, were tasks well forward in the work/reach area, i.e., when the task box was flush with the front edge of the access opening, and were especially true for tasks that required small forces. The setting and breaking of the eight bolts on the front of the task box were another matter. Seldom was a subject able to perform this task without coming partially or completely out of the dutch shoes (see Figures 4-121 to 4-122). If possible, the subject kept the toes of his feet in the front area of the Gemini shoes with his heels rising up to 4 in. above the heel (floor) of the Gemini shoe. In this position, when large muscular force was required, the subject had to gain positional stability by holding onto the structure or task box with his free hand. Unless the subject was willing to obtain a torso position so that his two arms could fully oppose one another, his force application was less than maximum. The correct procedure was demonstrated and practiced by each subject, but in general it was performed only by those subjects who had background experience in the use of tools.

When the subjects worked on tasks in the front area on the box, the restraint system was functional and stable. However, as the tasks extended away from the subject toward the back edge of the task box or into its interior, the foot restraints had to be at least partially abandoned to reach the work (see Figure 4-123). At such times, innovations for the restraints were made by the subjects to provide the capability to perform the work. In the two conditions where the task box was positioned 6 and 9 in. from the front edge of the mockup the subject often secured his position to the work by placing his head into the access opening and then pressing the back of the head and neck against the top edge of the access opening (see Figures 4-124 and 4-125). By maintaining an upward pressure with his free hand, the subject could secure some stability of position. The position was adequate for small wrenching tasks and manipulation of tools as long as no great muscular force was required. If the task box had been located in an open area, the subjects could not have obtained this position and probably would not have been able to perform all the tasks unless he could have remained at least partially in the foot restraints.

Had the mechanical capability been provided to elevate and lower the dutch shoe level to an appropriate height for each task of the sequence, the subject could have utilized the restraint system functionally throughout a greater portion of the test.

Many hours of work performed in underwater neutral-buoyancy tests confirm the effectiveness of restraining the lower portions of the body during task performance. Furthermore, this requirement appears to be essential when considerable strength application is required. Since mobility is also necessary, it must be concluded that the foot restraining mechanism, dutch shoes or otherwise, must be mechanically capable of moving with the subject to his various positions required to perform the task.

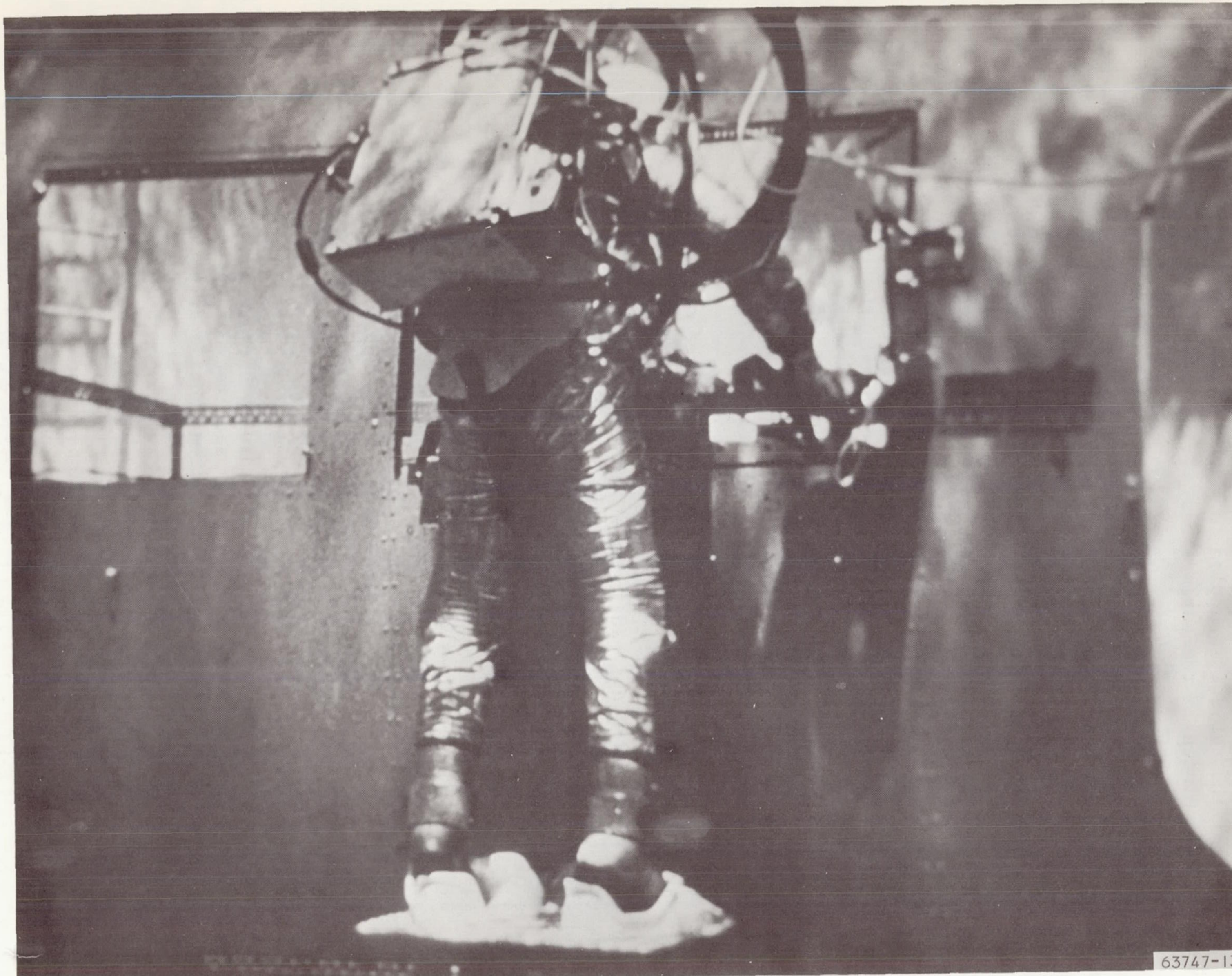


Figure 4-121. Subject Rising Out of Foot Restraints to Enable Him to Reach the Rear of Task Box

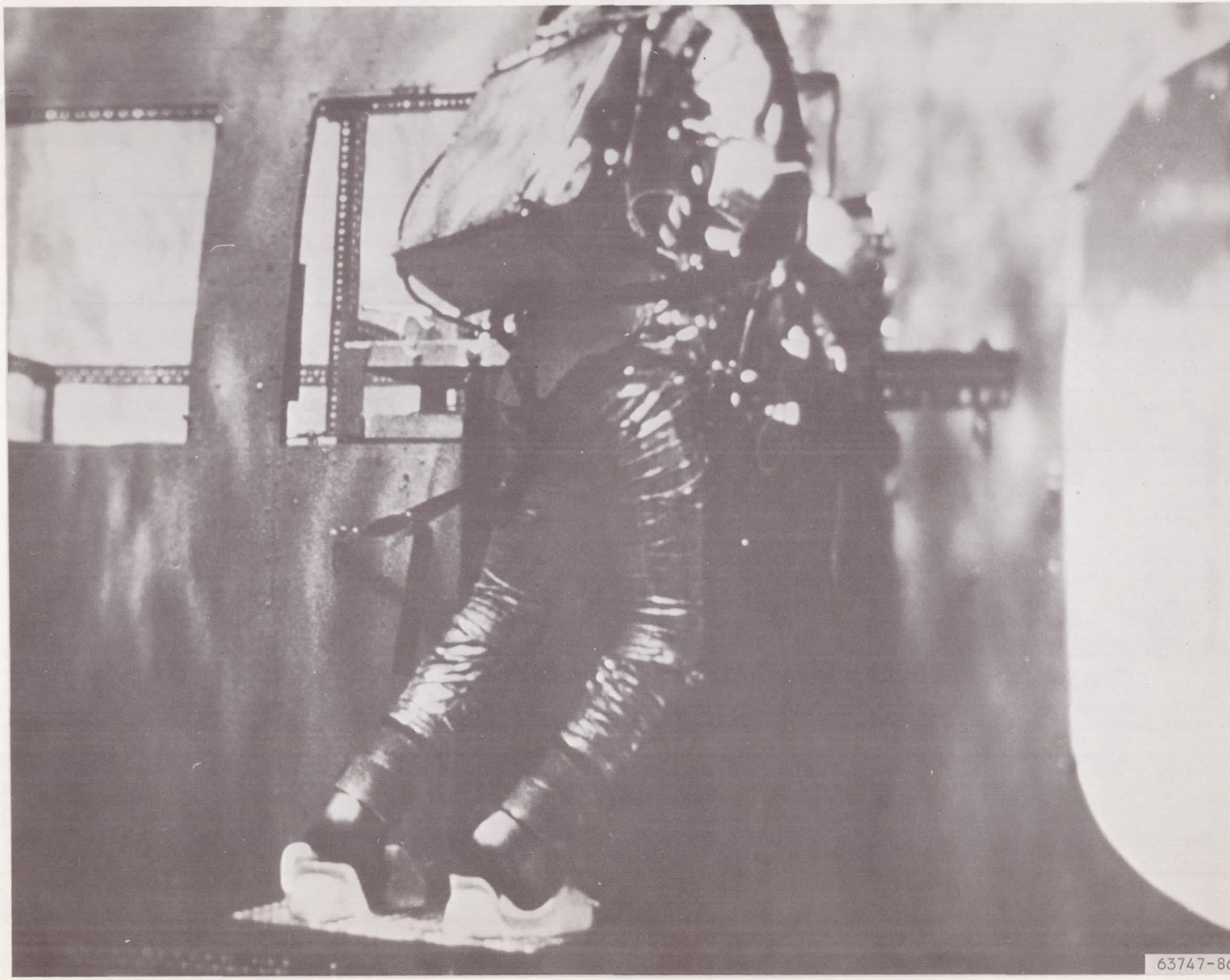


Figure 4-122. Subject Turning to Left to Reach Tool Kit

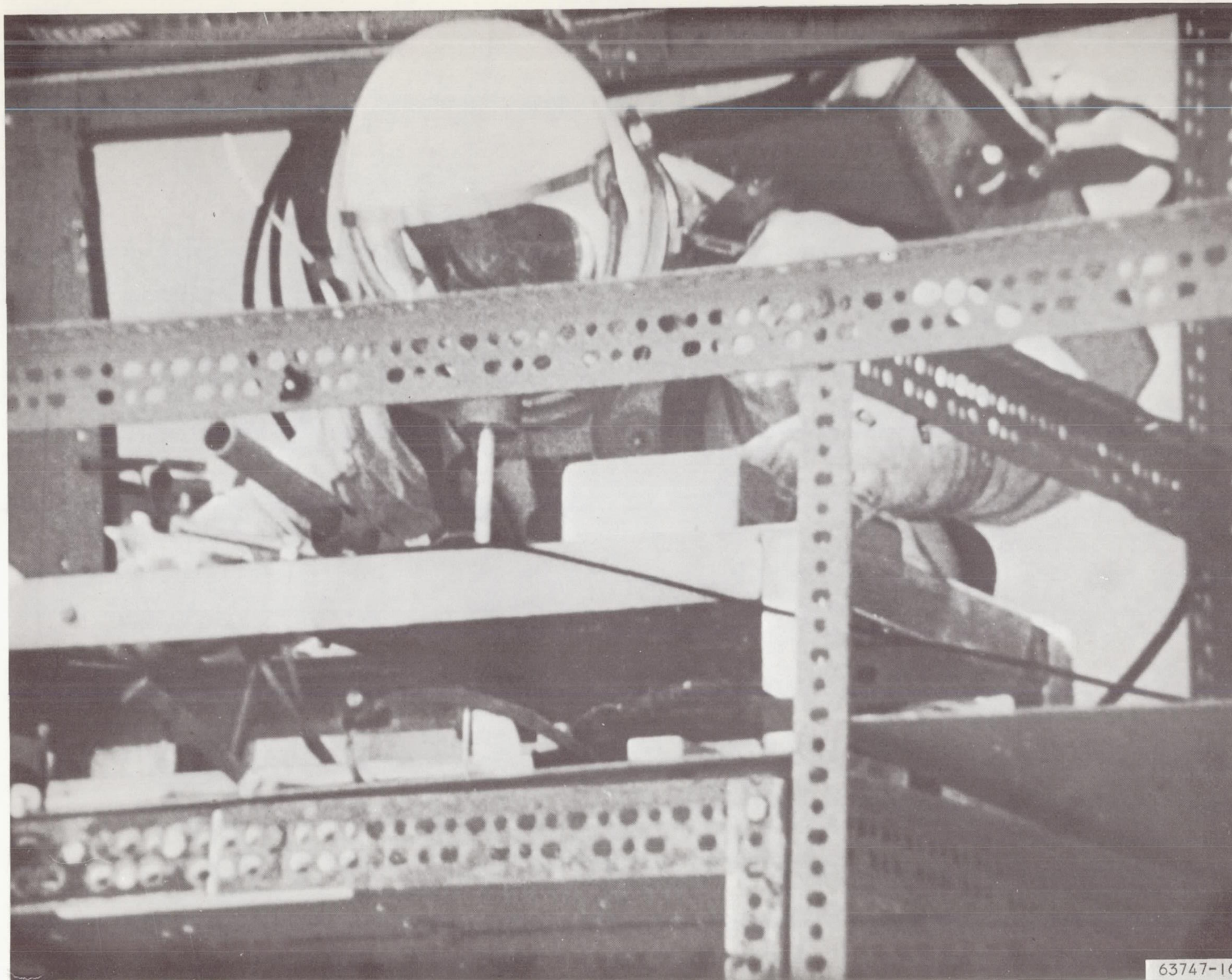


Figure 4-123. Subject's Position to Work on Rear of Task Box While in Foot Restraints. **Back of Helmet** is Pushing Against Top Edge of Access Opening.

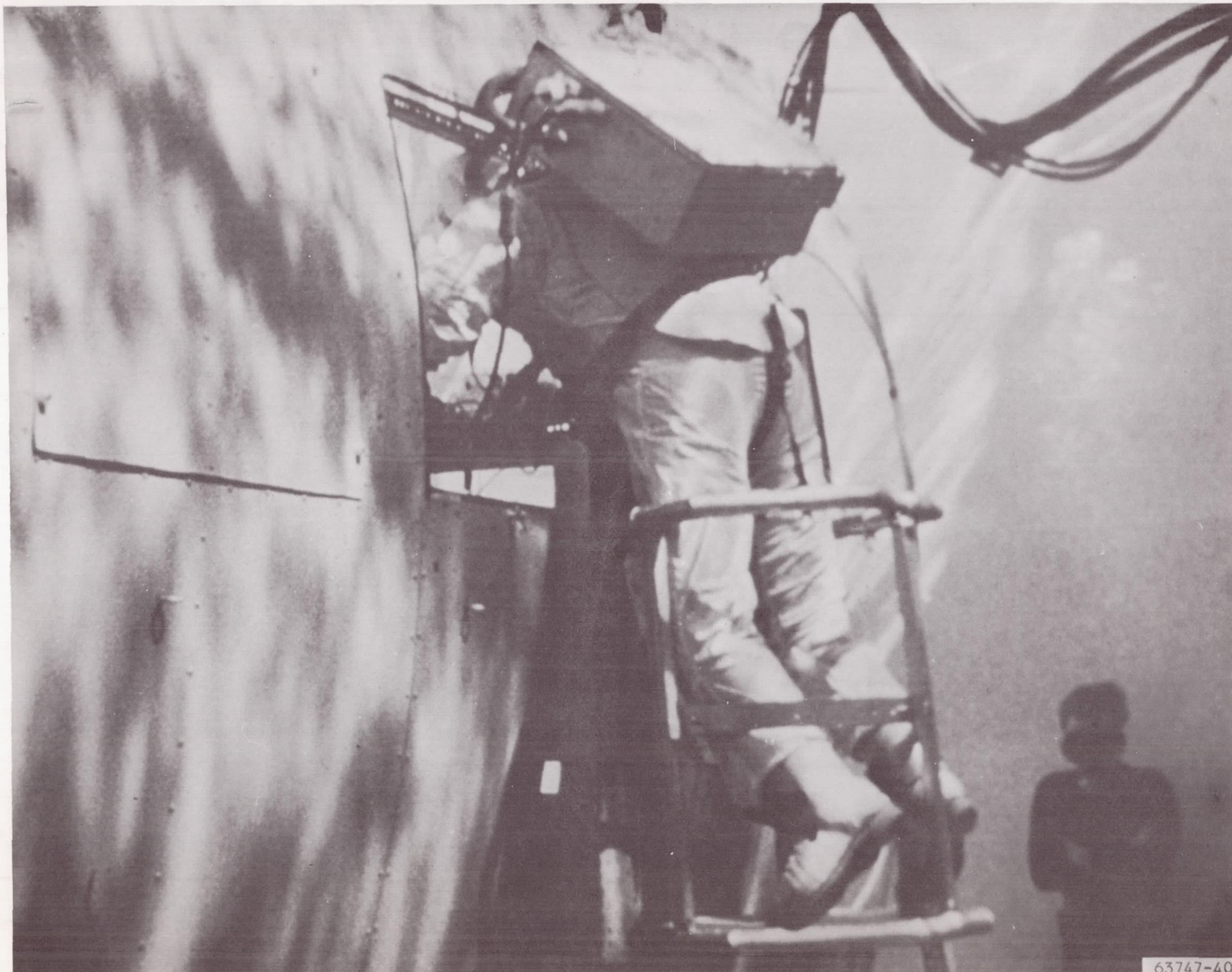


Figure 4-124. Subject Pushing on the Side of the Cage With His Knees to Maintain Positional Control of the Legs and Torso While Working on the Task Box

Figure 4-125. Subject Working Inside the Task Box, Maintaining Position by Sticking Legs Through the Side of the Cage

Gemini 12 foot and single-strap restraints.--This restraint condition was selected to evaluate the effectiveness of the Gemini 12 dutch shoes when they were not used in combination with the waist straps. These conditions were arrived at prior to receipt of the GFE dutch shoe restraints. The hypothesis was that the Gemini 12 dutch shoe could function as a restraint with no additional hardware assistance. During the training phase of the program, it was found that the subjects could not stay in the dutch shoes without some type of waist tethering. The decision was made to use a single adjustable strap extending from the front shell to the mockup, the strap was attached adjacent to the subject's sternum. Thus, the restraint difference was not as clearly separated as originally anticipated. In the restraint condition with the waist straps, the subject was encouraged to keep them properly adjusted so that he could maintain positioning and stability in the dutch shoes. With the single strap, centrally located to the subject's torso in condition, no instructions were given to the subject regarding his use of the strap tether. It was anticipated that the subject would neglect the use of the strap tether except when it was essential to use it to keep him from losing contact with the foot restraints.

Actually, the reverse of the above took place. The subject was inclined to use the single strap more perhaps because it did not consume as much time as two straps. Or possibly the use of a single strap located centrally to the subject's torso provided certain unknown and unobservable advantages over the two-waist-strap configuration. Possibly, the two-strap system provides some stabilizing advantage, although the single-strap system is faster.

The dutch shoes with the single-strap tether provide the subjects with a greater amount of torso flexibility than with the two-strap restraint system. His visual and positioning capability also increases without intertask restraint changes.

The straps (double strap or single tether) used with the dutch shoes were relied on more than the single strap in the cage restraint. It is believed that this results from the ability of the subject to move up within the cage restraint to utilize the rungs and vertical bars to alter his position and then lock it, thus enabling him to operate with a longer strap tether and still to maintain positioning control within the restraint.

Squatting is one position available in the dutch shoes not possible in the other restraint conditions. Although only one subject took advantage of this flexibility, the position was very effective for breaking and setting the torques on the front mounted bolts of the task box. Squatting improved the subject's view of the work and allowed him to more fully utilize the strength of his legs in the wrenching task.

Cage restraint.--Use of the cage restraint during testing under NASA Contract NAS 1-5875 demonstrated the need to adjust the cage to conform to the size of the subject and the task at hand. The cage restraint design is to confine the subject but at the same time provide the mobility to translate to left and right and to move up and down which is not available with other restraint devices. The cage built for this study was designed to be adjustable in width and height. Pilot studies with the cage in several sizes did not show an appreciable performance difference. The subjects, however, preferred the smallest configuration, and this size was used for the restraint tests. However, post-test considerations of the results cast doubt on their judgment.

Task performance in the cage is similar in many respects to that experienced with the dutch shoe restraints. The cage generally allowed the subject to assume an appropriate position for his work, but this was offset by the reduced stability of the position (see Figure 4-126). It is difficult to lock the feet in the cage to the same degree possible in the dutch shoes. The cage allows the subject to move left and right, forward and backward with more freedom than in the dutch shoes (see Figures 4-127 and 4-128). In the deep position of the task box, the cage provided good support for the legs. The subjects quickly learned to put one leg over and one leg under the middle rung of the cage (see Figure 4-132). This position from the cage allowed the subject enough stability of position to perform all the top and internal tasks with two hands. The single exception was the large strength task that required repositioning to apply maximum force (see photographic sequence, Figures 4-129 through 4-136).

In most of the tasks performed, the subjects hooked their feet over and under the middle rung of the cage and exerted pressure to the side of the cage with both legs simultaneously (see Figures 4-125 through 4-126). However, the cage provided a climbing structure that the subjects occasionaly used in such positions as straddling the top rail, lying over the top of the cage in a prone position, standing on the middle rung with a taut strap tether, and standing outside the cage with one leg hooked under the top rung and over the middle rung (see Figure 4-137). Figure 4-138 shows the subject going to the tool kit from the cage restraint. The potential cage restraint could not be utilized fully with the task box mounted deep within the access opening due to the size of the backpack. The furthest entry the subject could make was to position where his backpack came in contact with the skin of the mockup above the access opening (see Figure 4-123).

The cage restraint provides a larger work/reach area than the other restraints as was demonstrated in the prior study. The advantage of the cage in this respect was demonstrated during the large rigid module erection (see photographic sequence Figures 4-23 through 4-33). Although no comparison could be made for that task between the Gemini dutch shoes and the cage in respect to the flexibility and total work area available to the subject, the cage restraint appears much superior. During the experiment on the task box, however, the cage was the only restraint tested from which the subjects could perform all tasks under all conditions.

Rigid leg restraint.--The rigid leg restraint proved to be so unsatisfactory that its use was discontinued during the tests. Three initial attempts were made to perform the first task mode, i.e., with the task box flush with the front edge of the mockup. In the first of these tests, the subject broke the restraint while pulling on the task box as he tried to get close enough

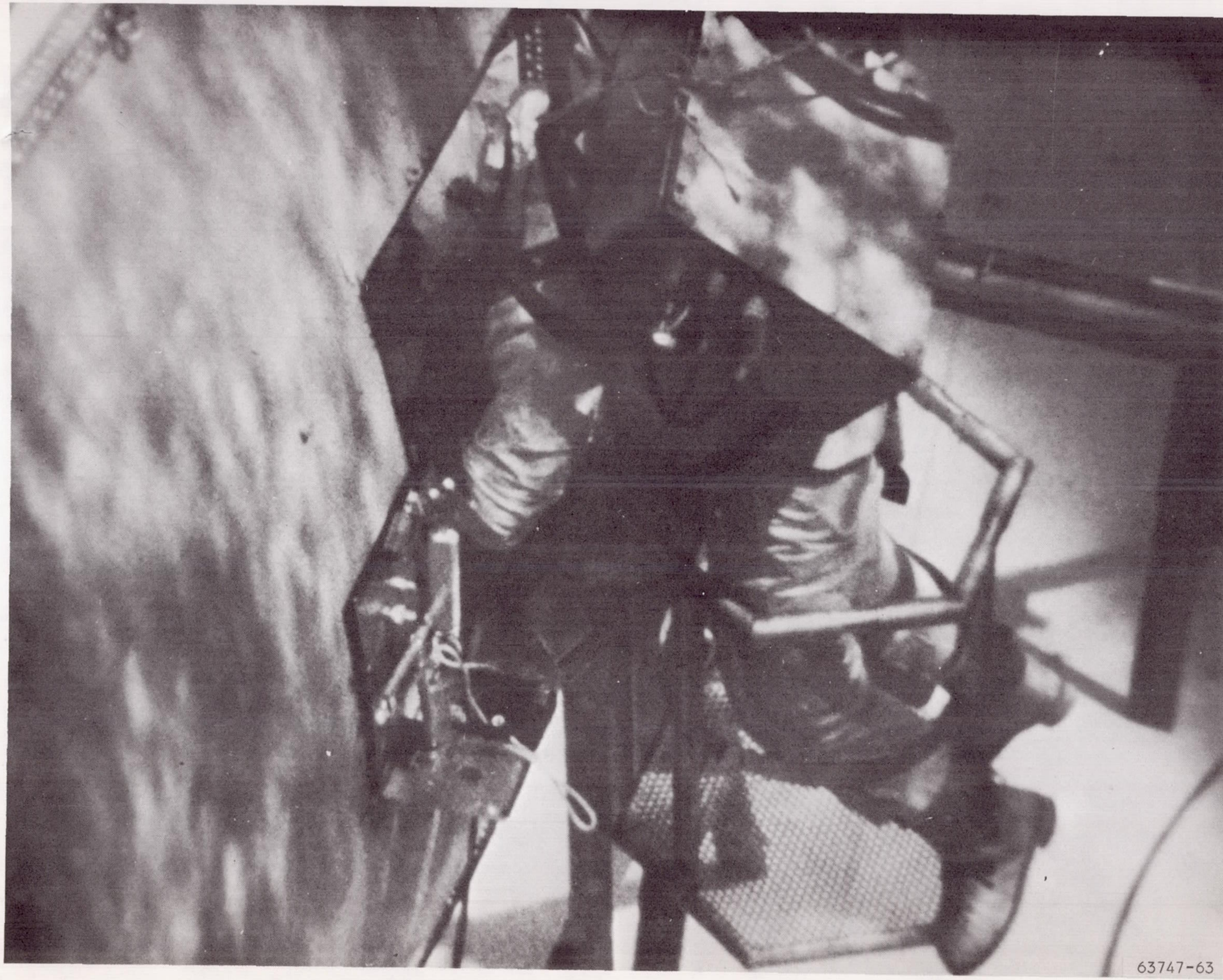


Figure 4-126. Subject Using Toes and Back of Legs to Hold Lower Torso Stable While Working on Task Box

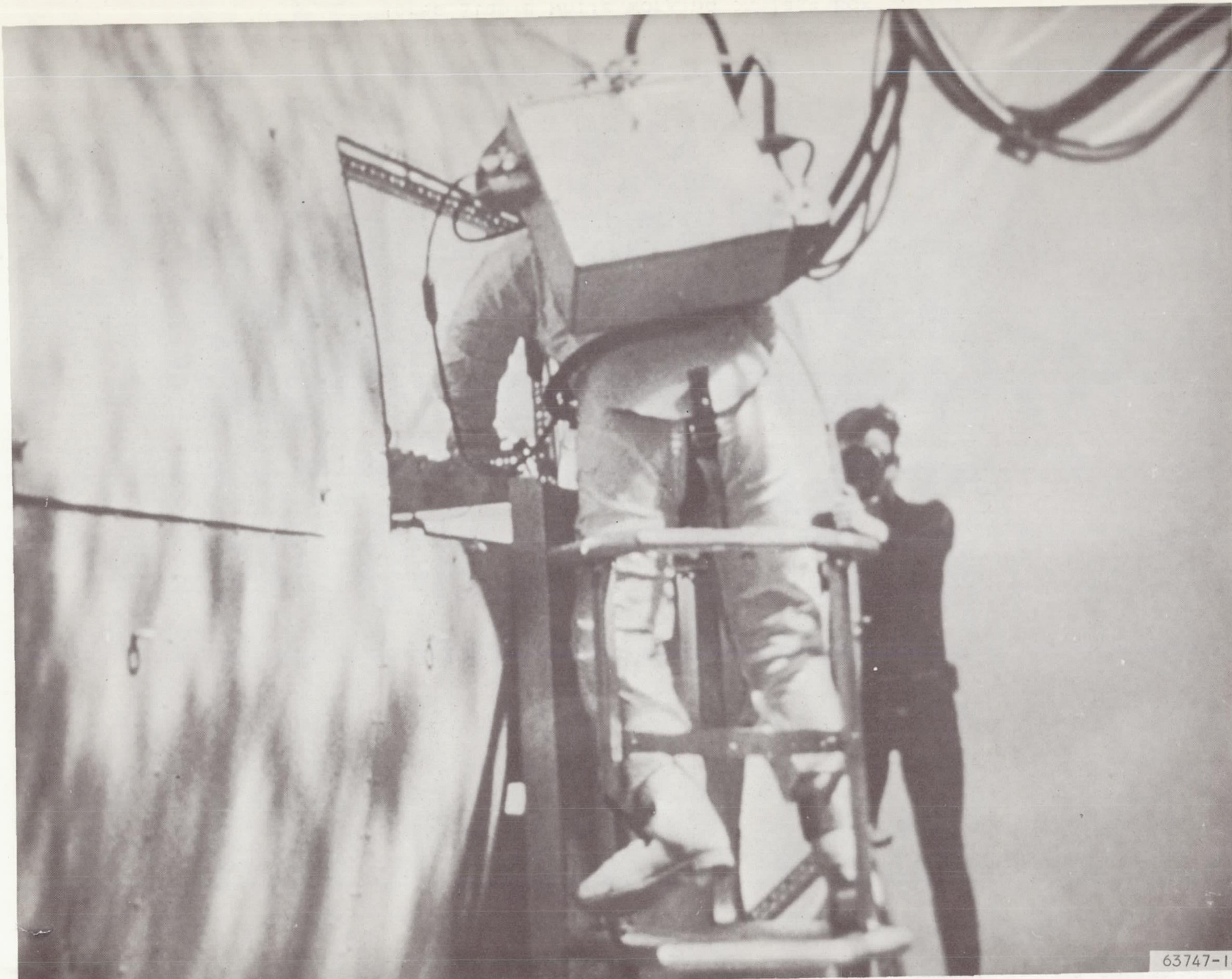


Figure 4-127. Subject Hooking Feet and Side of Legs Through Cage to Maintain a Work Position

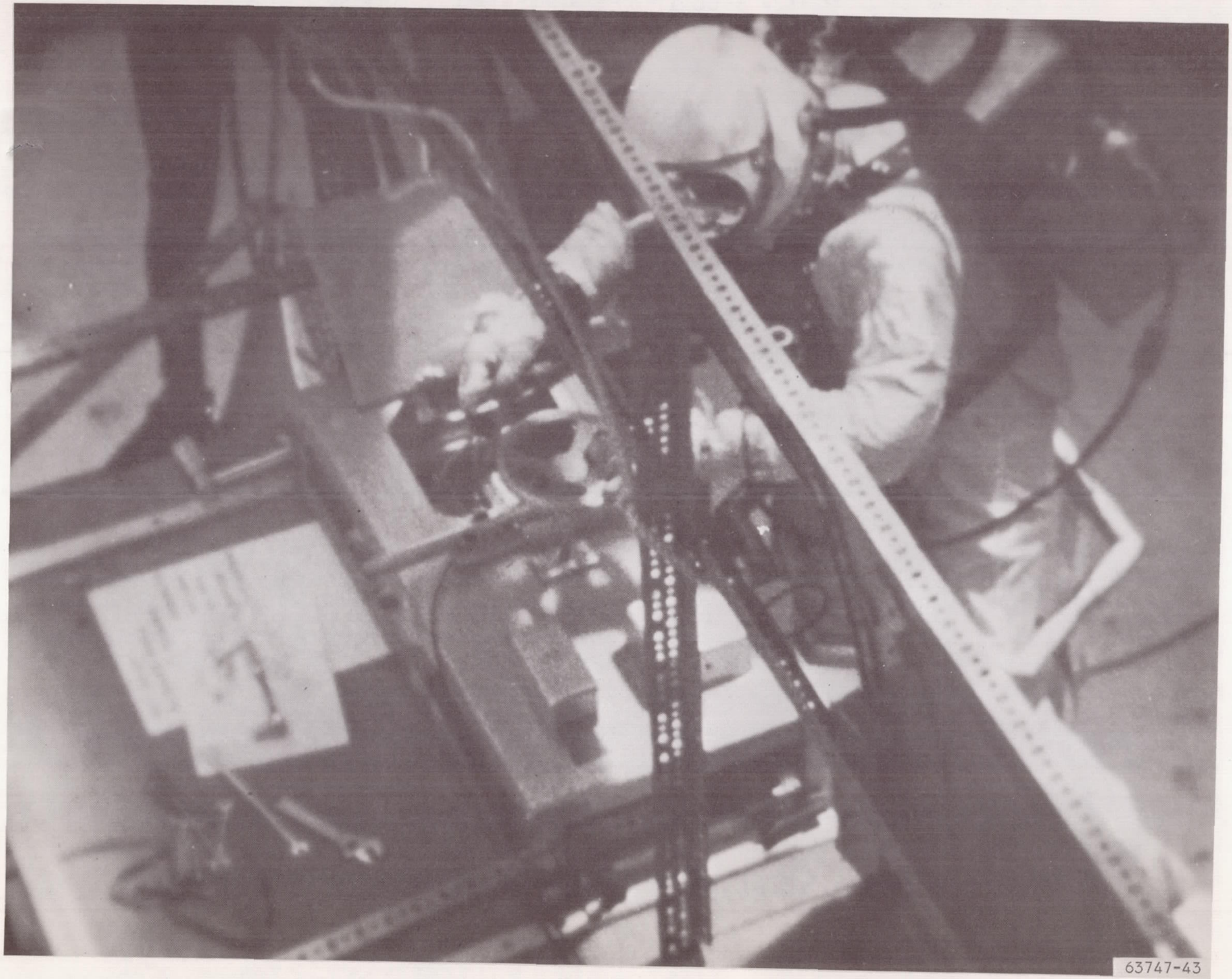


Figure 4-128. Subject Working Inside the Task Box with Legs Out Through Side of Cage and Maintaining Upper Torso Control by Holding on With His Left Hand

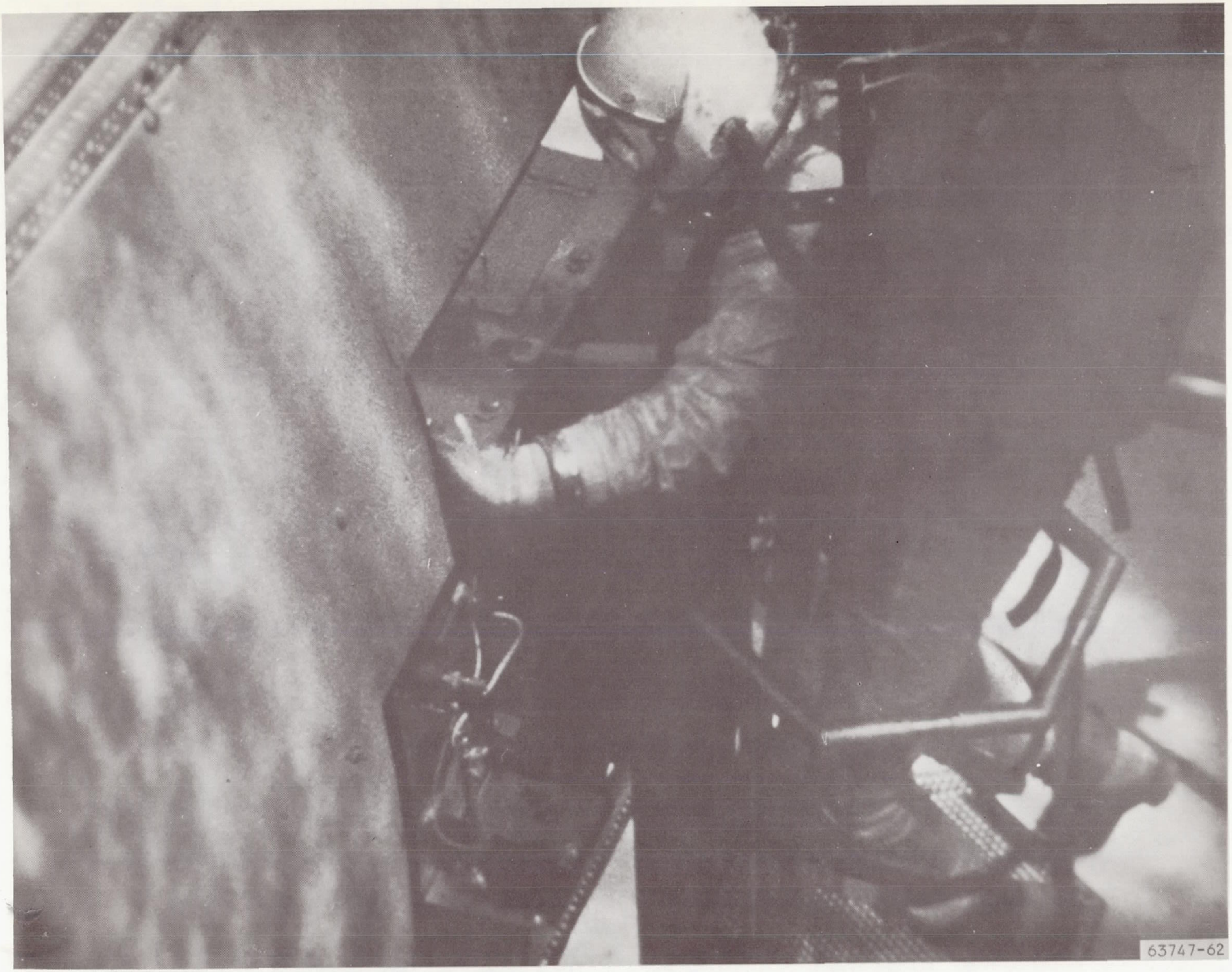


Figure 4-129. Subject Hooking Toe Under Floor of Platform and Stabilizing Position with Left Hand to Wrench Bolt on Task Box

Figure 4-130. Subject Falling Backwards From Wrench Slipping Off the Bolt Head; Cage Restraint Allows Quick Recovery

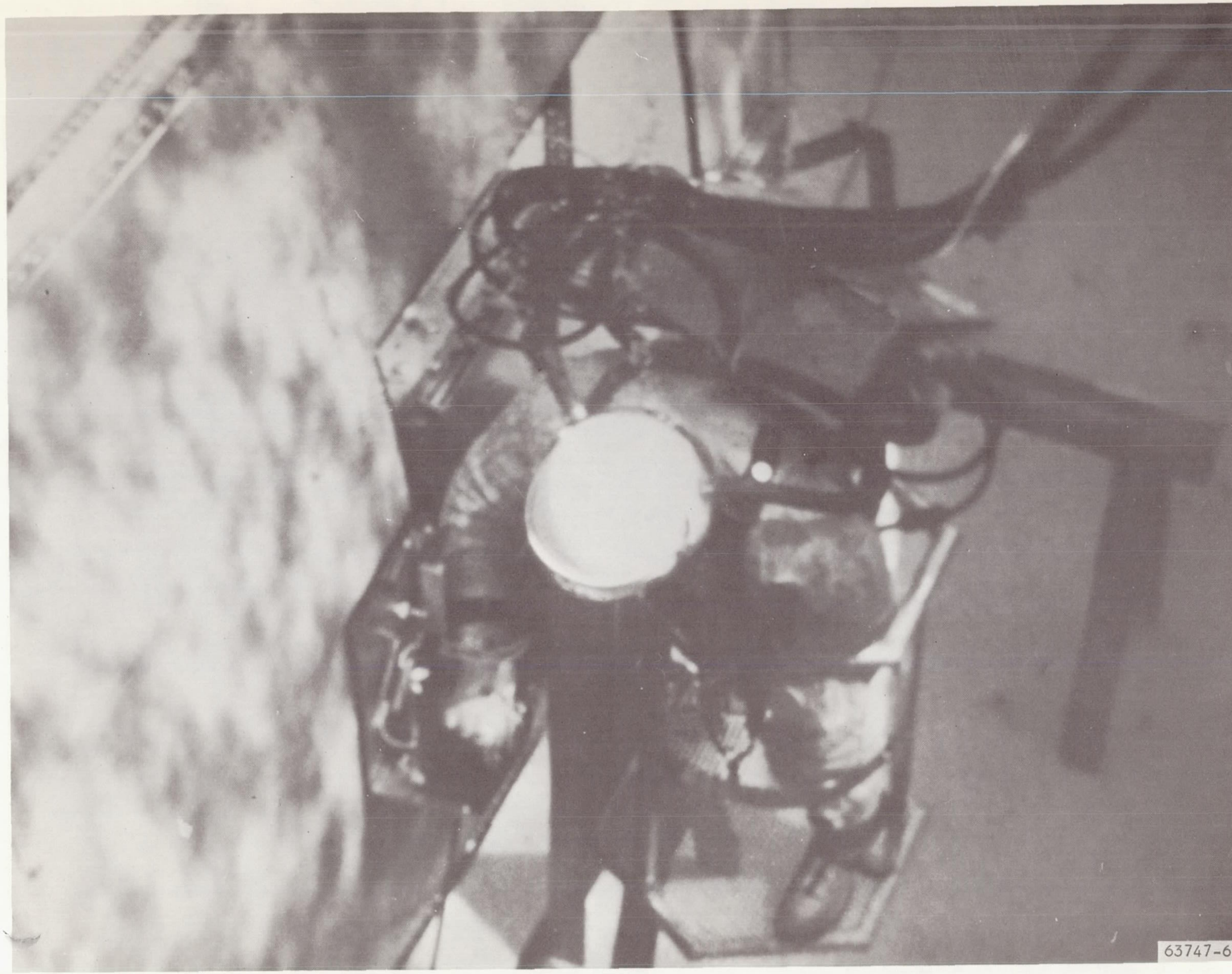


Figure 4-131. Subject Holding onto Top Rail of Cage During Wrenching of Bolt; Allows Subject to Use Mass of Upper Torso to Apply Greater Force

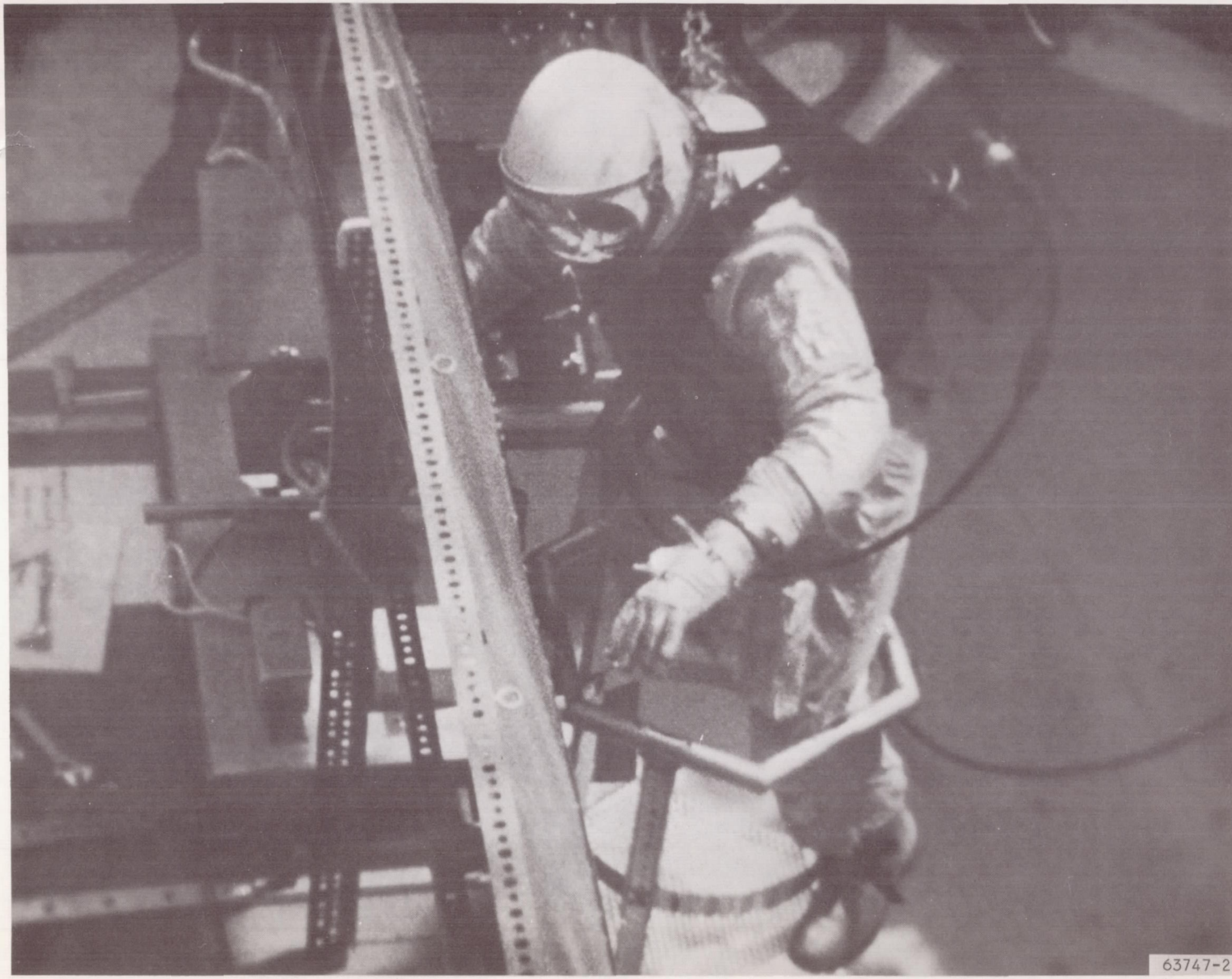


Figure 4-132. Subject Wedging Legs Between Upper and Middle Rail of Cage to Maintain Position When Pulling on Force Lever of Task Box

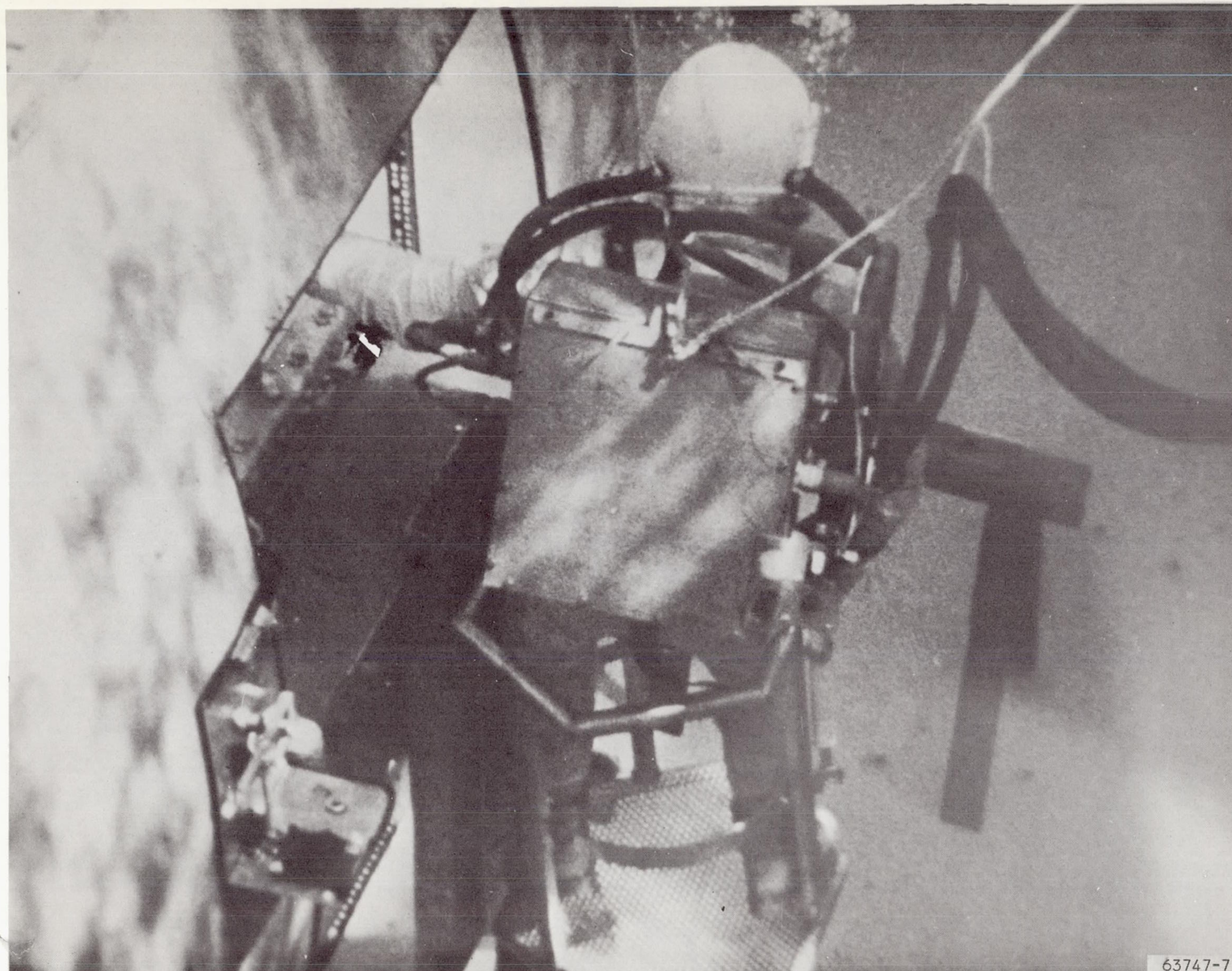


Figure 4-133. Subject Starting to Pull on Force Lever of Task Box. Subject's Knee Pressed Against Front of Cage and Right Hand Holding Onto Top Rail

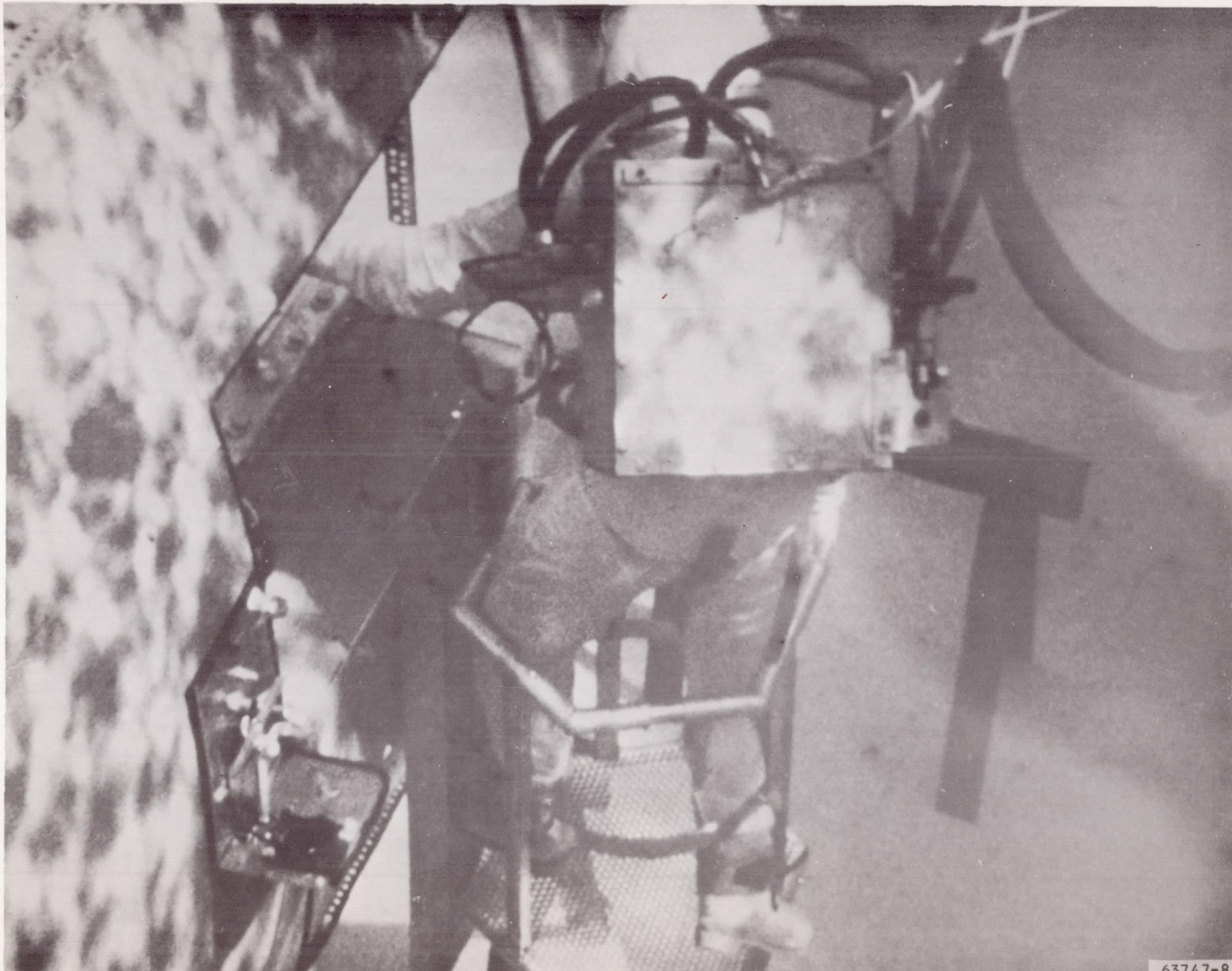


Figure 4-134. Subject Completing Pull on Force Lever of Task Box

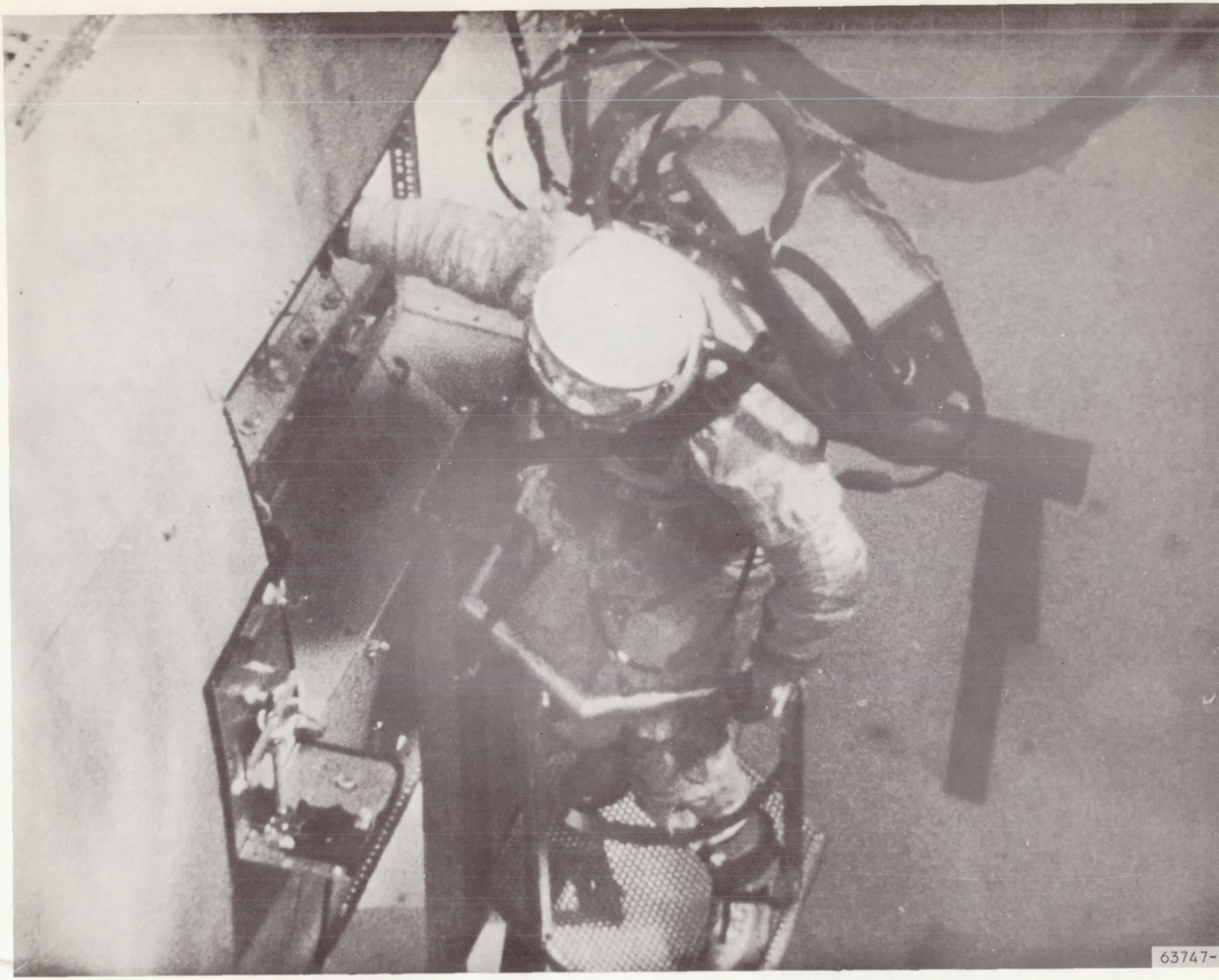


Figure 4-135. Subject Starting Right Hand Pull on Force Lever of Task Box

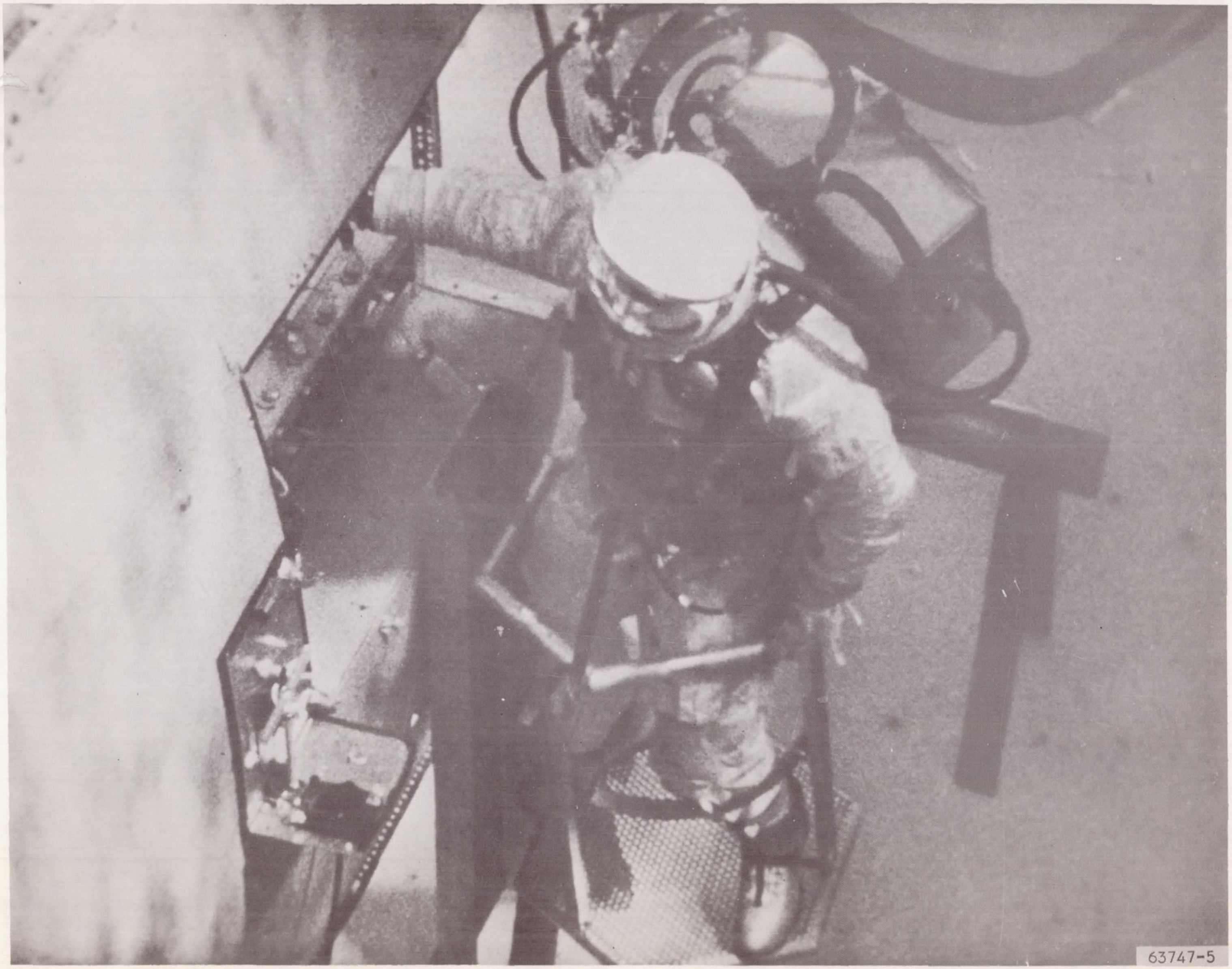


Figure 4-136. Subject Completing Right Hand Pull of Force Lever of Task Box

Figure 4-137. Subject Wedging Head and Backpack Against Upper Edge of Access Opening to Maintain Work Position

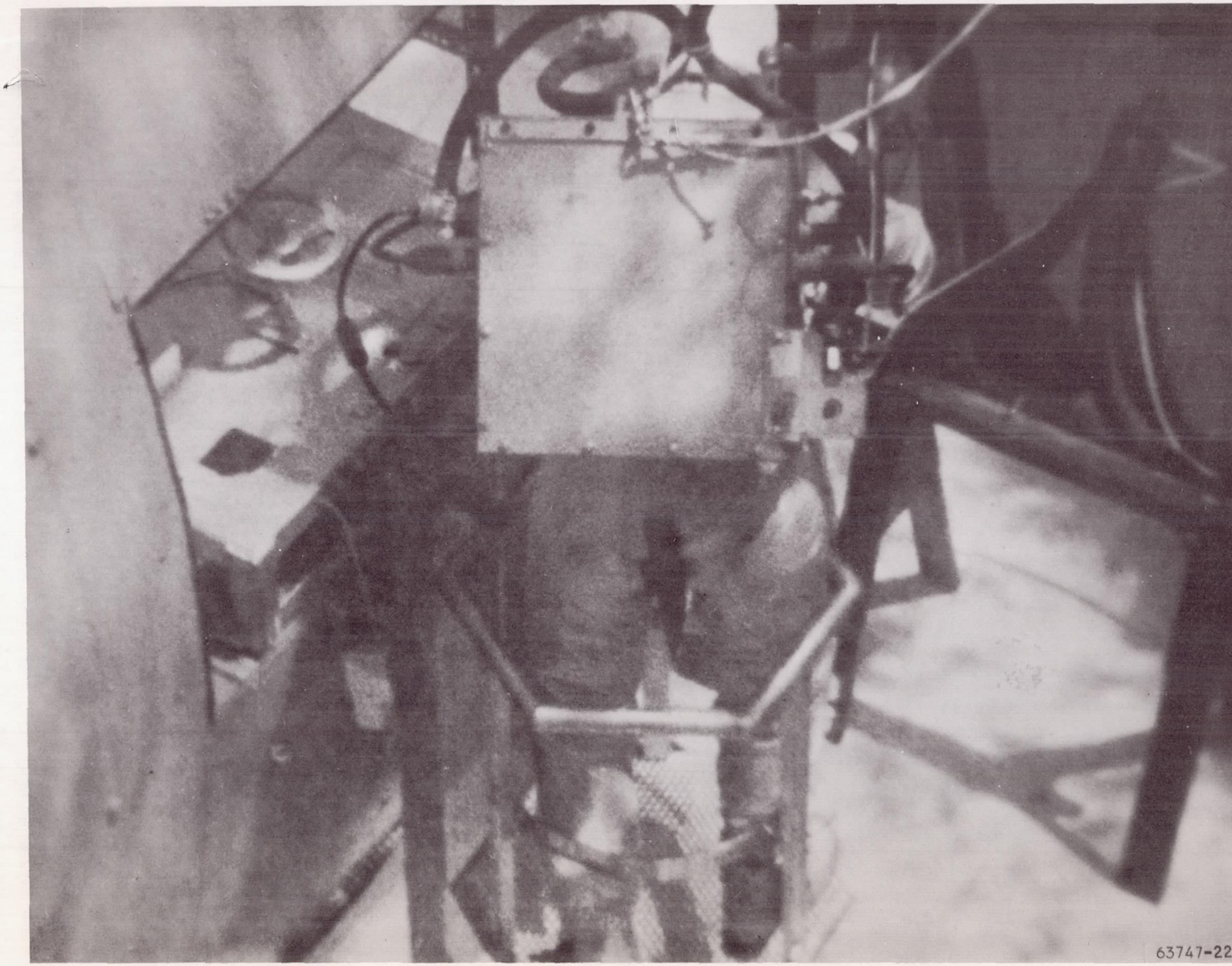


Figure 4-138. Subject Going to Tool Kit From Cage Restraint

to perform the work (see Figures 4-139 and 4-140). The second two attempts were partially performed. In Test 318, tasks 4, 7, and 8 were impossible for the subject to perform. Other tasks, such as 1 and 2, were discontinued because of excessive performance time.

GENERAL COMMENTS

Part of the human engineering effort for this program was to reexamine, where applicable, the conclusions drawn during NASA Contract No. NAS 1-5875. None of these conclusions was altered by these experiments.

Emphasis must be placed on the man/machine interface for EVA research. The multiple interaction and complexity of the numerous variables required diligent application in the simulation to develop adequate procedures and equipment. The major problems to date are in the following areas:

Restraint devices

Special tool design

Fasteners appropriate to EVA application

Apparatus for handling and presenting tools, component, and parts

The problems posed relative to these critical man/machine interfaces may be largely solved by applying the following principles, hypothesized from NASA Contract No. NAS 1-5875 and reinforced by the findings of this study:

(a) Good EVA in terms of both dexterity and force depends on stability and appropriate position of the worker and the ability to supply adequate traction, i.e., reactive loads

(b) Detailed hand-by-hand task analyses must be conducted in developing procedures for any EVA or IVA

(c) Complete and detailed simulation is required to check out all work projected for the weightless environment

(d) Extensive training is required to permit adequate study of EVA work

Neutral-buoyant/underwater research directed toward EVA should concentrate on restraint device design. The total work situation depends on the astronaut's capability to position correctly to the work, maintain the stability of the position throughout the task, and transfer the required reactive loads back to the spacecraft. All other variables depend on these requirements. Since the numerous variables involved extend the EVA problem well beyond the common sense solutions, it is necessary to build and then examine the man/machine interface in the best simulation possible. Rework through the iterative process is essential for developing both task techniques and support equipment.

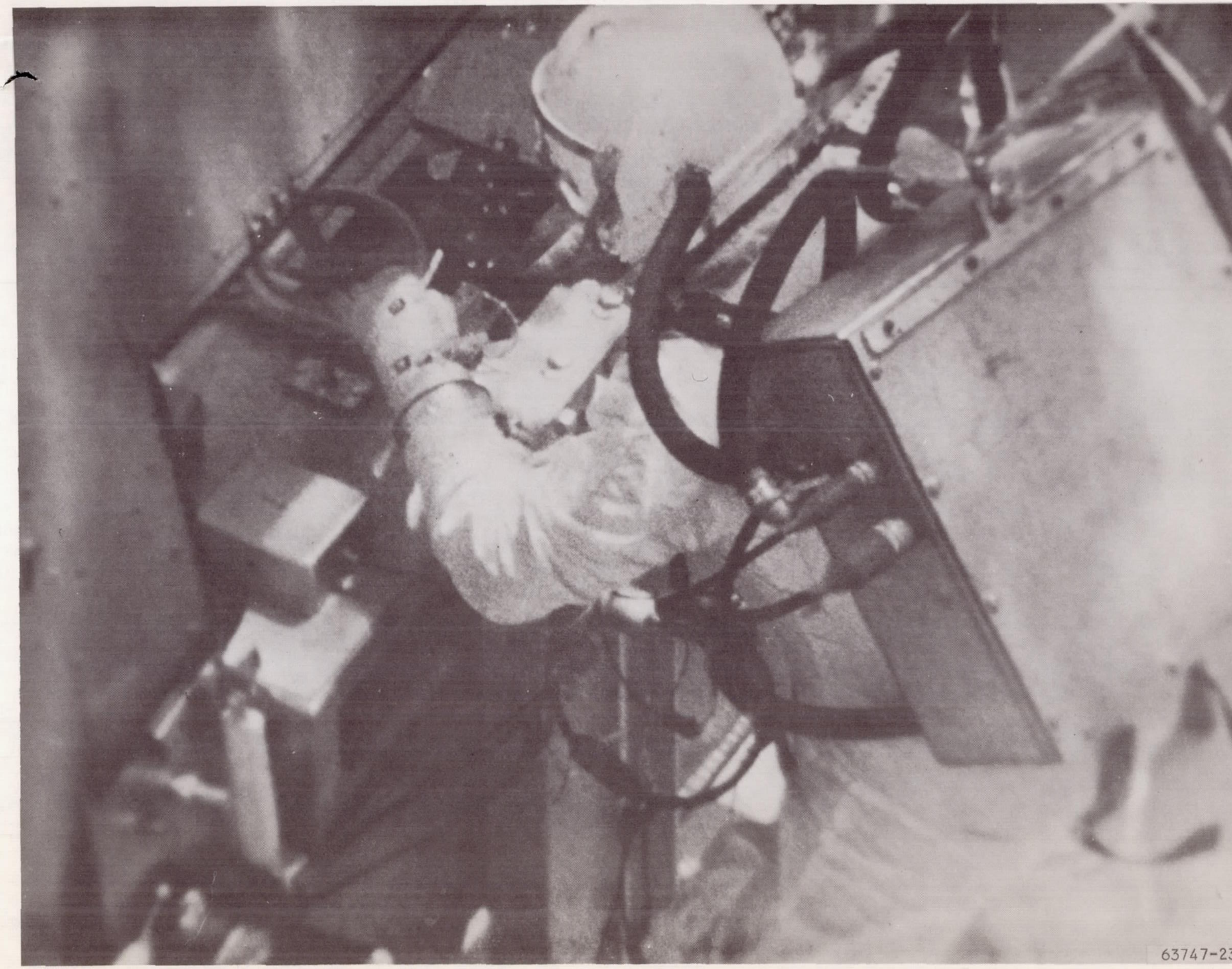


Figure 4-139. Subject On Rigid Leg Restraint Maintaining Work Position With His Left Hand

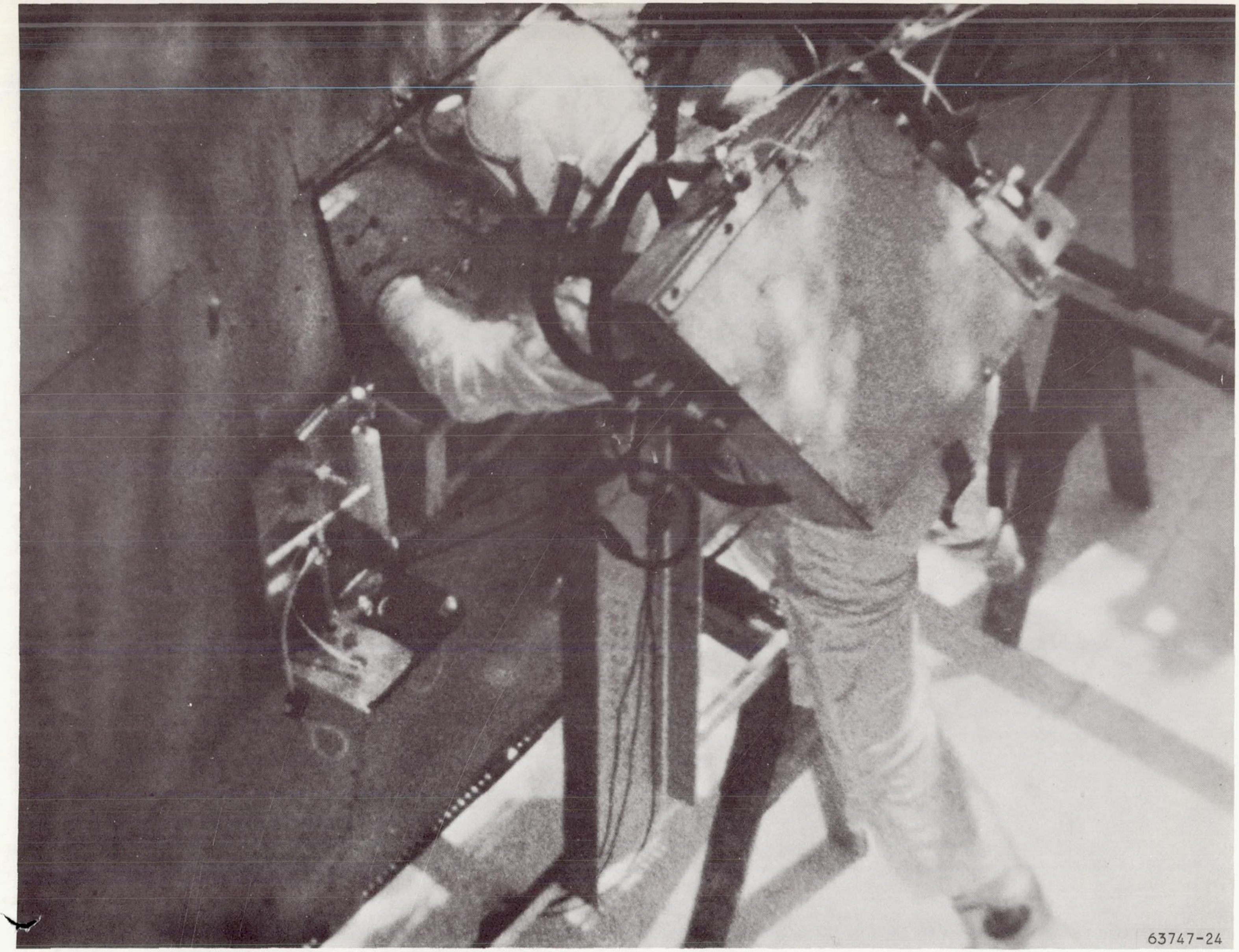


Figure 4-140. Subject on Rigid Leg Restraint Working on Task Box

Care must be exercised during attempts to develop universal principles for EVA from specific designed tasks and special hardware, designed and built for a given work situation.

EVA appears basically similar to other work in that it requires special tools and equipment to effectively and economically accomplish the work.

SECTION 5

CONCLUSIONS

1. Metabolic rates and heart rates reached higher peak values for the exploratory tasks than for the restraint studies of this effort or for the tasks reported in NASA CR-859.

2. In general, the subjects performed at work rates (metabolic rates) in the light-moderate to moderate work range, the level at which man can work for long periods of time.

3. Metabolic costs of those exploratory tests performed without prior training were higher than those performed after training. The results emphasize the need for training in neutral buoyancy in preparation for EVA. A hand-to-hand analysis of each task and training to such a performance time line would result in the astronaut pacing his efforts to the work task and would minimize wide excursions in metabolic rates.

4. The subject's thermal balance during testing must be evaluated to completely evaluate the metabolic costs of work during underwater simulation. The increased conductive cooling during underwater simulation could result in exacerbations of the metabolic data.

5. Evaluation made of EVA work aids in using metabolic rates as the objective criterion is enhanced by tasks of sufficient duration to allow the subject to reach a steady state physiologically. However, work aids and task sequences of relatively short duration can be evaluated in terms of energy expenditure.

6. Techniques to measure the reactive forces during weightless simulation are valuable in evaluating subject performance, restraint techniques, work aids, and task sequences.

7. Only the cage restraint permitted the subject to use the restraint system while performing all of the tasks conducted on the task box. Modification of other restraints by providing power-driven adjustments in elevation, train, and pitch would markedly improve the performance of these devices. Power assist in location of the restraint would also improve the cage device.

8. More efficient ratios of work load/load moment imparted to the spacecraft were obtained by subjects' use of the cage restraint than by use of the other restraint devices.

9. An improved method of rapidly adjusting strap tethers to the desired length would materially improve the performance of all restraint devices and significantly reduce the time and energy costs of EVA work.

10. Task planning should be sufficient to provide a relatively constant medium level of work throughout the EVA.

11. Due to the viscosity of water, great care must be taken in drawing conclusions about translation during underwater simulation.

12. Manual translations during cargo handling or during crew rescue should be accomplished as separate events by the astronaut and the item being transported since manual translation is a two-handed task.

13. A work station including restraint devices should be located at hatchways to adequately control objects inserted into or taken from an access area or airlock.

14. Manipulation of masses up to 15 slugs does not appear to pose difficulties for EVA.

15. Manipulation of 120-cu-ft rectangular volumes of 10-ft-dia cylindrical volumes pose no particular problems.

16. Manual assembly of large modules such as 10-dia cylindrical sections is easily achieved in weightlessness when appropriate tools, jigs, and fasteners are employed.

17. Manually operated, quick-acting fasteners exist which are suitable for assembly of many types of structures during EVA.

18. The conclusions previously reported in NASA CR-859 are still cogent.

NASA-Langley, 1968 —— 5