NASA TECHNICAL NOTE

NASA TN D-6674

c.1

NASA TN D-6674

DEVELOPMENT OF SKYLAB EXPERIMENT T020 EMPLOYING A FOOT-CONTROLLED MANEUVERING UNIT

by Donald E. Hewes and Kenneth E. Glover

Langley Research Center
Hampton, Va. 23365

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No. NASA TN D-6674	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DEVELOPMENT OF SKYLAB EXPERIMENT T020 EMPLOYING A FOOT-CONTROLLED MANEUVERING UNIT		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) Donald E. Hewes and Kenneth E. Glover		8. Performing Organization Report No. L-8045
		10. Work Unit No. 970-33-10-41
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A review of the plans and preparations is presented for Skylab experiment T020, entitled "Foot-Controlled Maneuvering Unit" (FCMU). The FCMU is an experimental system intended to explore the use of simple astronaut maneuvering devices in the zero-gravity environment of space. This review also includes discussions of the FCMU concept and experiment hardware systems, as well as supporting experiment definition and development research studies conducted with the aid of zero-gravity simulators.

17. Key Words (Suggested by Author(s)) Foot-controlled maneuvering unit; Skylab experiment T020; Extravehicular activities; Astronaut maneuvering unit; Astronaut maneuvering system; Space maneuvering		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 59	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

DEVELOPMENT OF SKYLAB EXPERIMENT T020 EMPLOYING A FOOT-CONTROLLED MANEUVERING UNIT

By Donald E. Hewes and Kenneth E. Glover
Langley Research Center

SUMMARY

This paper provides a review of the plans and preparations for Skylab experiment T020, entitled "Foot-Controlled Maneuvering Unit" (FCMU), which is scheduled to be conducted in the Skylab orbital workshop (OWS) in approximately $1\frac{1}{2}$ years from the time of this review. The FCMU is an experimental system which is being tested to explore the use of relatively simple unstabilized propulsion devices for astronaut maneuvering in zero gravity. The review covers various aspects of the experiment objectives and plans, as well as pertinent details of the FCMU concept and experiment hardware systems. Additional information covers supporting research conducted with the aid of zero-gravity simulators to define the experiment plan and to develop the experiment hardware.

INTRODUCTION

Although there have been no stated requirements for the operational use of astronaut maneuvering systems for extravehicular activities (EVA) in space missions for the next few years, the application for future missions appears to be quite desirable and there has been considerable study devoted to this subject. A large portion of this study effort has been directed toward the design of back-mounted configurations with the propulsion system integrated with the life-support and communication systems. These configurations generally have incorporated multiaxis translational capabilities coupled with automatic stabilization about the rotational axes operated by the pilot through hand controllers. An example of this relatively complex system design approach is the Astronaut Maneuvering Unit (AMU) which was developed for the Air Force and was scheduled to be operated experimentally in the Gemini missions (ref. 1). A notable exception to this complex design approach, however, was the experimental Hand-Held Maneuvering Unit (HHMU), also of the Gemini mission series, which was an attempt to explore the capabilities of a relatively simple propulsion system. It was from this same standpoint of exploring design simplification of astronaut maneuvering systems that experiment T020, entitled "Foot-Controlled Maneuvering Unit" (FCMU), was proposed by the NASA Langley

Research Center as an experiment for the Skylab mission. (See ref. 2.) A sketch of the Skylab orbital assembly in orbit around the earth is given in figure 1. Experiment T020 is to be conducted inside the orbital workshop, which is a part of this assembly.

The FCMU flight hardware developed for this experiment is based on the concept of a propulsion system mounted principally between the legs of the operator with a set of thrusters located just outboard of each foot, as illustrated in the sketch of figure 2. This sketch depicts the experimental hardware strapped onto a pressure-suited test subject as he maneuvers within the confines of the OWS. Propulsive thrust is generated by pressurized nitrogen stored in the backpack. All of the thrusters are operated by foot controls and provide translation capability along one axis and rotational capability about all three axes. Stability of the system is dependent on the pilot's control capabilities and not on an automatic stabilization system. Furthermore, this concept leaves the operator's hands free of the controlling task so that he may perform ancillary tasks involved in EVA operations, such as operating cameras and other instruments or providing anchorage and shock attenuation during the initiation and termination of transfer from one spacecraft to another.

The hardware is strictly a so-called test bed for experimental use only within the OWS to explore this concept in the zero-gravity environment and, as such, is not intended for EVA operations external to the spacecraft. The knowledge to be gained from this experiment, along with that of a companion Skylab experiment (experiment M509, entitled "Astronaut Maneuvering Equipment," ref. 2) dealing with other maneuvering system design approaches, will be useful in the development of advanced systems for future space missions.

The purpose of this paper is to discuss the development of the experiment and of the flight hardware and to provide some background information that is pertinent to a general understanding of experiment T020. Several aspects of the FCMU concept and experiment development are covered in greater detail in several appendixes to this paper.

SYMBOLS

t time

T_h fore-and-aft firing thrusters (see fig. 5)

T_v up-and-down firing thrusters (see fig. 5)

X,Y,Z orthogonal axes passing through center of mass with Z-axis alined parallel with operator's back

X_i, Y_i, Z_i principal inertial axes of FCMU system, system reference axes

ΔV residual velocity increment resulting from a discrete $\Delta\theta$ command

$\Delta\theta$ commanded pitch attitude change of FCMU system measured in the principal X_iZ_i-plane with respect to some initial attitude

BACKGROUND

The origin of the present FCMU lies with the "jet-shoe" concept developed by John D. Bird of the NASA Langley Research Center in early 1965, as discussed in reference 3. This approach involved the attachment of a single thruster to the bottom of each foot. The two thrusters were actuated by a switch located under the toes. A series of simulation and analytical studies were performed and, based on this simple conceptual approach, the proposal for experiment T020 was submitted.

Following approval of the proposed experiment in late 1966, intensive definition studies involving three zero-gravity simulators, described in appendix A, were initiated. As a result of some of this work, the FCMU configuration was developed to provide additional translational control capabilities and to provide more nearly discrete attitude control responses than those of the "jet-shoe" concept. The initial FCMU configuration was based on the use of the complete Astronaut Maneuvering Research Vehicle (AMRV) of experiment M509 mounted on the operator's back. This unit was to serve as the source of propulsion gas and electrical power for the FCMU, as well as the recording system for operational data. However, because of significant differences in definition and development schedules for the two systems and critical mass problems associated with this combination, the decision was made to develop a separate backpack system. A side view of the final configuration for experiment T020 is shown in the sketch of figure 3. The backpack uses the battery and Propellant Supply Subsystem (PSS) of experiment M509, both of which are removable from either assembly for recharging.

DISCUSSION OF EXPERIMENT T020 OBJECTIVES

In the design of an operational system intended for EVA use, there are many factors that should be taken into account to achieve a practical and useful device. From the user's standpoint some of the critical factors include EVA mission requirements, system performance, pilot handling qualities, size, accessibility, maintainability, and reliability. There are many others as well that must be considered in the manufacture and development of the operational system. It is, of course, very advantageous that, prior to the commitment to develop such a system for future applications, steps be taken to gain as much knowledge as possible concerning the impact of alternate design approaches on these various factors. The first objective of experiment T020 is to carry out a series of zero-gravity tests using an experimental test-bed version of an unstabilized foot-controlled system on the premise that this particular simplifying approach will have a favorable impact on at least a few of the critical factors.

It is recognized that such a simplifying approach may have detrimental effects as well, particularly in the areas of system performance and pilot handling qualities. These particular factors play a dominant role in the workload imposed on the astronaut as he attempts to carry out EVA maneuvering tasks. The only experience with an astronaut maneuvering device of any type in space is that with the HHMU, and this amounts to a total of only about 8 minutes split between two astronauts during the Gemini IV and X missions. Such experience has provided only very limited insight into the piloting workload of simple design approaches. In view of this situation, judgments concerning the trade-offs between design simplification approaches and pilot workload must be based primarily on experiences with other space vehicle systems and on studies involving ground-based, zero-gravity simulation techniques.

Although ground-based simulation studies have been used very extensively for a wide range of space applications, the fidelity of the different zero-gravity simulation techniques employed have not been firmly established, particularly in the area of pilot workload for some applications. In the case of the more complex maneuvering systems using automatic stabilization, the artifacts of simulation due to small misalinements, drift, and so forth, may be handled completely by the stabilization system and, therefore, may not be reflected into the pilot's workload. With simpler devices using no stabilization, on the other hand, the operator must cope directly with the effects of the simulation artifacts; as a result, his workload may be seriously affected. Consequently, although the ground-based studies may be very useful in several respects, they cannot be relied upon until much more is known about the fidelity of these techniques and the effects on workload. The second objective for experiment T020, therefore, is to obtain correlation between the in-flight tests and ground-based simulations of these activities for the purpose of gaining more knowledge as to simulation fidelity and piloting workload.

Inasmuch as the Skylab mission also has scheduled tests of other maneuvering systems in experiment M509 carried out under conditions similar to experiment T020, the third and final objective of experiment T020 is to obtain direct subjective comparisons of the various systems involved in support of the first two objectives. The purpose of this final objective is not to make a trade-off comparison of one system versus another but rather to obtain consistent information on the capabilities and limitations of the systems of interest in the actual zero-gravity environment. Inasmuch as the experiment time and expendables in the Skylab mission are extremely limited in relation to total information actually needed for maneuvering systems, evaluation during the same mission by the same astronauts is important in order to obtain the maximum return from both experiments.

DISCUSSION OF THE EXPERIMENTAL FCMU CONCEPT

In the following section, some of the features and operating techniques will be discussed briefly so as to provide a general understanding of the FCMU experimental design approach. More complete discussions of the system features and characteristics are presented in appendix B.

Design Simplification Features

There are several design features combined in the FCMU configuration that could contribute, either individually or in combination, to design simplification for some future device actually intended for operational EVA use. These features are: (1) foot-operated controls, (2) between-the-leg mounting of the device, (3) direct mechanically operated thruster valves, (4) single-axis translation capability, (5) unbalanced thruster configuration for pitch control, and (6) absence of an attitude stabilization system.

As mentioned previously, the use of foot-operated controls permits hands-free operation of the device which may be advantageous for the performance of some EVA tasks. Incorporation of the other features is an attempt to provide a compact system with a minimum number of operational components in conjunction with the foot-control approach. Inasmuch as the thrusters were placed at the feet, it appeared very desirable to operate the thruster valves by direct mechanical action of the feet rather than by indirect linkages or alternate electromechanical means. The translation capability and pitch control arrangement were the result of attempting to provide at least an acceptable degree of maneuvering capability with the smallest number of fixed thrusters. The absence of a stabilization system is based on the belief that the stabilization function could be performed adequately by the pilot for many of the EVA maneuvering tasks.

Special note should be taken concerning the use of the back-mounted arrangement using the pressure supply system and electrical storage battery of experiment M509. This arrangement was incorporated as an expediency to keep the design complications, as well as the overall costs and launch weights of the experiments, to a minimum. However, the arrangement did simulate the mass distribution characteristics for an envisioned future operational system based on the other features of the FCMU concept. In this hypothetical case, the back mount would be used for the portable life-support and communication systems and the FCMU would be completely self-contained with its own systems for supply of expendables.

Thruster Configuration

A photograph of a mockup of the complete FCMU system being worn by a test subject is given in figure 4. The two thruster assemblies, each of which houses four separate thrust nozzles, are located directly below the subject's feet. A diagram illustrating the location of the thrusters and the direction of the thrust vectors relative to the center of mass of the complete system is given in figure 5. The center of mass falls relatively close to the operator's hip joints. The fore-and-aft firing thrusters (T_h), directed parallel to the principal X_i-axis at approximately 0.91 meter (3 ft) below the center of mass and 0.27 meter (0.9 ft) outboard of the X_iZ_i-plane of symmetry, provide approximately 1.3 newtons (0.3 lb) force each. The up-and-down firing thrusters (T_v), canted outward from the Z_i-axis by an angle of 15^o, provide approximately 4.4 newtons (1 lb) force each. It should be noted that the principal X_i- and Z_i-axes are rotated about 20^o from the customary body-axes system alined with the backbone of the operator. The thruster assemblies have been purposely located relative to the principal axes so as to minimize inertial cross-coupling moments resulting from thruster firings. The principal axes are used as the set of reference axes for this maneuvering system.

Translational accelerations along the Z_i-axis are produced by firing the vertically oriented thrusters T_v in complementary pairs, that is, those firing in the same direction. Rotational accelerations about the roll axis (principal X_i-axis) are produced when these same thrusters are fired in opposed pairs. Likewise, pitch acceleration about the principal Y_i-axis is produced by complementary pairs of the horizontally oriented thrusters T_h, and yaw accelerations are produced by opposed pairs.

One unique aspect of this thruster arrangement is the use of the unbalanced thrusters, that is, a set of thrusters offset from the center of mass in only one direction rather than two opposite directions, to produce the pitch acceleration. This feature provides a considerable simplification in design by allowing a more compact thruster configuration than does a balanced thruster design. However, this approach results in translation accelerations along the principal X_i-axis being produced by pitch control inputs. The implications of this control interaction on the maneuvering tasks are discussed in some detail in appendix C.

Foot Control Logic

Several logic concepts were investigated by simulation techniques, with the result that the one selected (see table I) was preferred as being more closely related to conventional control systems and more quickly learned by pilots and astronauts. With this scheme, both feet are normally utilized in making the four types of discrete control inputs, that is, pitch, roll, yaw, and translation. Sometimes it may be advantageous to employ one foot action to achieve combined control inputs, but for purposes of this discussion only the normal control logic using both feet will be considered.

Pitch-yaw control inputs consist of simultaneous action on both ankles, herein referred to by the terms "toe up" or "toe down" to designate the direction of rotation. The term "pitch up" is the action of both toes up; the term "pitch down" is the action of both toes down. Yaw control can best be learned by thinking of the toe-down direction; that is, depressing the right toe down results in right yaw and depressing the left toe down results in left yaw. The ankle action of the opposite foot is the reverse of the command ankle. The roll and translation control inputs are similarly related to the up and down foot action, with both feet moving in the same direction to produce translation and in the opposite direction to produce roll.

General Maneuvering Techniques

The general scheme for maneuvering from one location to another with the translational thrusters directed along only the Z_i-axis is illustrated in figure 6. This figure depicts the sequence of events performed by the operator starting from some arbitrary position where the axis is not alined with the target and the operator's relative velocity is zero. Most attitude maneuvering can and should be done with the pitch-yaw thrusters (step 1). Roll-axis maneuvering is seldom required and should normally be used only to counteract roll-axis disturbances generated by the other controls in order to minimize fuel usage. Translation toward the target is initiated with a down-firing command of 2 to 3 seconds (step 2) to generate a closing velocity of about 0.15 meter (0.5 ft) per second. If the target is more than 4 to 6 meters (13 to 20 ft) away and the trajectory is observed to deviate from the line of sight to the target, the operator yaws to aline the X_i-axis with the cross-range deviation and then pitches up so as to aline the Z_i-axis approximately perpendicular to the target line of sight (step 3). The up or down thrusters are fired so as to cancel the cross-range deviations (step 4). At a range of 6 to 4 meters (20 to 13 ft), if the velocity is considered to be too high to permit a chest-on docking maneuver using the hands and arms for arresting the velocity, a pitch-up maneuver is performed to allow the Z_i-axis thrusters to decelerate the motion (steps 5 and 6). The operator then rotates the unit to whatever attitude is desired for the termination of the maneuver (step 7).

When the type of target permits, one variation of this general scheme is to aim the unit slightly below the target (step 2) so that the target passes within arms reach in front of the operator. This permits him to decelerate without the jets impinging on the target (step 6) and gives him a better view of the target as he gets within close range. If he so desires, by having a few degrees pitched-down attitude as he decelerates, a slight drift into the target can be generated that ensures his being able to grasp the target.

The problems associated with the translation interactions due to pitch control inputs as produced by the unbalanced pitch thrusters are discussed in appendix C.

EXPERIMENT PLAN

Experiment T020, planned to be carried out in three parts, is to be performed before, during, and after the Skylab mission itself. Each of these parts contributes an essential element in meeting the objectives of the overall experiment.

Aside from the obvious necessity of providing detailed training to the mission crews for this experiment, the premission training sessions will be used to develop baseline data pertinent to the simulation and operation of the FCMU. In addition to providing a check on timeline estimates of the experiment run times and fuel utilization, these data will provide the basis for a direct quantitative comparison between ground-based simulation and in-flight operation.

The tests conducted in the OWS will provide both subjective and quantitative evaluation of the FCMU concept in the real zero-gravity environment. The limited number of variables in these tests, as dictated by constraints of crew time and equipment and by expendable weights, are expected to provide a bare minimum of essential information. The variables are (1) the test subject, (2) the garb of the subject, and (3) the specific maneuver performed by the subject. Two subjects will be employed, with each having an equal opportunity to operate the FCMU. When one is acting as the test subject, the second is serving as the observer and operational assistant.

The shirt-sleeve mode for the experiment is intended to investigate the basic capability of the FCMU concept with the subjects wearing the garb of lightweight flight suits. Following this, the pressure-suit mode is used to establish the degree of interference imposed by the pressurized suit. This interference is expected to be primarily in the form of a reduction in the field of view of the test subject and other piloting cues. Although it is desirable to determine the effects of the pressure suit independent of other factors, the suit can be used only with a rather large and cumbersome gas-supply umbilical because of mission limitations. It is believed that the effects of the pressure suit can be reasonably identified even though the umbilical can be expected to impart random force and torque inputs to the system and impose restrictions to the FCMU motion.

In judging the results of the flight experiment, emphasis will be placed on the subjective evaluations of the two crewmen who perform the experiment. Readings of the backpack pressure gage by the observer will provide a direct measure of fuel expenditure for each type of maneuver performed. A data-acquisition camera mounted at the hatch in the OWS will provide general information as to the maneuvers performed, and another camera mounted in the FCMU will yield specific data on the angular and translational motions involved. A short sequence of foot-control minimum inputs will also be obtained with this unit. A still camera is to provide general documentary information on the experiment setup.

The post-mission activities are considered to be a vital aspect of the total experiment and will consist of the return of the flight crew members to the ground-based simulators to obtain an after-the-fact impression of the simulation fidelity. This session will provide a very helpful interchange of ideas, impressions, and facts between the mission crew and the experiment personnel.

EXPERIMENT DESCRIPTION

The initial training and baseline-data gathering phase of experiment T020 will be carried out using two zero-gravity simulators, the visual-task and the dynamic-air-bearing, which provide six-degree-of-freedom motion and three-degree-of-freedom motion, respectively. Details of these simulators are presented in appendix A. A series of training sessions are planned for the flight crews who will be conducting the experiment in the OWS. Data and subjective comments will be obtained on the performance of the trainees while executing the planned maneuvering tasks for the in-flight phase of the experiment, as discussed subsequently. Part of the data will be the pilot ratings (ref. 4) assigned by each of the subjects to these individual maneuvering tasks which will be performed using the air-bearing simulator.

Following completion of the in-flight phase of the experiment, the final step will consist of the return of the flight crew to the simulators for a postflight session. This session will include the gathering of additional performance data and the impressions of the crew concerning fidelity of the simulators based on their actual flight experiences.

The second phase of experiment T020 will be conducted during the Skylab mission in the forward area of the OWS, which is depicted in figure 7 by the top-view and side-view sketches and in figure 8 by the photographs of an OWS mockup. Some of the equipment pertinent to the experiment working space within the OWS is identified in these figures. The internal dimensions of the OWS are approximately 6.1 meters (20 ft) in diameter and 6.1 meters from the grid floor to the center of the domed ceiling. A fireman's pole, used to assist traveling from the floor to the ceiling for other activities, will be removed for this experiment.

The FCMU and backpack are stored in an area which has sufficient clear space to permit assembly of the system without relocation of the mounting stand. The PSS and battery of experiment M509 are stored separately from this stand. All OWS equipment including the FCMU are positioned in the OWS so as to provide a cleared volume of at least 4.6 meters (15 ft) in diameter. A series of discrete rotational and translational maneuvers will be performed generally within this space. It is intended that specific attitude and translational maneuvers will be performed in a plane approximately 2.1 meters (7 ft) from the grid floor and parallel to it. Translations generally will be performed from the area of the FCMU mounting stand to the wall space between the Force Measuring Units (FMU) of experiment T013, entitled "Crew-Vehicle Disturbance," shown in figures 7 and 8.

This arrangement for the conduct of the experiment provides an optimum view of the maneuvers for the overhead camera located in the dome hatch. A camera mounted within the FCMU generally will be viewing the wall areas near the floor, which are better lighted than the areas near the dome. These conditions greatly facilitate the postmission photogrammetric analysis of the sequence camera films used to determine maneuver attitudes, positions, and velocities.

Activities During In-Flight Test Runs

The maneuvers for experiment T020 are planned to investigate the basic control capabilities of the FCMU system and are arranged approximately in the order of increasing complexity. The first three maneuvers will be simple 90° attitude changes about each axis with a return to the initial attitude. At the termination of each attitude change the subject will attempt to maintain that attitude with minimum attitude drift for about 10 seconds. No attempt will be made to correct for translational drift. The fourth maneuver will be a translation from the wall near the FCMU mounting stand to the opposite wall, and a return.

The next maneuver will be a pitch attitude change of 90°, and return, with an attempt to correct the translation error due to the pitch thrusters, as described in appendix C. This is then followed by a translation maneuver across the OWS with the subject pitching down 90° so that he arrives at the target area with his hands extended forward to arrest his velocity at the opposite wall. Following a similar return translation maneuver, the subject will be placed into a random tumbling motion by the observer after being placed near the center of the maneuver space. The subject will then attempt to recover from the tumble by use of the attitude thrusters.

During the test runs, the observer will be stationed near the hatch in the center of the grid floor. In this location he will position the subject for the start of the run, operate the overhead camera through a remote control switch cable, manipulate the pressure-suit umbilical when used, and help retrieve and reposition the test subject at the end of each run.

Typical In-Flight Procedures and Test Conditions

A breakdown of the experiment procedure into typical simultaneous and sequential tasks for the two crewmen is given in table II. A nominal experiment timeline is given in table III, which also shows the accompanying utilization of the primary expendables, camera film, and propulsion gas. (Expendables such as electrical power for lighting, photography, and battery recharge, as well as suit ventilation gas, are not shown.) This nominal timeline shows a test session in the shirt-sleeve mode and a second one in the pressure-suit mode, each lasting about 3 hours. Each session provides for the two crewmen to serve as test subject performing three runs for each maneuver. The first two runs of each maneuver serve as practice runs and the third serves as the data run with cameras running. This timeline indicates that the FCMU camera magazine and PSS will be changed when the crewmen exchange their experiment roles.

The actual experiment timeline may be changed from that shown here as a result of further integration planning of all activities involved in the OWS mission. An alternate to the two sessions described here would be to use four sessions with each test subject performing these maneuvers for two sessions. This step requires more time to allow for the additional setup and storage of equipment for the two extra sessions.

EXPECTED RESULTS

The most important results of experiment T020 are expected to be the qualitative evaluations by the Skylab crewmen of the FCMU system and of the ground-based simulators based on their actual in-space experience. Comments on the crewmen's ability to perform the various specified maneuvers and other activities will be vital to the assessment of the fidelity of the simulators used in this project.

Quantitative measurements will be derived from the actual experiment timeline, the camera films, and pressure readings from the PSS. These data will be combined with similar measurements obtained during the premission and postmission baseline-data sessions to assist in the correlation of the ground-based simulators with the so-called real world experience. Measurements will consist of the following: time duration to perform each maneuver, fuel used (tank pressure drop) to perform each maneuver, maximum and minimum angular and linear velocities developed during the maneuver, and cross-coupling motions resulting from discrete control inputs.

The in-flight phase of the experiment provides a very unique opportunity to operate a maneuvering system in the actual zero-gravity environment. It must be remembered, however, that the environmental conditions within the OWS may be significantly different from those that normally will be encountered in typical EVA operations outside a spacecraft. There are at least two considerations that could have a marked impact on the interpretation of the in-flight experimental results. The first consideration is that of the space limitations of the OWS which restrict the maneuvering distances to less than 6.1 meters (20 ft); the second consideration is that of the differences in the visual environment between the OWS and actual EVA operation where the visual cues to assist the operator in judging the motions of the maneuvering system may be greatly reduced from those cues of the OWS operation. The effects of these environmental differences on the operator's workload and ability to control his motions are the subject of continuing research using the simulators discussed in this paper in order to assist in making meaningful interpretation of the in-flight experimental results.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 17, 1972.

APPENDIX A

FCMU EXPERIMENT DEFINITION AND DEVELOPMENT STUDIES

Following the approval in November 1966 of the proposal for experiment T020, special zero-gravity simulation facilities were developed at the NASA Langley Research Center and several studies were carried out as part of the definition and development of the experiment. The three facilities used most extensively are the six-degree-of-freedom visual-task simulator, a three-degree-of-freedom dynamic-air-bearing simulator, and a water immersion simulator. The following sections cover discussions of these facilities and some of the pertinent study results.

Visual-Task Zero-Gravity Simulator

The visual-task simulator consists of two major elements, the television projection dome, illustrated in figure 9, and the television camera and target-model drive system, shown in figure 10. The test subject is seated on a mockup of the FCMU inside the 360° spherical viewing dome next to a servo-driven television projection system. The subject views the images of the spacecraft and a simulated earth horizon projected onto the screen, as illustrated in the photograph of figure 11. He operates the foot controls in response to what he sees and how he wants to maneuver around the simulated spacecraft. A photograph showing more details of the test subject seated on the FCMU mockup is given in figure 12. Here the viewing dome has been rolled out of the way so that the photograph could reveal details of the equipment mounted on the sting that normally projects into the spherical screen.

The foot controls operate switches connected to a digital computer programed to calculate the dynamic responses of the FCMU to these control inputs for conditions of an astronaut maneuvering anywhere around a 5.5-meter-long (18-ft-long) spacecraft within a range of from 61 meters to about 3 meters (200 ft to about 10 ft) away from the spacecraft. The simulator provides continuous tumbling capability and can be used to represent alternate control systems with a variety of systems characteristics. The orbital mechanics terms of the equations of motion can be included but generally have not been used in this simulation because the effects of these terms are considered to be relatively small for the spacecraft ranges involved.

This fixed-base simulator has proved very useful in studying the dynamics of the FCMU in six degrees of freedom and in demonstrating the basic feasibility of the concept for EVA maneuvering. However, this system does not represent the conditions involved in the intravehicular task of maneuvering within the OWS where visual cues are much more readily available and where maneuvering space is very limited. Furthermore, in this simulator, the test subject is not exposed to the proprioceptive cues associated with the motion of the FCMU and operation of the actual hardware. Because of these limitations of the visual simulator, the dynamic-air-bearing zero-gravity simulator was developed as a companion research tool.

Dynamic-Air-Bearing Zero-Gravity Simulator

The dynamic-air-bearing zero-gravity simulator, a moving-base system, provides a three-degree-of-freedom simulation of the zero-gravity environment and employs an operational mockup of the FCMU hardware with an active propulsion system, as shown in the photograph of figure 13. The basic elements of this system are the special flat and level epoxy-coated floor area, an air-bearing supported mounting frame, and the operational FCMU mockup. The mounting frame and mockup form a self-contained system with electrical power and sufficient pressurized gas to sustain operation of the air bearings and the propulsion thrusters for periods of 5 to 10 minutes. This time can be extended for much longer duration by use of a small, flexible plastic hose from the shop air supply to supply the low-pressure air to the bearings separately from the onboard high-pressure propulsion system.

The air-bearing unit shown in figure 13 provides the three degrees of freedom associated with the pitch plane of the FCMU. A similar unit with the subject oriented on his back has also been provided to study maneuvering in the roll plane. Inasmuch as yawing maneuvering represents a relatively easy task not directly associated with the translational maneuvers, it was considered unnecessary to develop a unit providing freedom of motion about the yaw axis.

An overhead view of the facility showing a test subject operating the air-bearing unit inside a 6.1-meter- (20-ft-) diameter ring representing the walls of the OWS is given in figure 14. This view, taken with a 5-mm lens on a 16-mm camera, is approximately the same as will be seen with the camera mounted in the hatch of the OWS during the Skylab experiment. The circular partition represents a portion of the OWS interior walls near the floor. The epoxy floor, as seen in this view extending beyond the circular walls, consists of a 4.6- by 15.2-meter (15- by 50-ft) rectangle adjoined on one long side by a 4.6- by 9.2-meter (15- by 30-ft) rectangle. Measurements of the simulated zero-gravity maneuvers have been obtained from the overhead camera by using reference targets on the air-bearing unit for attitude and position measurements and neon lights indicating thruster firing times. The inertial characteristics and thruster levels have been varied to determine the effects of these parameters on the maneuvering characteristics of the FCMU.

The major shortcoming of this simulation technique is the basic restriction to only three degrees of motion at any one time; however, this approach provides an important duplication of many other factors relative to the Skylab space mission environment. Especially significant are the motion and visual cues relative to the intravehicular task and the realistic operation of an active propulsion system. The test subject is able to develop an appreciation for the response of the unit to very low forces such as produced by an umbilical. The very small forces required to arrest the motion of the unit during the docking maneuvers can be demonstrated.

Water Immersion Simulator

In order to develop a further understanding of the six-degree-of-freedom, zero-gravity environment, several operational aspects of experiment T020 were studied with the aid of the water immersion simulator at the Langley Research Center. This simulator, shown in the photograph of figure 15, employs a 12.2-meter- (40-ft-) diameter tank with a water depth of 6.1 meters (20 ft). It is equipped to simulate both shirt-sleeve and pressure-suit conditions.

This simulator was used to evaluate the body-harness and foot-restraint designs for the FCMU, the foot-controller operating characteristics, and the equipment setup and storage, as well as other operational procedures. These activities helped in establishing the basic experiment timeline. The photograph of figure 16 shows some of the equipment donning procedures underway for the suited mode.

Although providing essentially the basic six degrees of freedom for zero-gravity simulation, the water-immersion technique has several limitations relative to fidelity of simulation. The principal limitations here were due to the restrictions of the umbilicals and ballasting equipment and to various bouyancy and balancing problems. The resistance of the water to movement did not appear to present any problem for the types of activities and low rates of motion involved.

General Discussion of Study Results

The initial effort following the development of the simulators was to explore the feasibility of the FCMU concept by studying the original configuration and various alternate approaches. It was concluded from these efforts that although there are other approaches of somewhat greater complexity which could function equally as well as, or perhaps better than, the original FCMU configuration, this configuration appeared feasible as a fundamental research tool for providing information on the design and utilization of relatively simple maneuvering systems. The thruster control logic was finalized on the basis of a preference expressed primarily by the pilot-type subjects who related the logic selected to aircraft control systems.

The definition and development studies explored questions as to the force and travel characteristics of the foot controller, the minimum control inputs, the maneuvering capability of the man-machine combination, and the sizing and operational characteristics of the thrusters. Some of the results of these studies are indicated in figures 17(a) and 17(b), which are plots of attitude and translation rates versus the control power or acceleration values of the respective control systems. The lower two curves correspond to minimum or shortest control inputs which could be performed without unusual effort by several different subjects (in the range of 0.2 sec to 0.3 sec). These minimum rates were considered to be acceptable and did not interfere with the performance of the overall maneuvering tasks. Actually, it was possible for the test subjects to cancel these low rates by applying more concentration to the task; however, this generally is not regarded as being necessary. The highest rates, corresponding to the upper sets of hatch lines, indicate the maximum rates that the subjects were generally willing to generate in performing most of the maneuvers studied. These rates were the result of control inputs of 2 to 3 seconds duration and correspond to a ratio of more than 10 to 1 between maximum and minimum control inputs for the nominal values of control power for the FCMU flight hardware.

Some typical visual-task-simulation results of the study to determine optimum thruster sizes for the flight hardware are illustrated by the plots in figure 18. These plots show the variation of three evaluation parameters used to determine optimum values for the fore-and-aft thrusters (T_h) involved in pitch and yaw maneuvering. The values for the pilot rating, fuel used, and time used are shown for a sequential attitude maneuver of yawing about 60°, pitching 90°, and then returning to the original attitude. The pilot-rating scale is the same as that used in reference 4 and consists of a series of numbers from 1 to 10 indicating the degree of desirable pilot handling qualities. A value of 1 represents the most desirable characteristic and a value of 10 the worst. A value of 3.5 represents the boundary between satisfactory and unsatisfactory and a value of 6.5 is the boundary between acceptable and unacceptable. These results were obtained using three different subjects for a specific set of thrust and cant angle values of the vertical thrusters.

The trends in the data and optimum values selected by all three subjects are very similar. The differences in the absolute values of each of the curves can be attributed to differences in experience, piloting technique, and personal preference. It is interesting to note that the optimum values occurred at the "knee" of the time-used curve indicating that similar trade-off judgments were made by each of the subjects between the time required to change his attitude and his ability to maintain a given attitude. These data are indicative of the results from similar tests conducted on the air-bearing simulator and also of those results for the translation-roll thruster tests conducted on the visual simulator.

Several tests were conducted with the development-type hardware to determine that the body and foot restraint systems provided proper fit and comfort for both the suited and unsuited modes and that suitable adjustments could be made by the subjects to ensure proper operation of the foot controls. These tests were conducted both in the water immersion facility and in special setups such as shown in the photograph of figure 19, where the weight of the legs and feet of the suited subject was supported on spring-loaded slings.

APPENDIX B

FCMU FLIGHT HARDWARE DESCRIPTION

The following sections provide detailed descriptions of the various elements of the flight hardware to be used in Skylab experiment T020, as shown in the photograph of figure 20. The Foot-Controlled Maneuvering Unit and its mounting stand are shown along with the backpack, the Propellant Supply Subsystem (PSS), and the electrical storage battery. These latter three items are referred to as the Propulsion Gas Supply Unit (PGSU) when assembled. During the Skylab mission prior to experiment T020, the FCMU and backpack are stored together on the stand. The battery and PSS, which are shared with experiment M509, are stored separately.

FCMU System Characteristics

A list of some of the nominal physical characteristics of the complete FCMU system after separation from the mounting stand is given in table IV. The range of values shown is due to the differences between the shirt-sleeve and pressure-suit conditions of a 50-percentile test subject. Variations from these values can be expected because of differences in the physical characteristics of the test subjects themselves. The operating characteristics of the foot controllers are illustrated by the diagrams of figure 21, which show the design variations of the foot forces by preloaded centering springs used to return the pedals to neutral position and by hard stops used to restrict pedal travel to the prescribed limits. The thruster valves are actuated at about two-thirds of this travel, causing the stepped force variation at that point.

Structure

The structural elements of the FCMU, as shown in figure 22, consist of an upper unit that forms the saddle-type seat for the operator and a lower unit that serves as the mounting base for the foot-control pedal assemblies, control valve assemblies, and thruster assemblies. The upper unit is a welded and riveted aluminum sheet-metal structure with a machined rectangular sleeve mounted in the base of the unit. This sleeve provides a nonrotating sliding joint between the upper and the lower units. The lower unit is an inverted T-shaped structure, also of rectangular cross section, with the vertical member of the "T" mating to the sleeve in the upper unit. A plunger-type latch in the sleeve is used to lock the lower unit in any one of 10 positions that are spaced approximately 25.4 millimeters (1 in.) apart to accommodate test subjects of various leg lengths.

The backpack is a lightweight welded aluminum structure constructed from tubing, sheet metal, and angle stock with quick-release mounting provisions for the PSS and storage battery. A roll-bar and a hinged sheet-metal cover are provided as bump protection for the pressurized bottle and regulator assembly. The front face of the backpack is covered with sheet metal to provide a comfortable fit on the test subject's back.

The mounting stand is a welded aluminum structure of tubing and sheet metal which bolts directly to the floor of the OWS and remains in place throughout the Skylab mission. The stand is provided with several hand-operated, quick-release latches that lock the FCMU and backpack rigidly in place for launch and storage. During the experiment setup operations, all but one of these latches will be released. The remaining latch can be easily released by the test subject after he has mounted the FCMU in preparation for the test runs. The height of the handlebars on the mounting stand can be adjusted. These bars are used as an aid for the test subject in adjusting his position on the FCMU.

Harness System

A harness system, illustrated in figure 23, is used to firmly attach the FCMU and PGSU to the test subject. A single strap at the bottom of the PGSU attaches to the back of the FCMU seat with a quick-release harness clip. A shoulder strap from the PGSU and two seat straps from the FCMU are clipped together at each hip. Both seat straps are attached to a slotted plate which is slipped over a D-ring; this is then secured with a clip on the shoulder strap hooked to the ring. In case of the pressure-suit tests, the D-rings are provided by the suit. For shirt-sleeve tests, an adjustable waist belt is used, which has rings attached. All straps are adjustable in length and marked so that the proper strap lengths for donning the equipment by each subject can be predetermined. When the equipment is donned, the straps are tightened by the test subject to the predetermined adjustment. The equipment can be doffed by the subject merely by releasing the two clips from the D-rings at the hips.

Foot Pedal Assembly and Restraint System

The foot pedal assemblies shown in the photographs of figures 22 and 24 are attached to the crossmember of the T-shaped lower unit on the FCMU. The foot pedal slides up and down on two parallel, vertical shafts on linear ball bushings and the travel is limited by preloaded centering springs and mechanical stops built into the assembly. Rotation of the pedals in the toe-in—toe-out directions is restrained by the two shafts which are spaced about 50.8 millimeters (2 in.) apart.

Fore-and-aft sliding of the foot pedal along a curved track beneath the pedal provides the desired toe-up and toe-down rotation of the pedal about the ankle joint. The foot pedal is mounted on ball bearings to minimize friction between the pedal and the track. Preloaded centering springs and mechanical stops are used to provide proper centering action of the pedal and to limit the rotational travel.

The feet are attached to the pedals by means of removable footplates that strap to the subject's feet prior to his mounting the FCMU. These plates each have an adjustable toe and ankle strap to provide proper fit for both the shirt-sleeve and pressure-suit modes in which the footwear differ considerably. The heel of the foot is held into a cup at the back of the plate by the ankle strap, and the ball of the foot is held firmly against the plate by the toe strap. The buckle for the toe strap is fastened rigidly to the front of the plate and provides a lateral restraint for the toe. The footplates are provided with a thumbscrew adjustment to accommodate variations in the foot-slue position (that is, the toes in or out position) that normally exists from subject to subject. This adjustment will be made prior to strapping the plates on the feet and is aided by a scale marked on the plate. The footplates are held onto the foot pedals by means of spring-loaded catches that permit the subject to fasten his feet to the pedals and release them without the use of his hands and without having to see the action. The footplates are stored merely by attaching them to the foot pedals.

Thruster Assemblies and Valve Assemblies

The two thruster assemblies, each of which consist of four independently operated nozzles alined on orthogonal axes, are mounted outboard of the foot pedal assemblies on the crossmember of the lower unit of the FCMU structure as shown in figure 22. The nozzles screw into the manifold block and may be replaced to make any necessary final thrust-level changes. These changes may be required to achieve the desired control responses with the flight system which may have inertial characteristics that differ from the design nominal values due to significant differences in sizes of the crew members assigned to the mission.

The thruster assemblies can be rotated about an axis normal to the X_iZ_i-plane to allow for deviations of the actual center of mass location from the design location in the X_iZ_i-plane. These deviations could cause excessive pitch motion resulting from the application of translation thrust. To facilitate this adjustment, a scale on each assembly is graduated in 1° increments for 10° either side of the design neutral setting. A thumbscrew locks the thruster assembly at the desired setting.

Two valve assemblies are located on the crossmember, just inboard of each foot pedal assembly. There are two poppet-type valves in each assembly which require a travel of 2.3 millimeters (0.090 in.) to achieve full open porting. The two assemblies are mounted such that actuator arms extending from the foot pedal assemblies can push the exposed stem of the appropriate valve for each type and direction of pedal motion, that is, foot travel or ankle rotation in the up or down directions.

Camera and Mirror Installation

The upper unit of the FCMU structure serves as a housing and mounting structure for a 16-mm data-acquisition camera and a mirror assembly as indicated in figure 22. The mirror assembly provides a split field of view for the camera. The camera is mounted on a standard camera mount tongue-and-groove track which permits the camera to be easily installed and removed through an opening in the back of the FCMU for changing the film magazine and adjusting the lens settings. (The camera is stored separately from the FCMU prior to the conduct of the experiment.)

The mirror assembly is an integral part of the mounting track and is permanently attached to the FCMU so that the alinement of the camera and mirrors can be maintained. A sheet-metal hood on the front face of the FCMU protects the mirrors from damage. The mirrors are arranged to reflect two views to the camera through the 18-mm lens. These views are about 11.8° by 32.3° each and are centered along axes parallel to the principal axes in the forward and downward directions. Both views are recorded on the same frame of the camera film. The camera will be operated at framing speeds of 2, 6, and 24 frames per second for different portions of the experiment.

FCMU Operational Systems

Schematics of the pneumatic and electrical subsystems are given in figures 25 and 26. A list of some of the operating characteristics is shown in table V.

In the FCMU system the propellant, nitrogen gas, is stored in the spherical PSS which has a permanently attached pressure regulator assembly. This assembly contains a manual shut-off valve, filter, charging port, pressure-relief valve, tank-pressure gage, and a quick-disconnect output fitting. A flexible hose from the backpack connects the output of the regulator assembly to an electric shut-off valve and terminates in a quick-disconnect outlet fitting at the base of the backpack. Another flexible hose from the FCMU is connected to this outlet during the experiment setup operation. This hose connects through an inlet fitting under the back of the FCMU seat to a manifold in the lower structural unit. A flexible hose is also used inside the upper structural unit to accommodate the height adjustment between the upper and lower units of the FCMU. From the manifold, the gas is carried to the valve assemblies by rigid tubing and then to the individual thrusters by small flexible hoses.

The PSS is charged from the Skylab nitrogen storage system by means of the charging port on the pressure regulator. The Skylab nitrogen storage pressure initially will be about 2070 N/cm^2 (3000 lb/in^2) which provides a charge of about 5.4 kilograms (12 lb) of gas in the bottle at the time of the OWS launching. However, the pressure is expected to be considerably below this value by the time experiment T020 is scheduled because of usage for other purposes. Minimum practical recharge pressure is considered to be about 690 N/cm^2 (1000 lb/in^2) which would provide a charge of about 1.4 kilograms (3 lb) of gas. Regulated pressure for the FCMU system is 100(±7) N/cm^2 (145(±10) lb/in^2) with a maximum flow rate of about 22.6 grams per second (0.05 lb/sec) produced by simultaneous operation of two vertical and two horizontal thrusters.

Electrical power is required for operation of the gas shut-off valve in the backpack and the data-acquisition camera in the FCMU. Power is required to hold the valve in the closed position in order to block gas flow to the thruster system. This power is supplied by a rechargeable, 28-volt, 6-ampere-hour, nickel-cadmium battery. A recharge station for this battery is provided at the mounting fixture for the M509 experiment located adjacent to the T020 equipment. A quick-disconnect battery mount and cable connector on the backpack facilitate installation and removal of the battery. Less than 2 amperes of current are drawn from the battery with both the valve and camera operating. This power is routed through an umbilical from the backpack to a small switchbox used by the test subject to control operation of the solenoid valve and the camera. This switchbox clips onto the harness or pressure-suit equipment near the subject's waist.

Power to the camera is routed through a quick acting connector at the base of the backpack into an electrical line attached to the gas-supply umbilical. A remote-control switch for setting the camera framing speed is mounted at the back of the FCMU near the umbilical connection.

Protection against electrical short circuits is provided by a thermal overload switch built into the battery and by a fuse in the camera. The camera has small built-in lights indicating whether or not it is operating and when it is out of film. These lights are visible through the access holes provided in the FCMU.

APPENDIX C

EFFECTS OF UNBALANCED PITCH THRUSTERS ON MANEUVERING TASKS

As a result of attempting to provide a fairly compact configuration with a reasonably small number of thrusters, the use of thruster offset from the center of mass in only one direction was employed. The implication of this unbalanced thruster arrangement on the maneuvering tasks is discussed in this appendix.

To illustrate the source of the interaction on translational motion due to the unbalanced thruster inputs, two cases of the calculated responses of the FCMU to commanded pitch attitude changes of 10° and 90° are given in figure 27. Both cases assume the initial condition of zero translation velocity. In the case of a commanded 10° pitch-up maneuver, the operator is assumed to have fired the aft facing thrusters for slightly over 1 second in order to initiate the pitching motion. This also produced a forward motion of the center of gravity. About 3 seconds later as the 10° pitch attitude was approached, the opposite facing thrusters were fired for the same period of about 1 second in order to arrest the pitching motion. Inasmuch as the FCMU had rotated about 10° from the starting position, the translational deceleration of the center of gravity produced by the pitch-down thrusters did not completely cancel the initial induced forward motion. The residual velocity increment ΔV was only about 0.003 meter per second (0.01 ft/sec) directed halfway between the original and final pitch attitudes. This small velocity is considered to have a negligible effect on the overall maneuvering task.

In the case of the 90° pitch-up maneuver, the residual velocity was much larger, $\Delta V = 0.037$ meter per second (0.12 ft/sec), due to the fact that the two velocity vectors were no longer closely alined in opposing directions. Note, however, that the residual velocity was still directed halfway between the two pitch attitudes. Following this line of analysis, the maximum induced velocity is produced by an attitude change of 180°. Here the two induced velocity vectors are alined in the same direction. In actual circumstances, however, this particular case probably would seldom occur, inasmuch as the up-and-down thrusting capabilities of the FCMU system generally require pitch changes only up to 90°.

The calculated trajectories of the center of mass of the maneuvering system in the X_iZ_i-plane for several pitch attitude changes are given in figure 28 for the initial condition of zero translational velocity. Positions of the center of gravity for every 5 seconds after initiation of the attitude change are indicated by each point. These trajectories illustrate the buildup of the induced motions in greater detail than covered in the previous figure.

Various piloting techniques can be employed either to cancel the induced translational velocity or to put it to use in accomplishing the subsequent maneuvers. For example, if it is desired to cancel the induced velocity, the operator has merely to fire the up-firing thrusters (down-facing nozzles) for a very brief moment as he passes the halfway point in the attitude change. (In the case of the 90° maneuver, the up-thrusting time was calculated to be about three-fourths of a second for the assumed conditions.) This scheme requires the attention and judgment on the part of the operator, but experience with the FCMU simulators has shown this to be an effective technique which is quickly learned.

As an alternate technique to canceling the induced translational velocity, the operator may elect to utilize this motion in assisting a subsequent translational maneuver. In this event, the operator will learn to overshoot or undershoot the line of sight to his target by a small amount, depending on the maneuver involved. He will then fire the translational thruster such that the combined translational velocities will carry him to the desired destination. Here again, of course, the controlling technique appears to be rather complex, but simulation experience indicates that the induced velocities do not pose serious problems, at least for the maneuvers studied.

The calculated cost in fuel (pressurized nitrogen gas) to perform various pitch changes up to 180° is given in figure 29. This cost is in terms of thrusting impulse used by the attitude thrusters to produce a given pitch change and by the up-firing thrusters to cancel the induced translational velocity. For the larger attitude changes, the translation correction has nearly doubled the cost of making the change without the correction. The maximum total fuel used is for the 180° maneuver; this represents less than 1 percent of the nominal available fuel.

REFERENCES

1. Anon.: Gemini Summary Conference. NASA SP-138, 1967, pp. 91-106.
2. Anon.: Skylab. Astronaut. & Aeronaut., vol. 9, no. 6, June 1971, pp. 20-77.
3. Thomas, David F., Jr.; Bird, John D.; and Hellbaum, Richard F.: Jet Shoes – An Extravehicular Space Locomotion Device. NASA TN D-3809, 1967.
4. Cooper, George E.; and Harper, Robert P., Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

TABLE I.- FOOT-CONTROL LOGIC FOR FCMU

Commanded acceleration		Control input		Active thruster nozzle	
Axis	Direction	Left	Right	Left	Right
Pitch	Up	Toe up	Toe up	Aft	Aft
	Down	Toe down	Toe down	Fore	Fore
Yaw	Right	Toe up	Toe down[a]	Aft	Fore
	Left	Toe down[a]	Toe up	Fore	Aft
Translation	Up	Foot up	Foot up	Bottom	Bottom
	Down	Foot down	Foot down	Top	Top
Roll	Right	Foot up	Foot down[a]	Bottom	Top
	Left	Foot down[a]	Foot up	Top	Bottom

[a]Reference input for control, that is, toe down for yaw control and foot down for roll control.

TABLE II.- TYPICAL SEQUENCE OF TASKS TO BE PERFORMED DURING EXPERIMENT T020

First crewman	Second crewman
Unstow FCMU and backpack Install bottle and battery Install FCMU camera Check out FCMU operation Don FCMU [a]	Unstow pressure bottle and battery Unstow cameras and mirror assembly Install remote camera Unstow and install high-intensity lights
Pressurize FCMU Check all adjustments and settings Position subject for test run	
Start FCMU camera	Turn on lights (high-intensity); start remote camera; and check FCMU camera operation
Conduct test run	Observe test run and act as safety tetherman
Stop FCMU camera and depressurize	Stop camera; turn off lights
Reposition to read gas pressure; record comments	
Stow FCMU Recharge bottle and battery	Stow cameras, lights

[a] Assisted by second crewman for pressure-suited tests.

TABLE III.- NOMINAL TIMELINE AND UTILIZATION OF EXPENDABLES FOR CONDUCT OF EXPERIMENT T020 IN TWO SESSIONS

Activity	Subject	Run	Time, hr:min	FCMU film, ft (a)	PSS impulse used (b)
Shirt-sleeve mode; session I					
Set up equipment; subject A don FCMU	A, B		:15	0	0
Two practice maneuver sequences, comments [c]	A	1, 2	:42	0	300
Record maneuver sequence, comments	A	3	:22	[d] 90	150
Record minimum impulse	A	4	:01	[e] 10	0
Change PSS, FCMU camera magazine; subject B don FCMU	A, B		:10	0	0
Subject B repeat practice and record	B	1 to 4	1:05	100	450
Stow equipment film; recharge PSS and battery	A, B		:25	0	0
			Total 3:00		
Pressure-suit mode; session II					
Set up equipment; subject A don FCMU	A, B		:31	0	0
One practice maneuver sequence, comments	A	5	:26	0	250
Record maneuver sequence, comments	A	6	:27	[d] 90	200
Record minimum impulse	A	7	:01	[e] 10	0
Change PSS, FCMU camera magazine; subject B don FCMU	A, B		:31	0	0
Subject B repeat practice and record	B	5 to 7	:54	100	450
Stow equipment, film	A, B		:30	0	0
			Total 3:20		

[a] OWS camera (400-ft magazine) on same time, 2 fps.
[b] Nominal PSS charge is 2000 N-sec (450 lb-sec).
[c] Obtain PSS gage reading after each maneuver.
[d] FCMU camera (140-ft magazine), 2 and 6 fps.
[e] FCMU camera at 16 fps.

TABLE IV.- NOMINAL VALUES FOR THE FCMU SYSTEM CHARACTERISTICS

	SI Units	U.S. Customary Units
Weight:		
FCMU and backpack	32.7 kg	72 lb
PSS and battery (M509)	29.9 kg	66 lb
N_2 charge	3.6 kg	8 lb
Total	66.2 kg	146 lb
Equipment	66.2 kg	146 lb
Test subject	77.1 kg	170 lb
Pressure suit	31.8 kg	70 lb
Total	175.1 kg	386 lb
Principal moments of inertia:		
Pitch	43.4 to 52.9 kg-m^2	32 to 39 slug-ft^2
Roll	46.1 to 54.2 kg-m^2	34 to 40 slug-ft^2
Yaw	4.1 to 8.1 kg-m^2	3 to 6 slug-ft^2
Inclination of principal axes	19° to 23°	19° to 23°
Thruster size:		
Pitch-yaw[a]	136.1 g	0.3 lb
Roll-translation[a]	453.6 g	1.0 lb
Thruster location below c.m.	0.91 m	3 ft
Control acceleration:		
Pitch	3.3 to 2.7 deg/sec^2	3.3 to 2.7 deg/sec^2
Yaw	9.8 to 5.1 deg/sec^2	9.8 to 5.1 deg/sec^2
Roll	2.5 to 2.1 deg/sec^2	2.5 to 2.1 deg/sec^2
Translation	61 to 49 mm/sec^2	0.20 to 0.16 ft/sec^2
Translation-pitch[b]	18 to 15 mm/sec^2	0.06 to 0.05 ft/sec^2

[a] Each of four required.

[b] Translation due to unbalanced pitch thrusters.

TABLE V.- FCMU OPERATIONAL CHARACTERISTICS

	SI Units	U.S. Customary Units
Pressure system:		
PSS tank volume	24 600 cm^3	1500 in^3
Specific impulse (gaseous N_2)[a]	52 sec	52 sec
Recharge pressure[b]	2070 to 690 N/cm^2	3000 to 1000 lb/in^2
Regulator operating range	2070 to 170 N/cm^2	3000 to 250 lb/in^2
Regulated pressure	100(±7) N/cm^2	145(±10) lb/in^2
Relief valve cracking pressure	150 N/cm^2	220 lb/in^2
Usable gas in tank	5.4 kg at 2070 N/cm^2	12 lb at 3000 lb/in^2
	1.4 kg at 690 N/cm^2	3 lb at 1000 lb/in^2
Total impulse available in tank	2715 N-sec at 2070 N/cm^2	610 lb-sec at 3000 lb/in^2
	712 N-sec at 690 N/cm^2	160 lb-sec at 1000 lb/in^2
Maximum gas flow:		
Through pressure regulator	43 g/sec	0.010 lb/sec
Through pitch or yaw thrusters	63 g/sec	0.014 lb/sec
Through roll or translation thrusters	16.3 g/sec	0.036 lb/sec
Combined thruster operation	22.6 g/sec	0.050 lb/sec
Electrical system:		
Battery voltage		28 V
Battery capacity		6 A-h
Shut-off valve solenoid current[c]		1 A
Camera operating current		500 to 700 mA

[a] Based on results of development tests where nozzle was discharged into 34.5-kN/m^2 (5-psia) back pressure.

[b] Depends on OWS nitrogen storage system pressure.

[c] Valve is normally open, energized closed, so that no power is consumed while the FCMU is in operation.

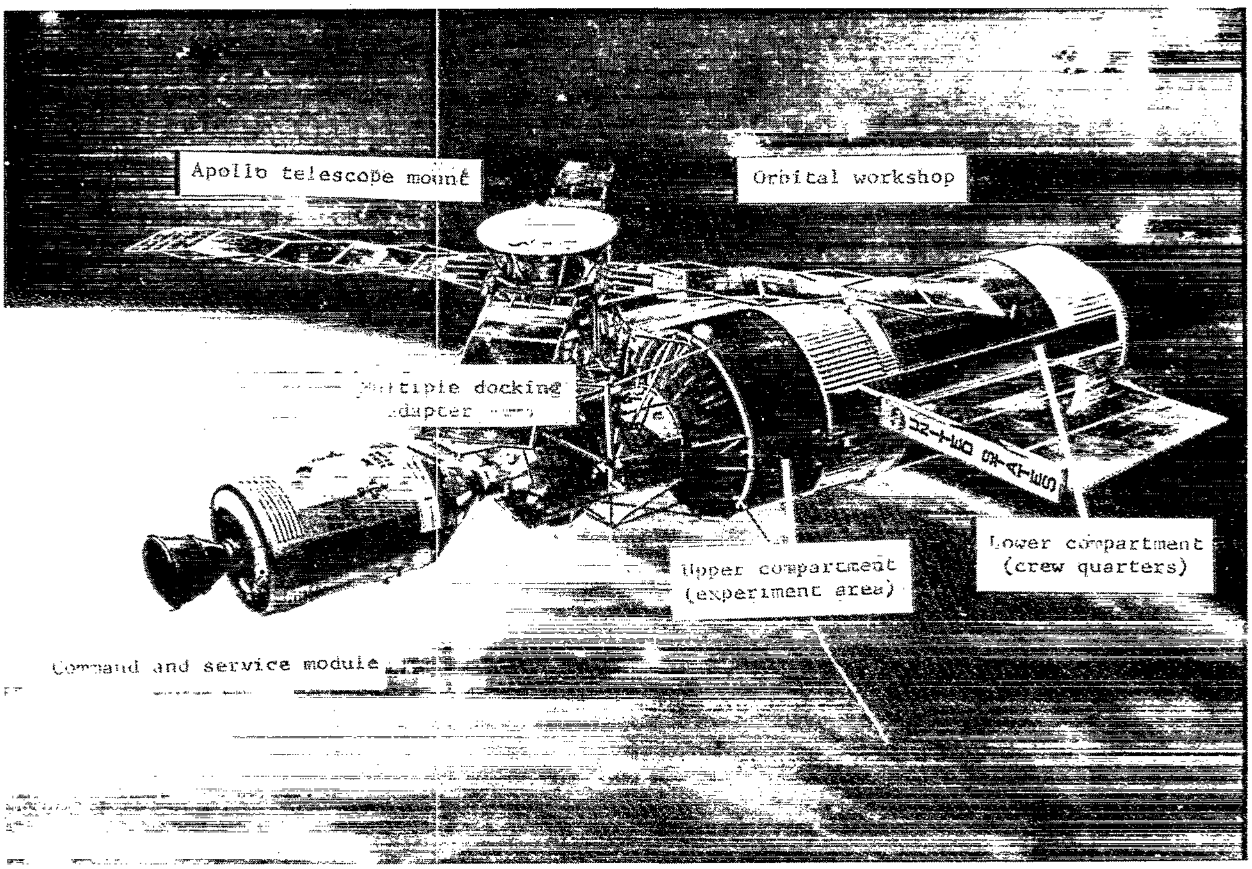


Figure 1.- Artist's conception of the Skylab orbital assembly.

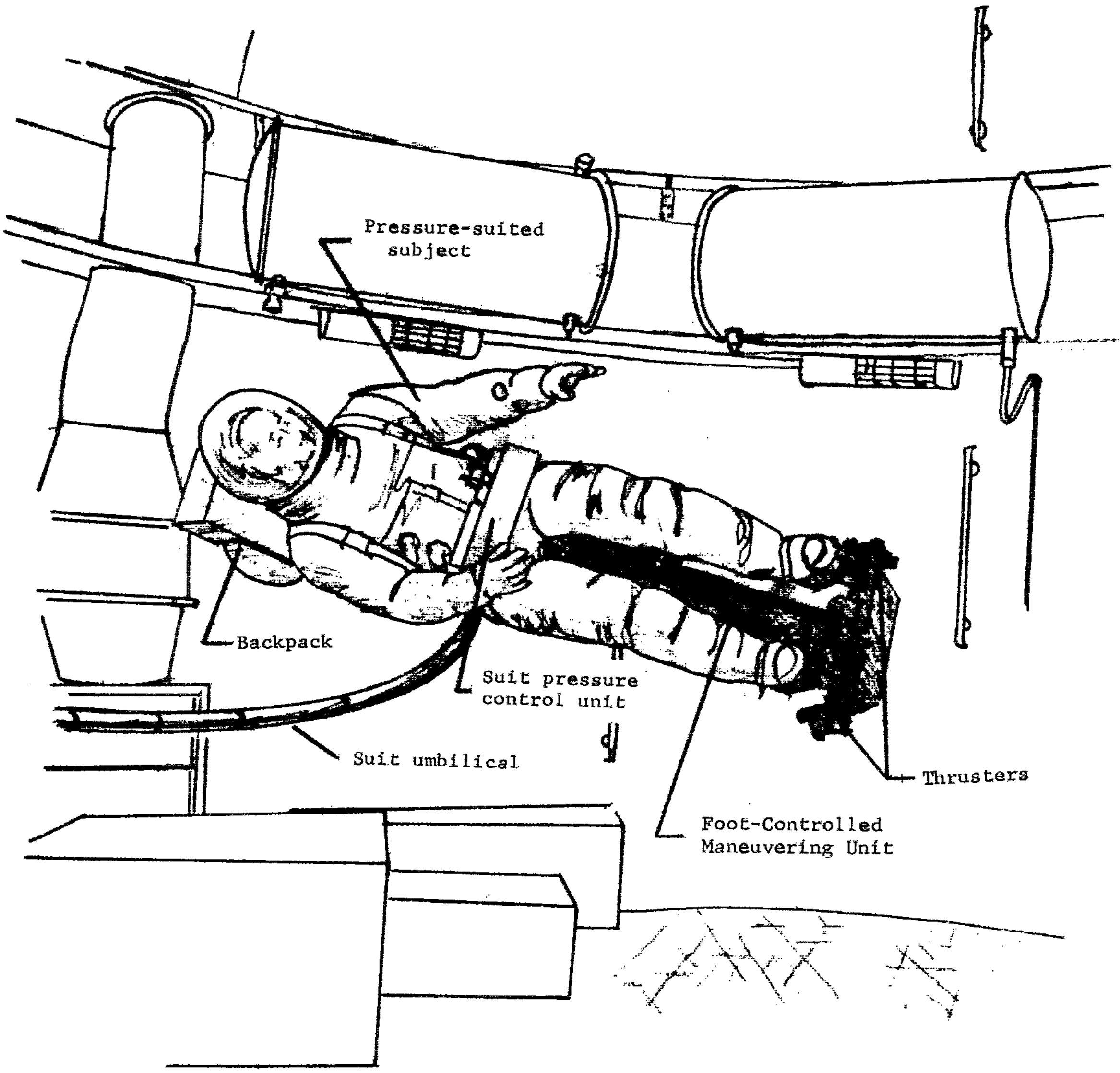


Figure 2.- Sketch of Foot-Controlled Maneuvering Unit being maneuvered inside the Skylab Orbital Workshop in the pressure-suited mode.

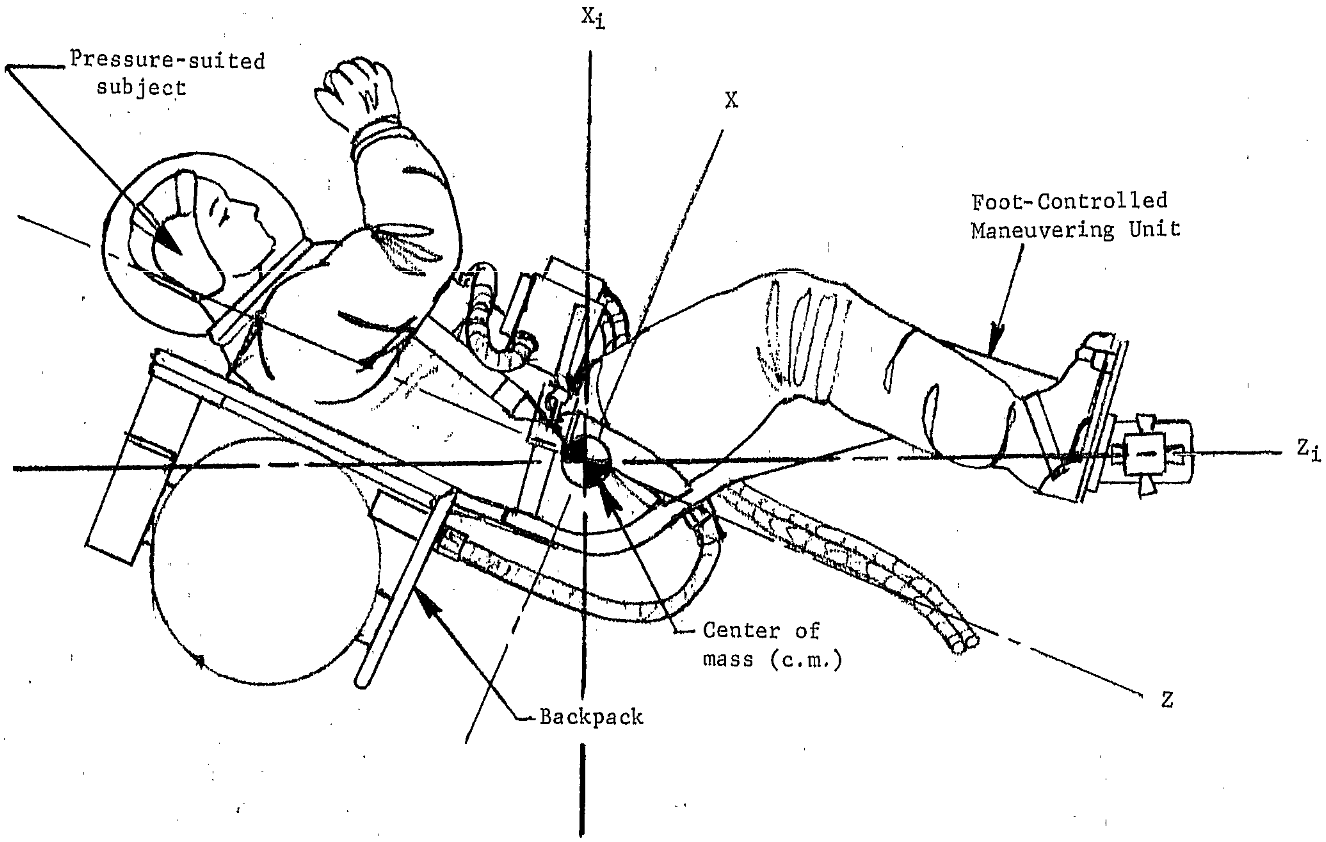
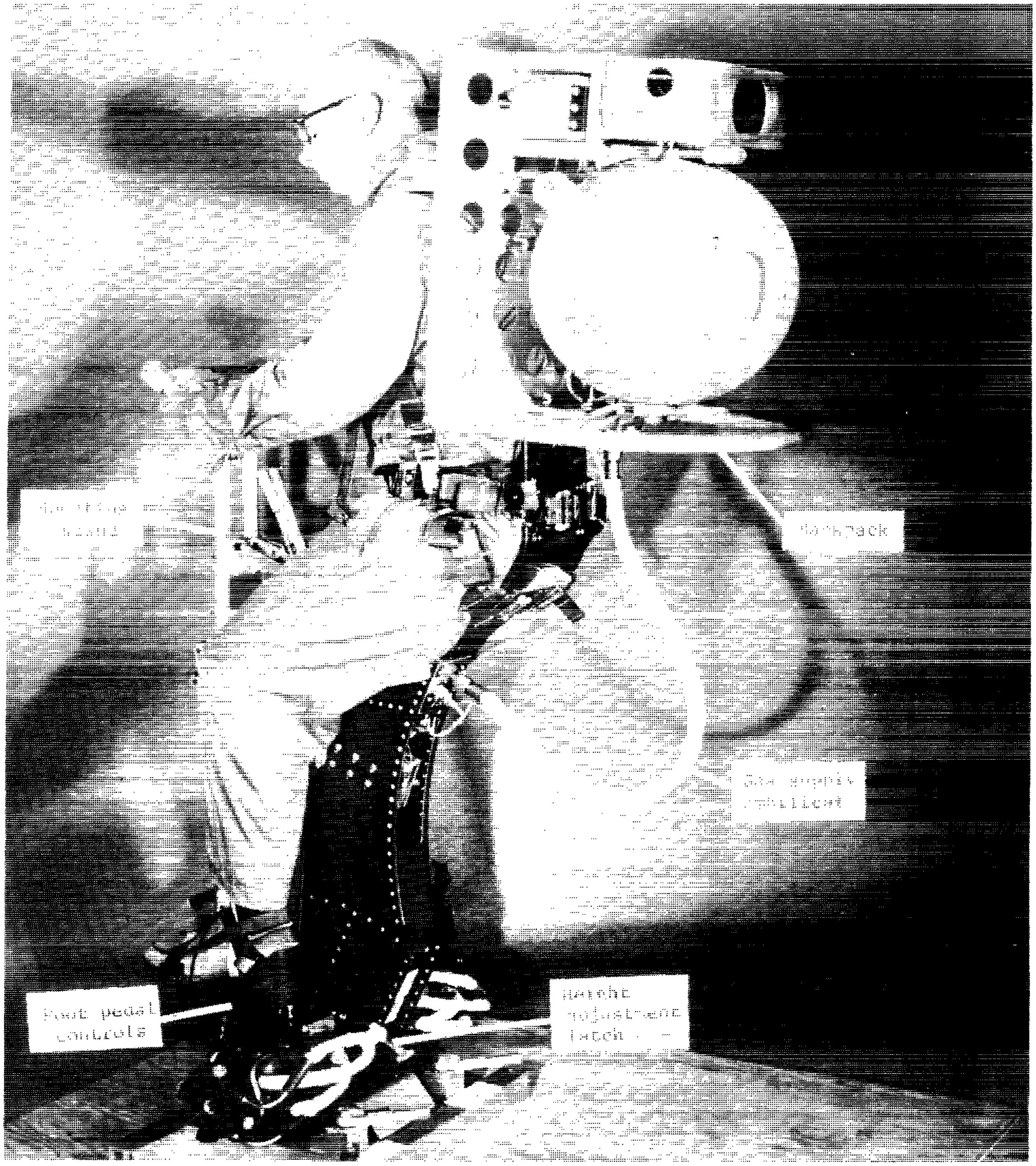


Figure 3.- Side-view sketch of flight experimental FCMU configuration.



L-71-950.1

Figure 4.- Photograph of a subject with a mockup of the FCMU in the test configuration on the mounting stand.

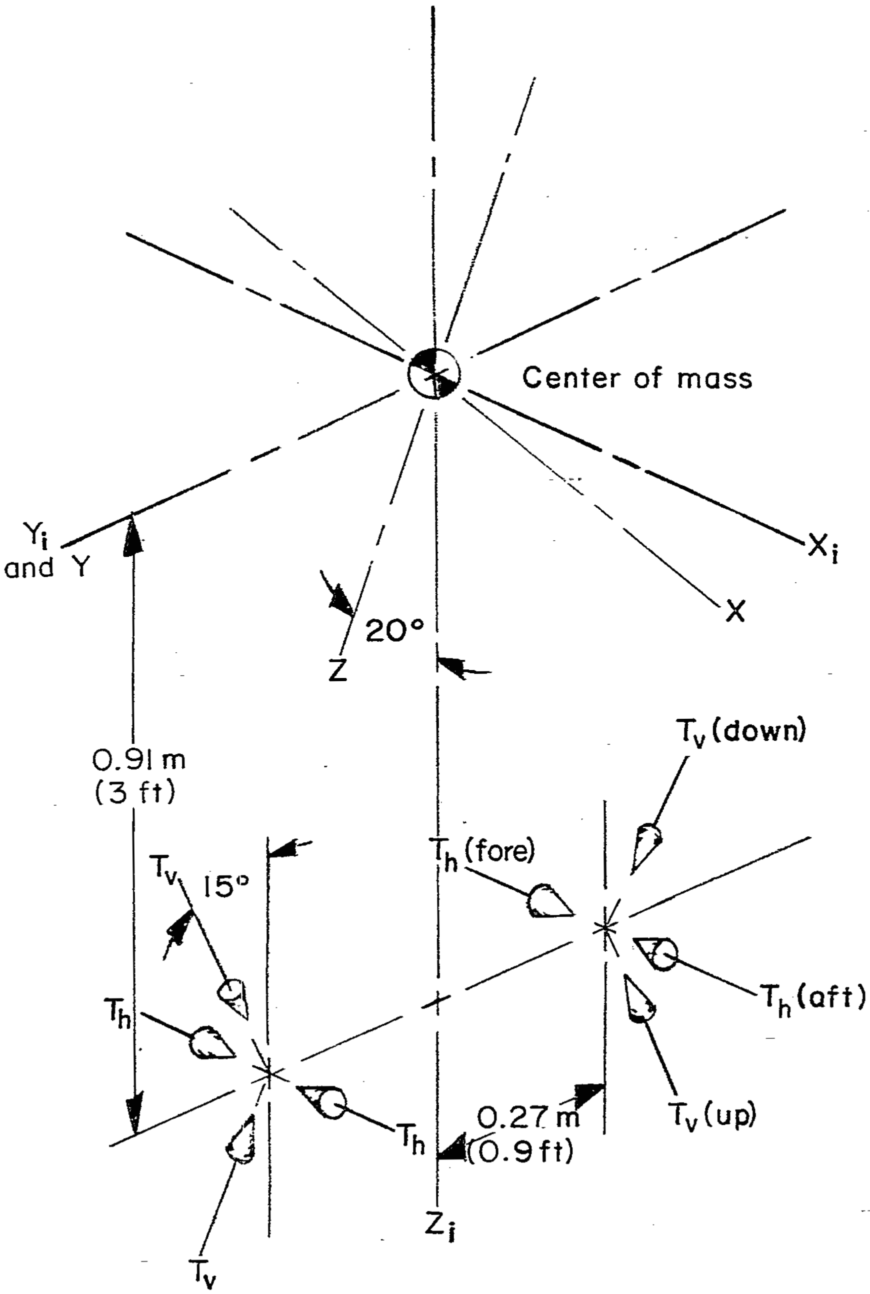


Figure 5.- Diagram of FCMU thruster configuration. $T_h \approx 1.3$ N (0.3 lb); $T_v \approx 4.4$ N (1 lb).

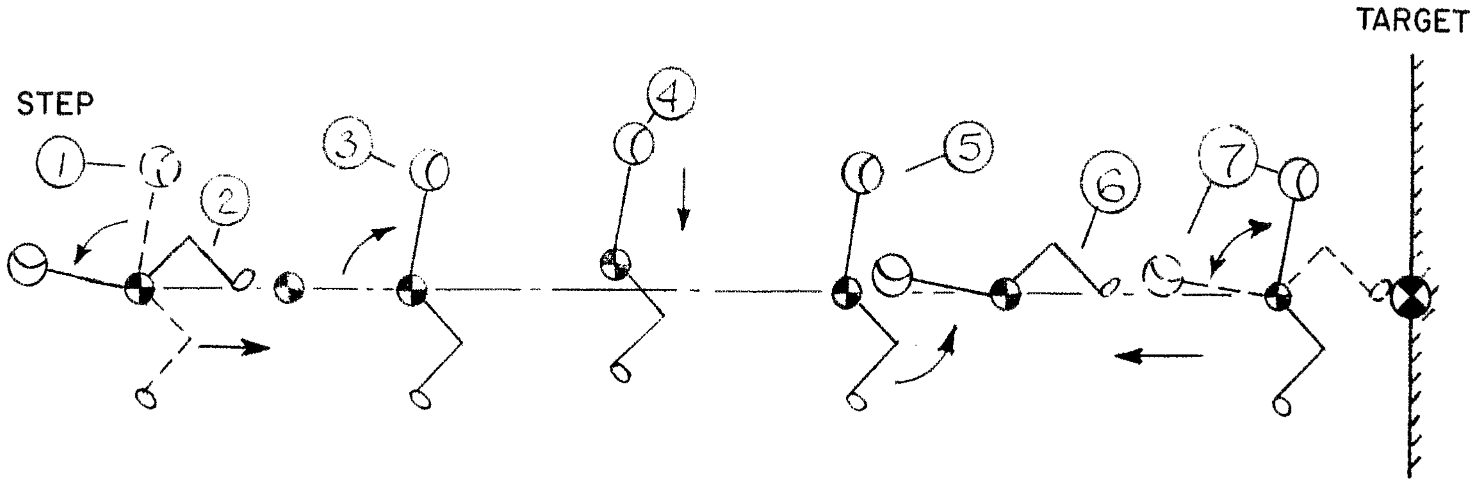


Figure 6.- General scheme for maneuvering with a Z_i-axis translation system.

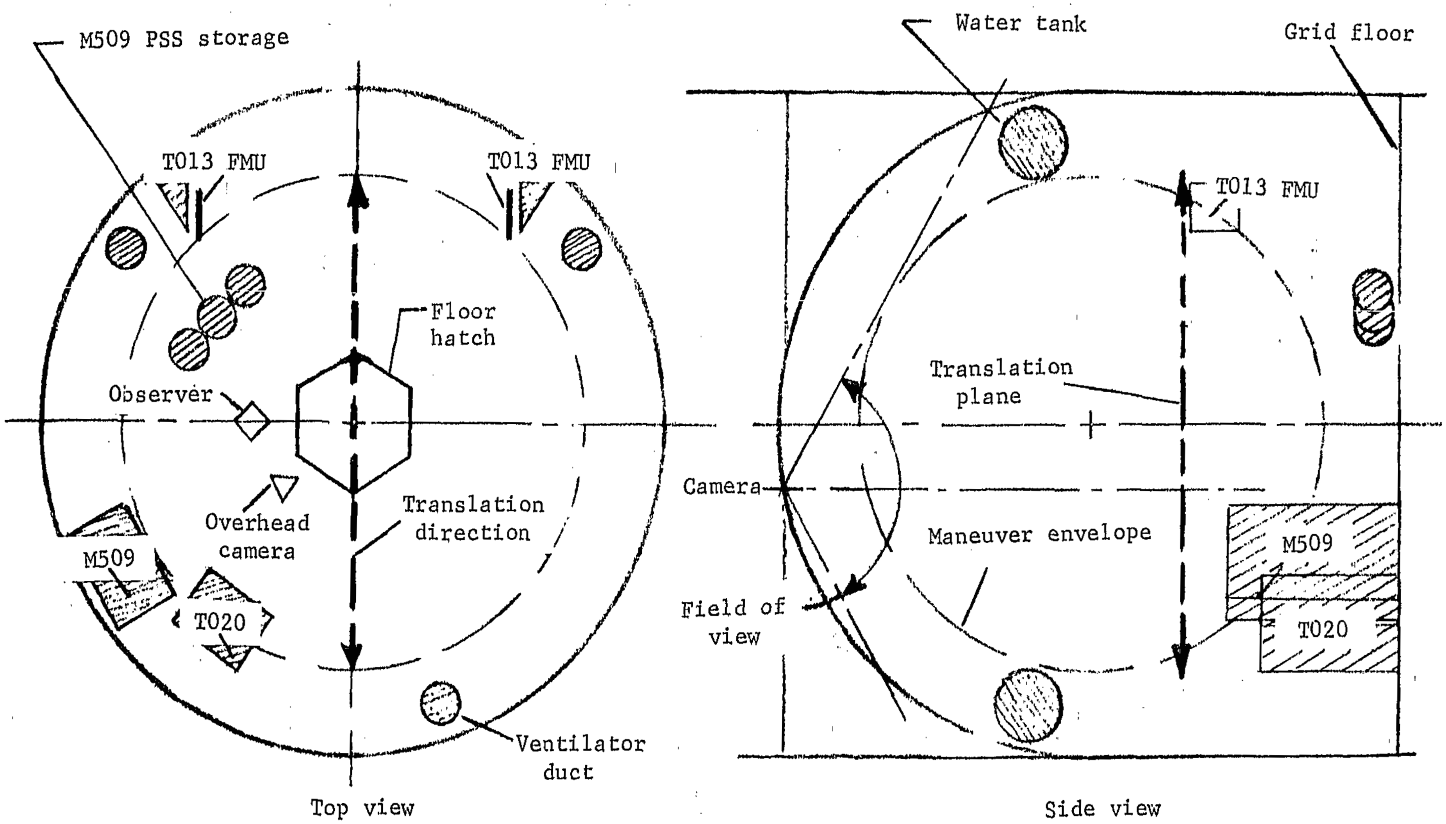
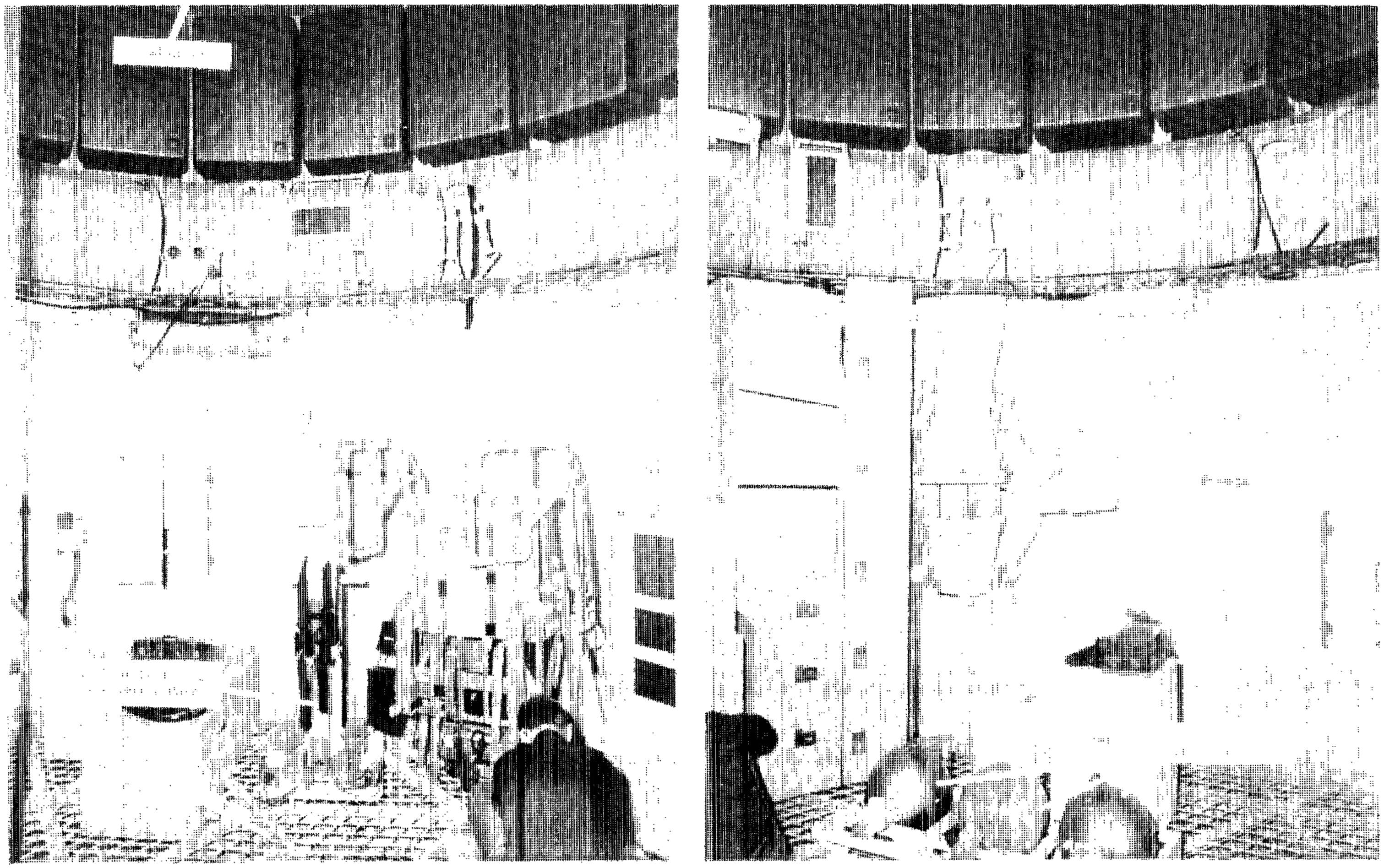


Figure 7.- Sketch showing orientation of experiment T020 in the OWS.



L-72-134

Figure 8.- Photographs of an OWS mockup showing areas of primary interest to experimental maneuvering.

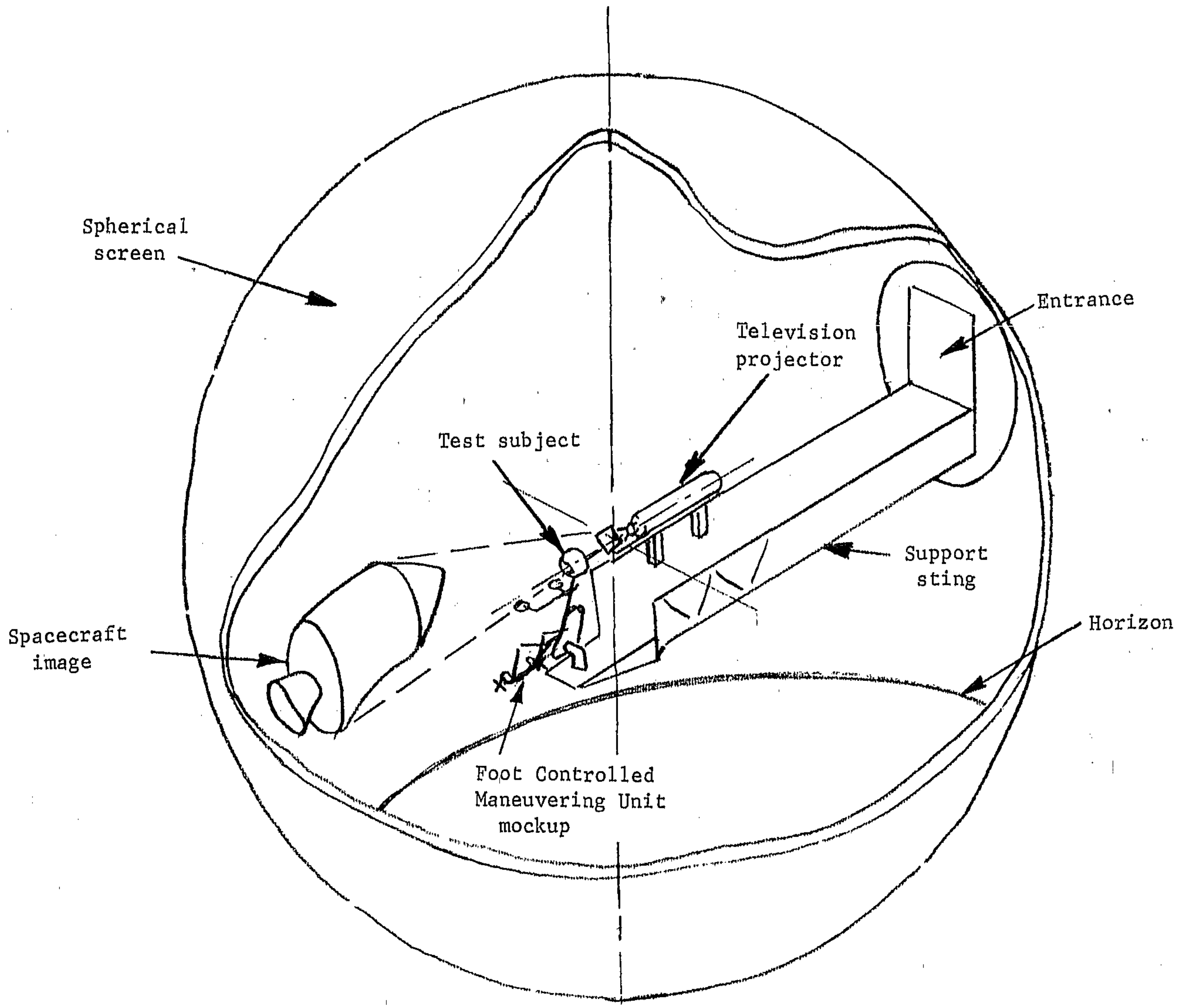
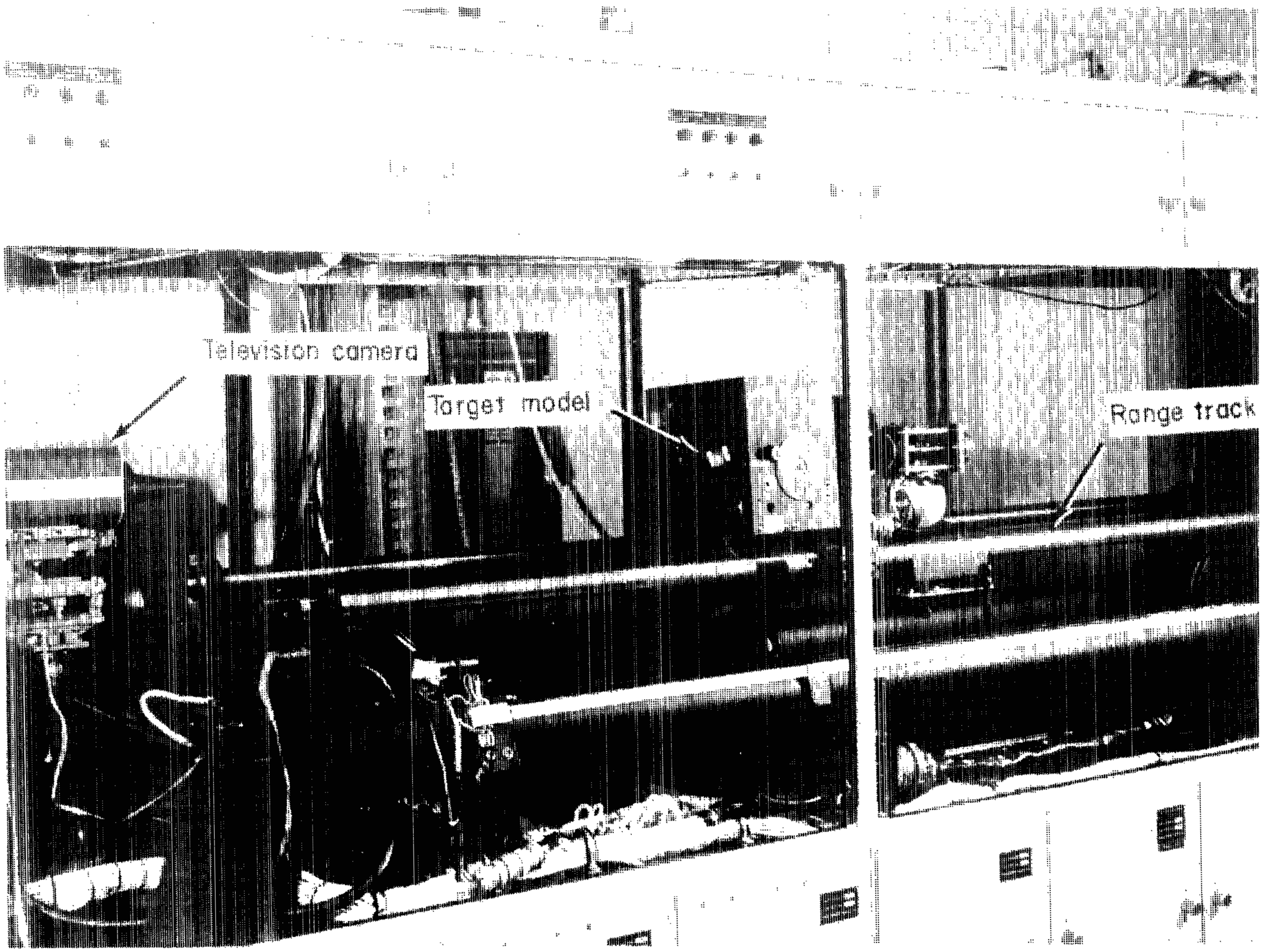
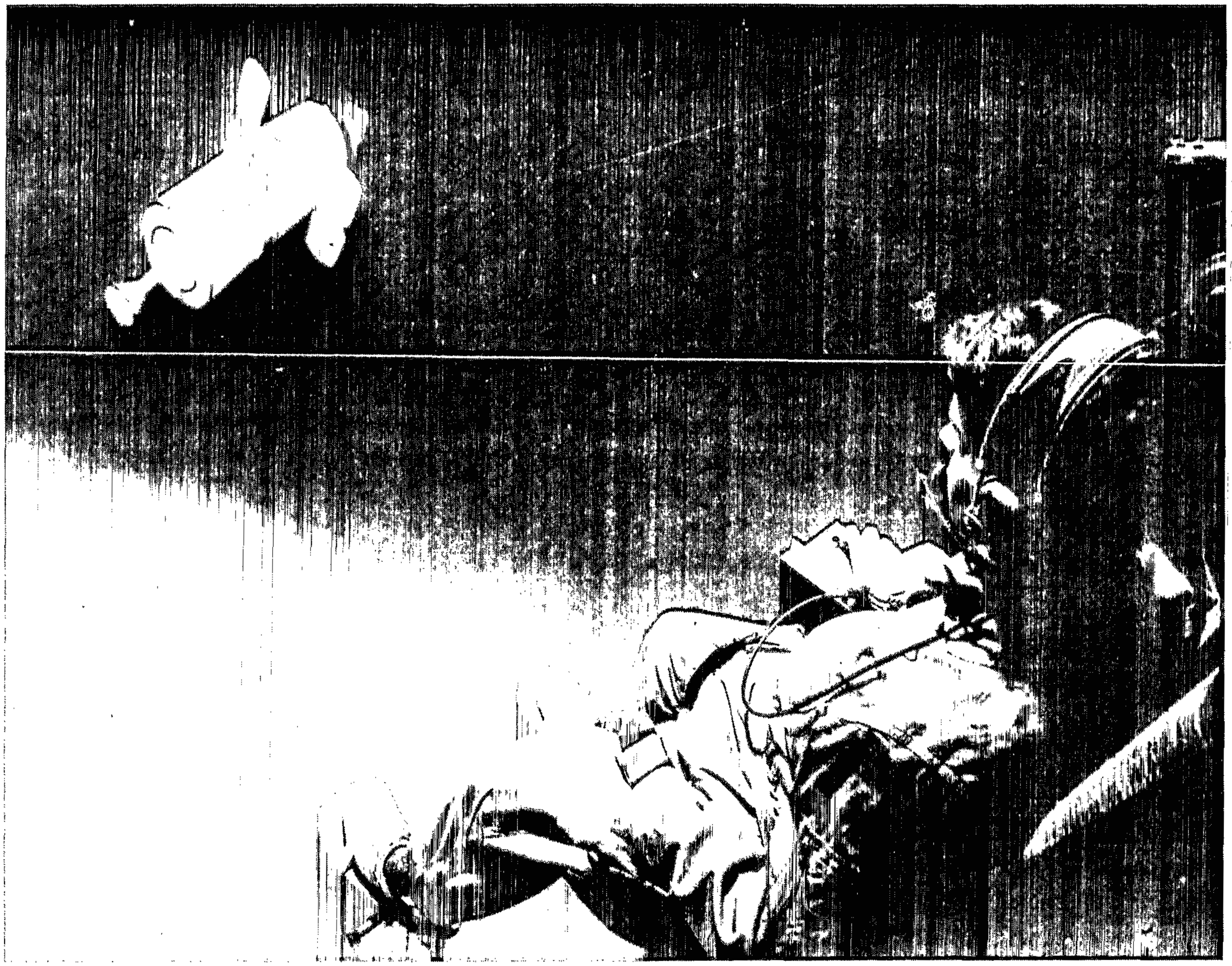


Figure 9.- Sketch of FCMU visual-task simulator projection and viewing system.



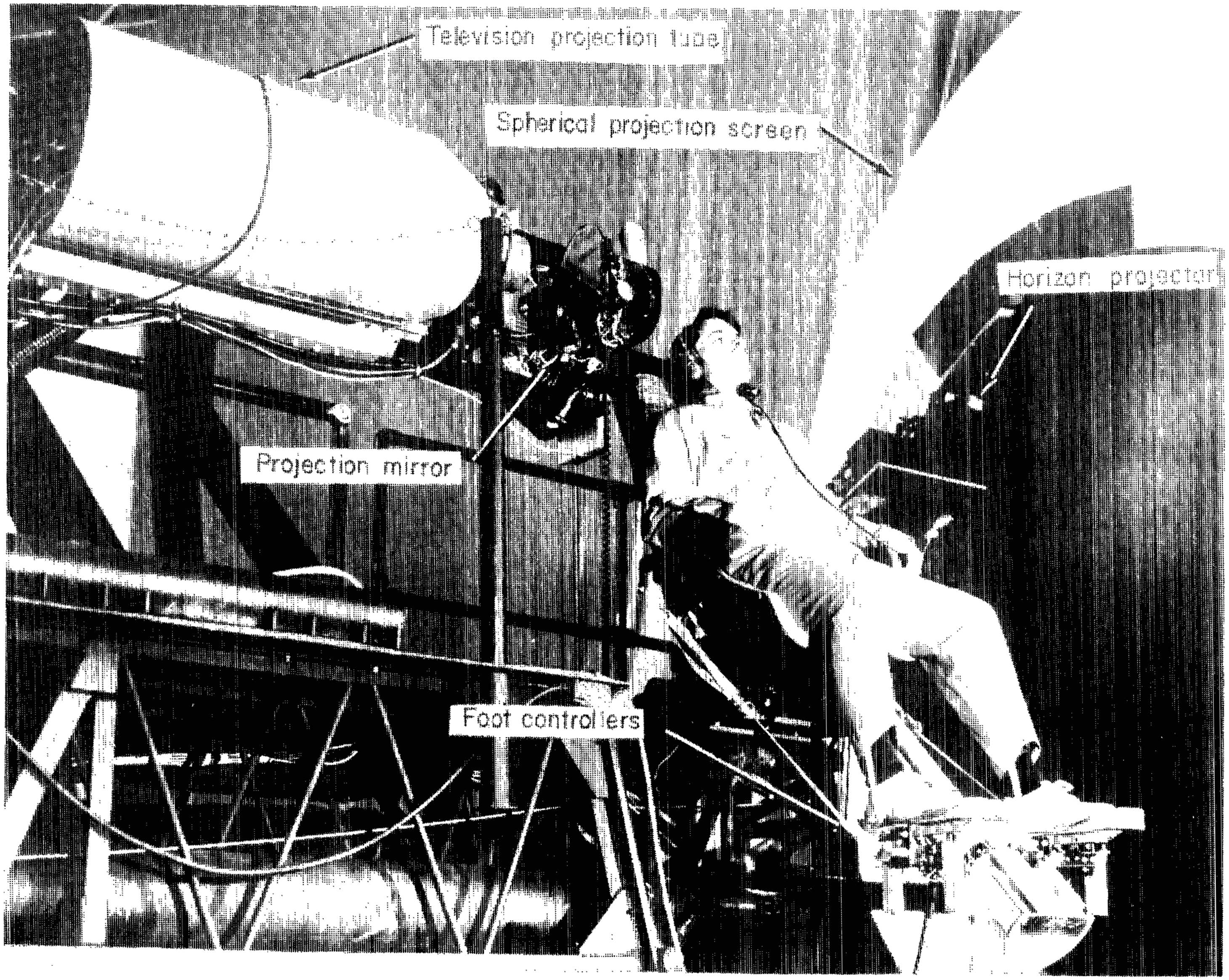
L-70-5338.1

Figure 10.- Photograph of television camera and spacecraft target-model drive system.



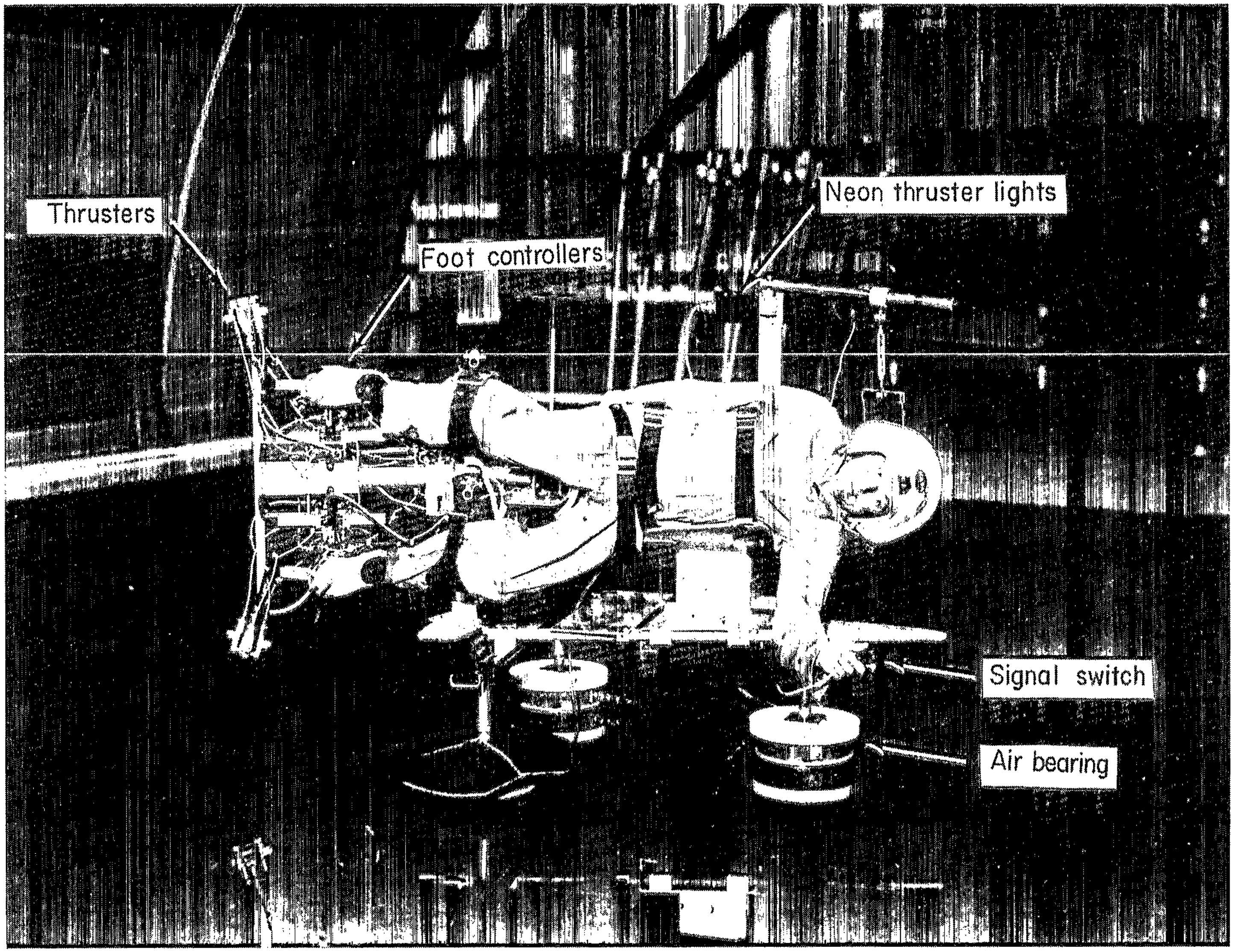
L-71-1439

Figure 11.- Photograph of subject viewing visual scene in the FCMU visual-task simulator.



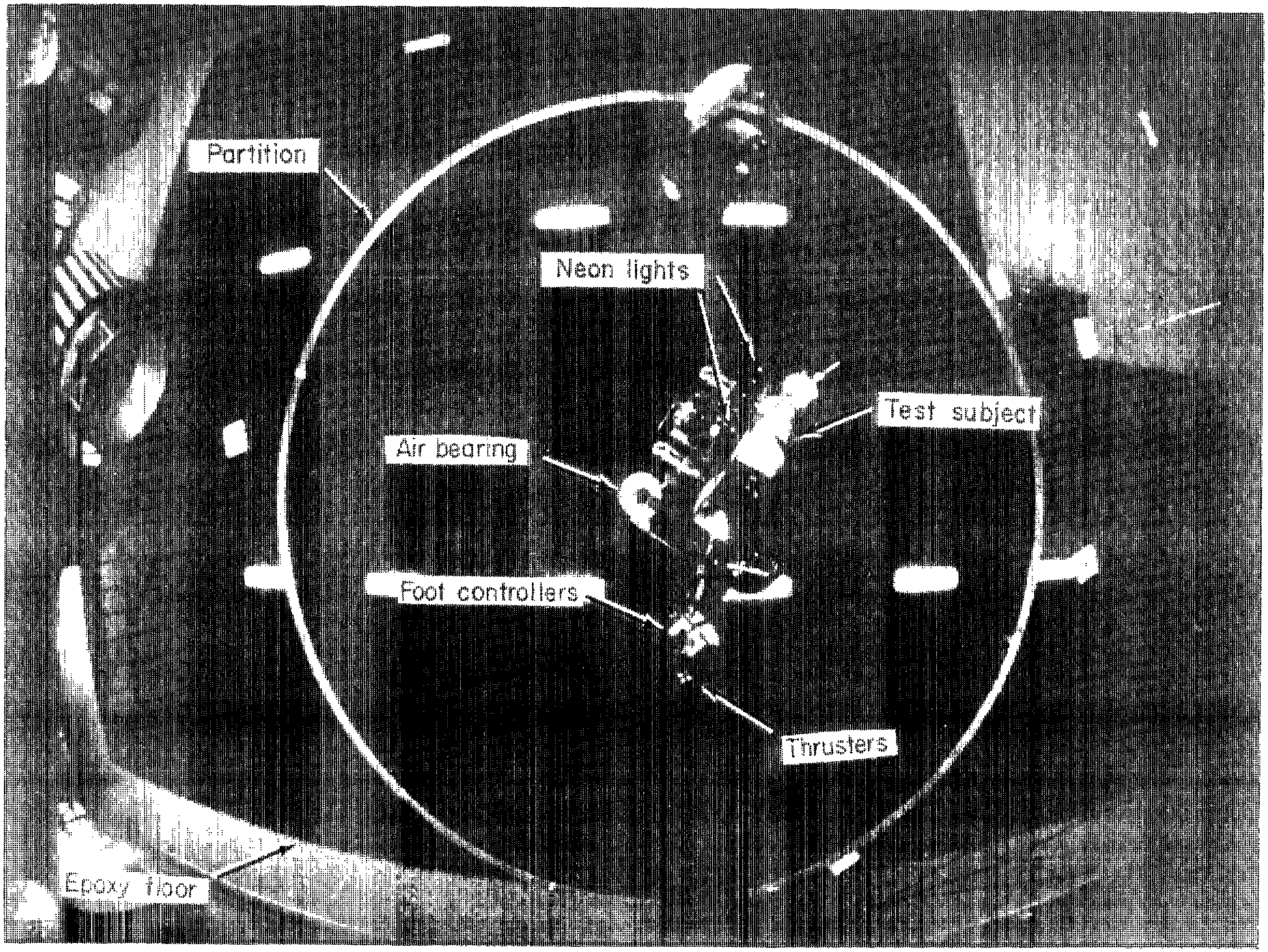
L-70-1855.1

Figure 12.- Photograph of details of FCMU visual-task simulator.



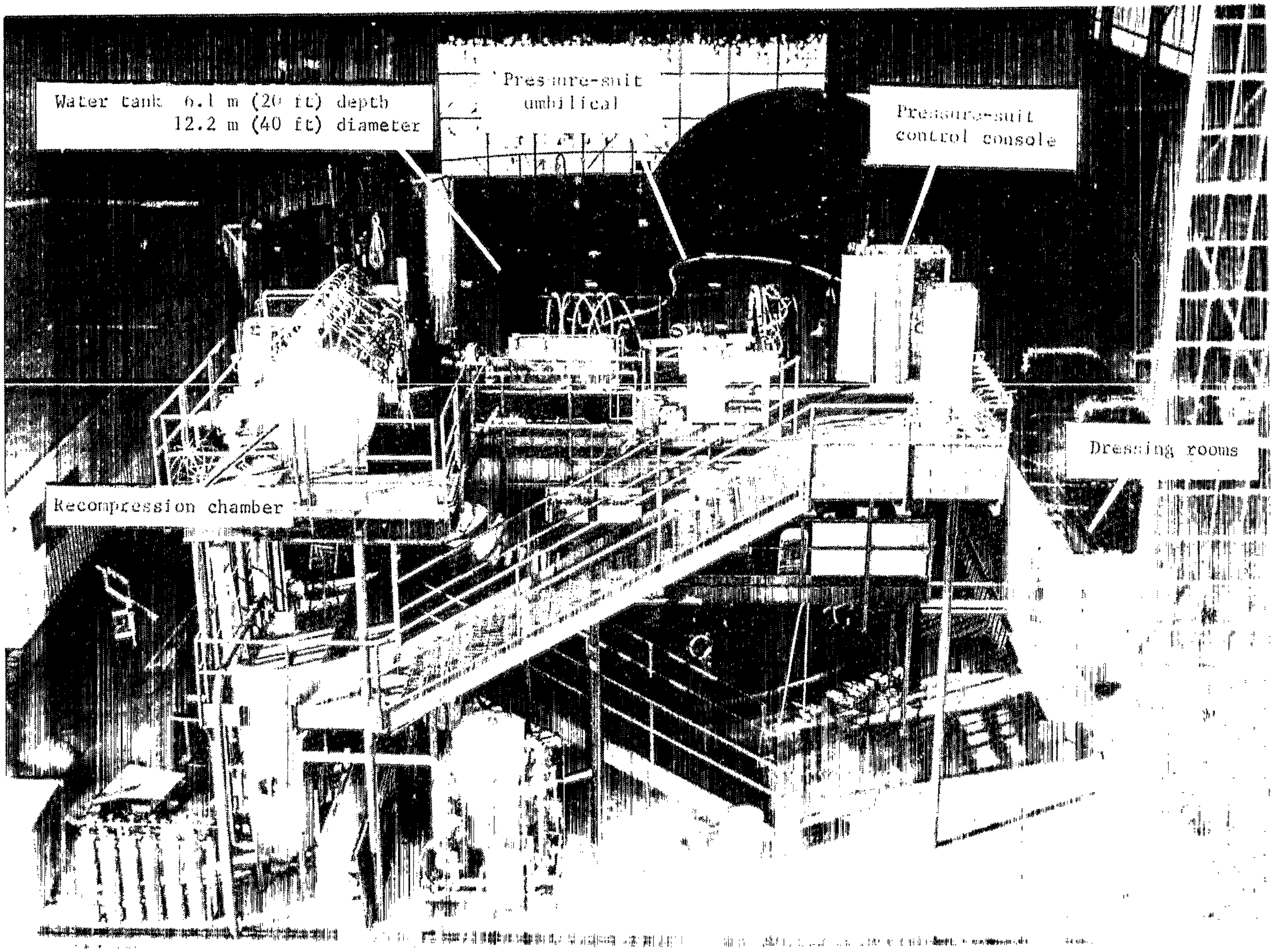
L-70-5337.1

Figure 13.- Photograph of the FCMU dynamic-air-bearing simulator showing subject in the pitch-plane unit.



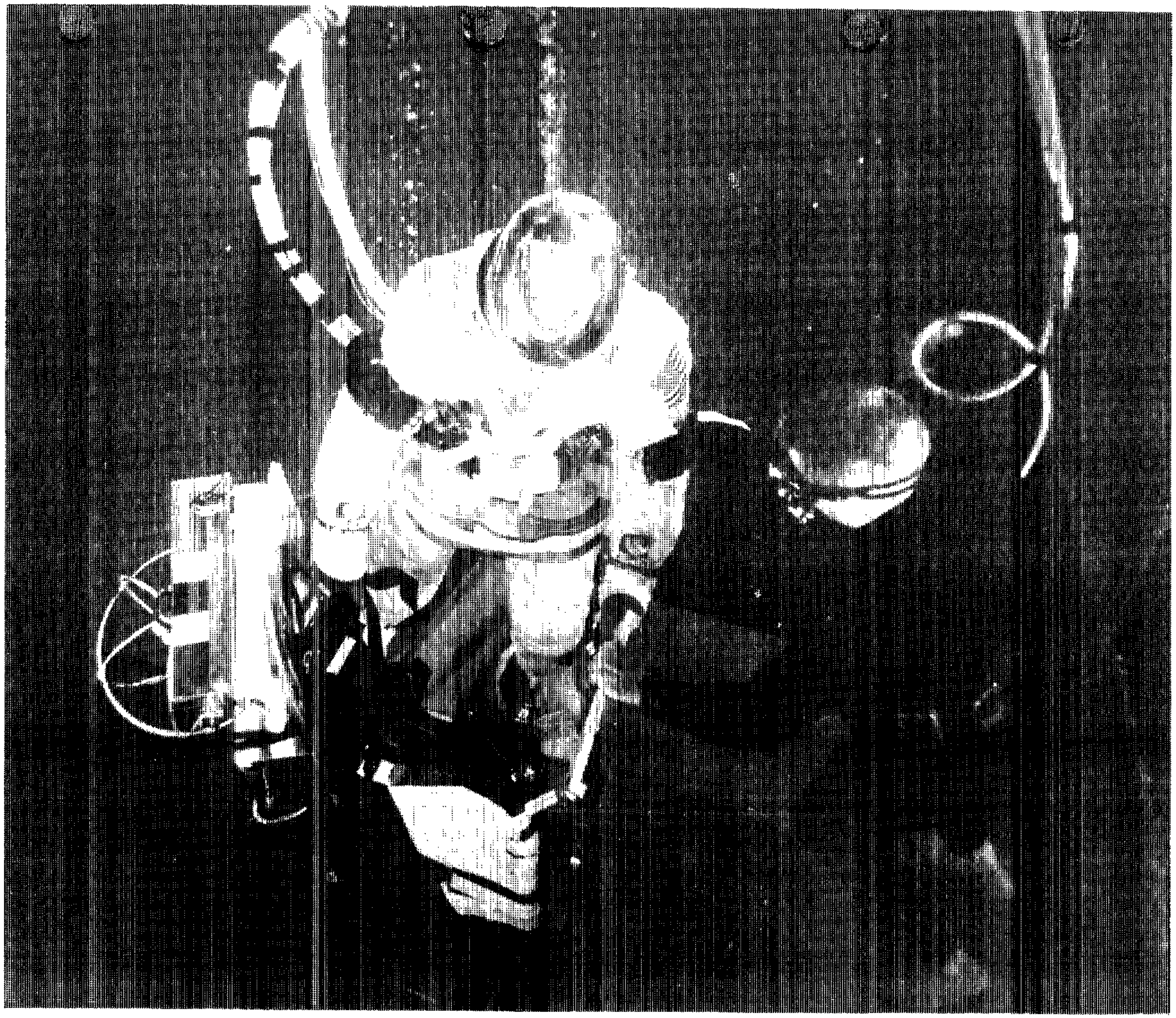
L-72-135

Figure 14.- Overhead view of the FCMU dynamic-air-bearing simulator taken with 16-mm motion-picture camera and a 5-mm wide-angle lens as used during experiment T020. Circular portion represents inside walls of the OWS.



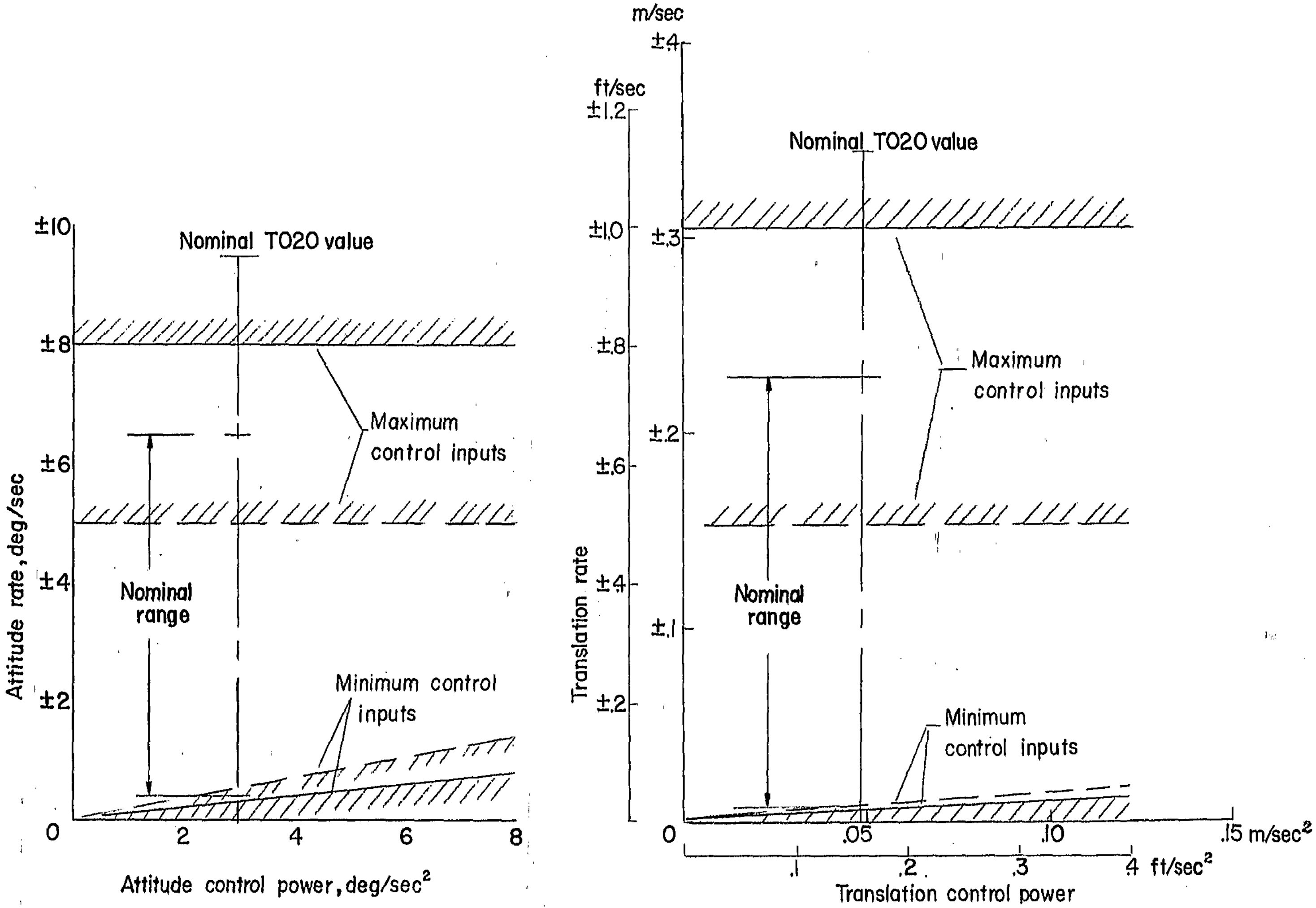
L-71-3034.1

Figure 15.- Photograph of the water immersion simulator used for zero-gravity simulation.



L-72-136

Figure 16.- Photograph of equipment procedure tests conducted in the water immersion simulator.



(a) Plot of attitude rate versus attitude control power.

(b) Plot of translation rate versus translation control power.

Figure 17.- Typical results obtained in the simulation studies of pilot performance with the FCMU.

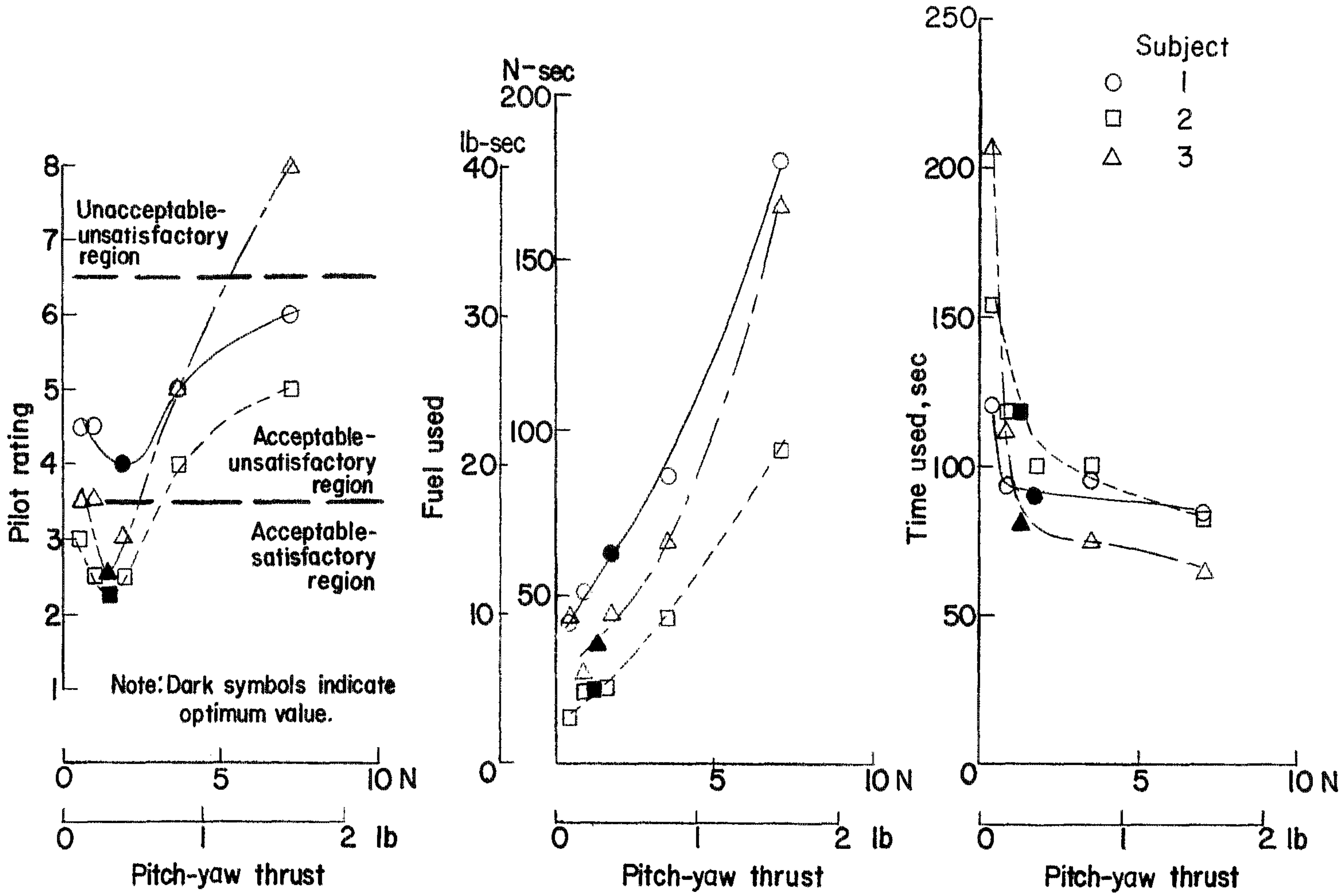
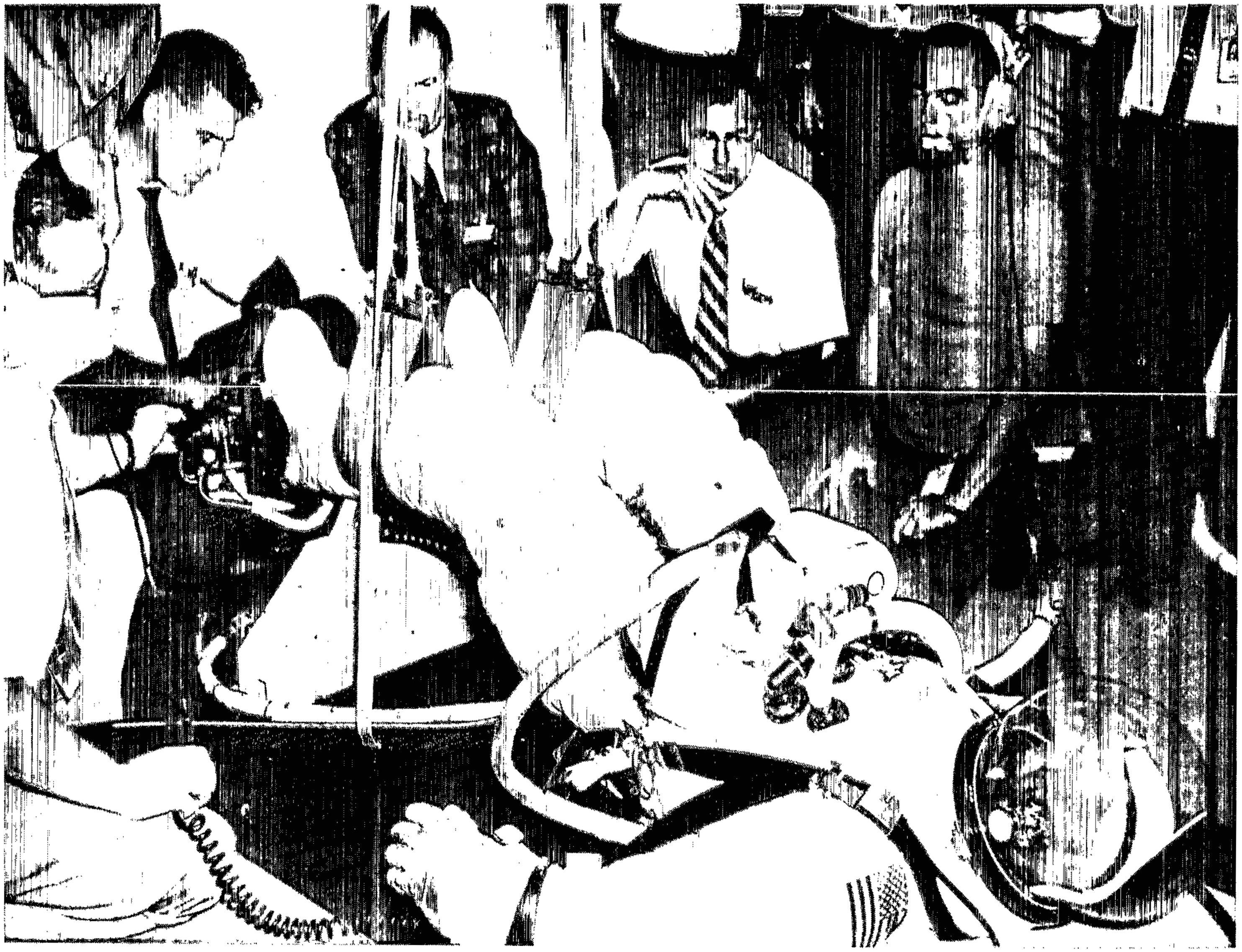
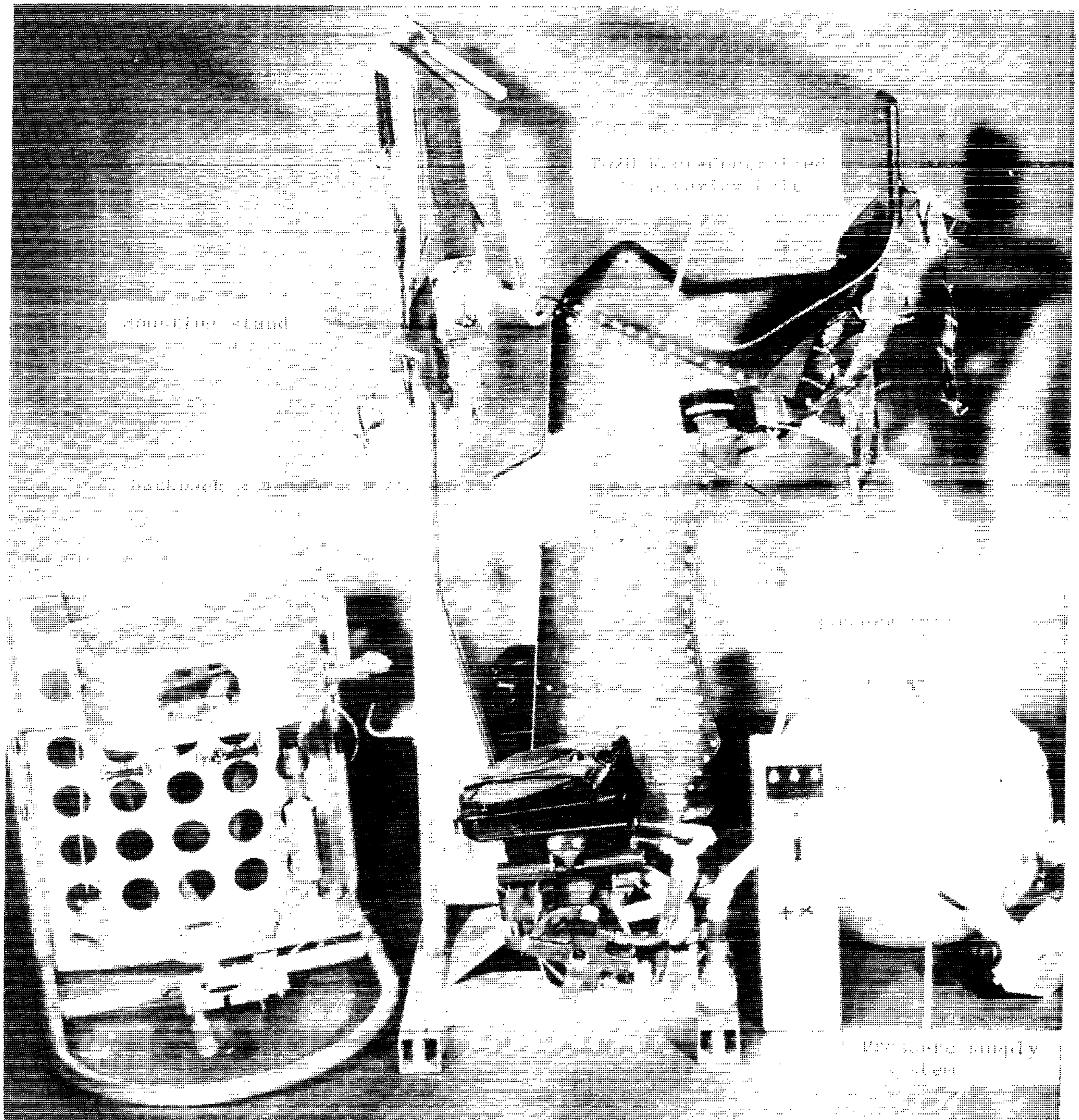


Figure 18.- Typical results from the visual-task simulation studies for three subjects with several pitch-yaw thruster values between 0.4 and 6.6 newtons (0.1 and 1.5 lb) each.



L-70-5856

Figure 19.- Photograph of special suit fit and function tests showing spring-supported slings used to minimize effects of leg-foot weight on pedal operation.



L-71-955.1

Figure 20.- Photograph of elements of the FCMU system.

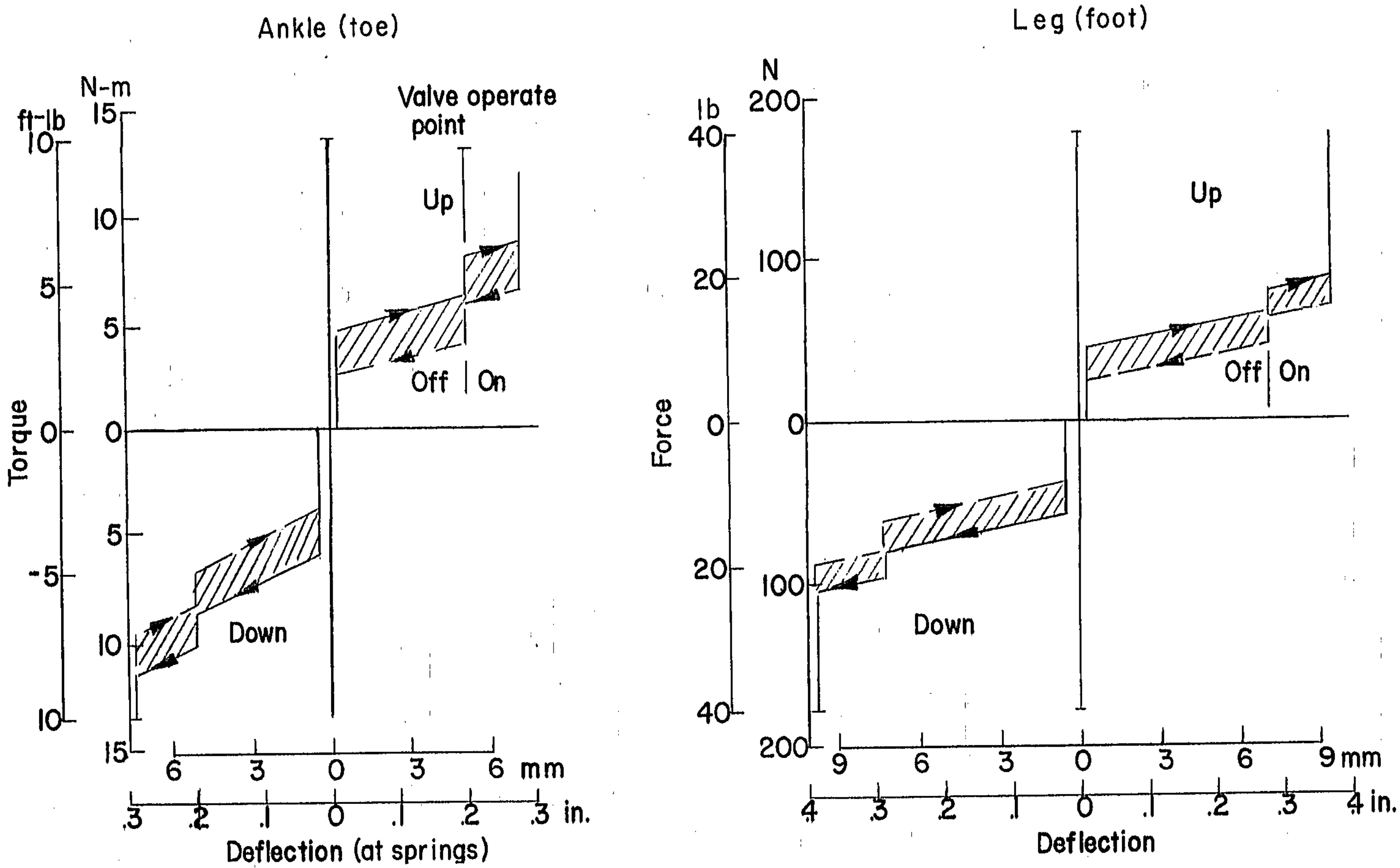
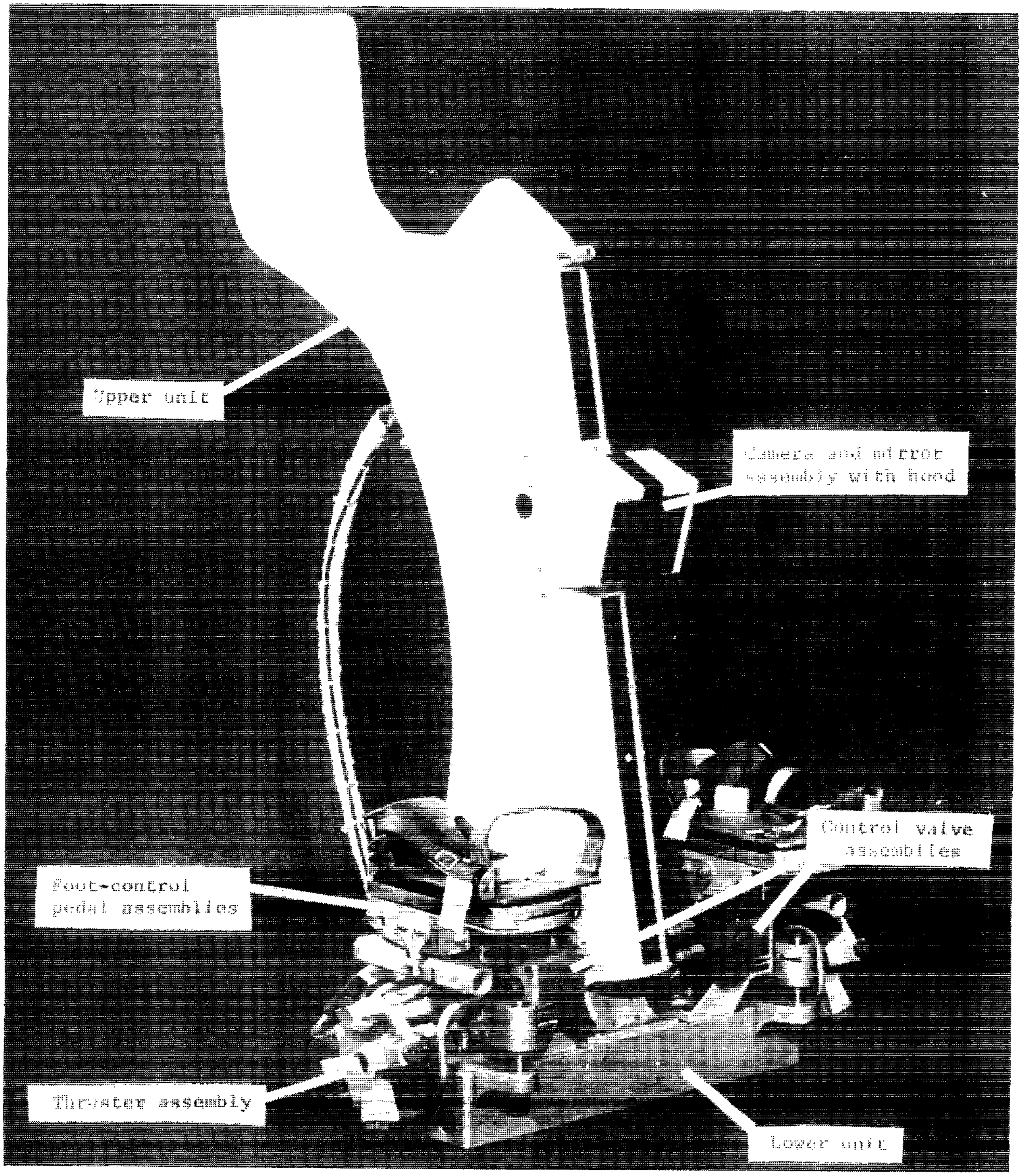


Figure 21.- Foot-controller spring-force characteristics with respect to pedal deflection.



L-71-9344.1

Figure 22.- Photograph of the qualification test unit for the experiment T020 flight hardware showing details of the FCMU.

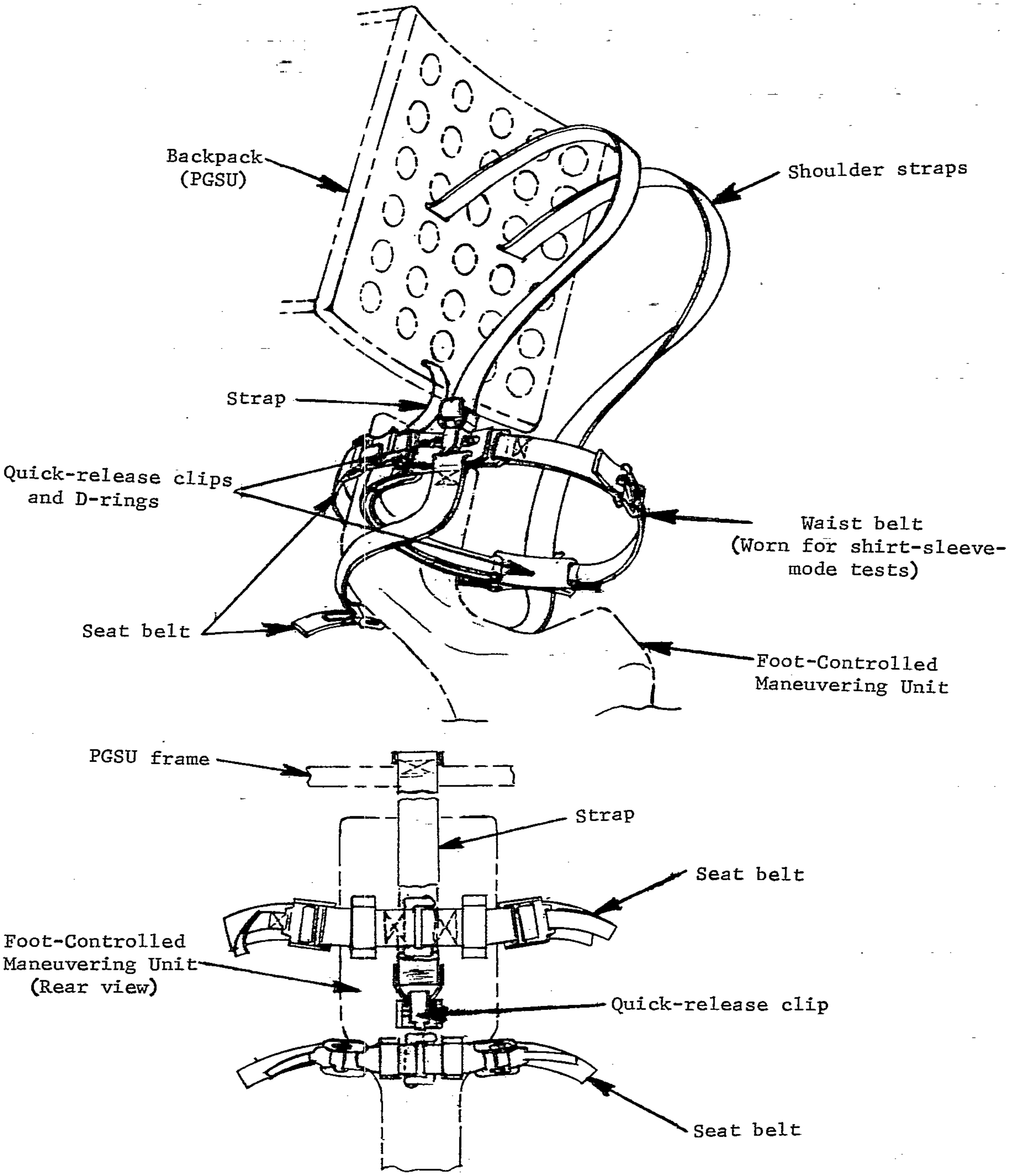
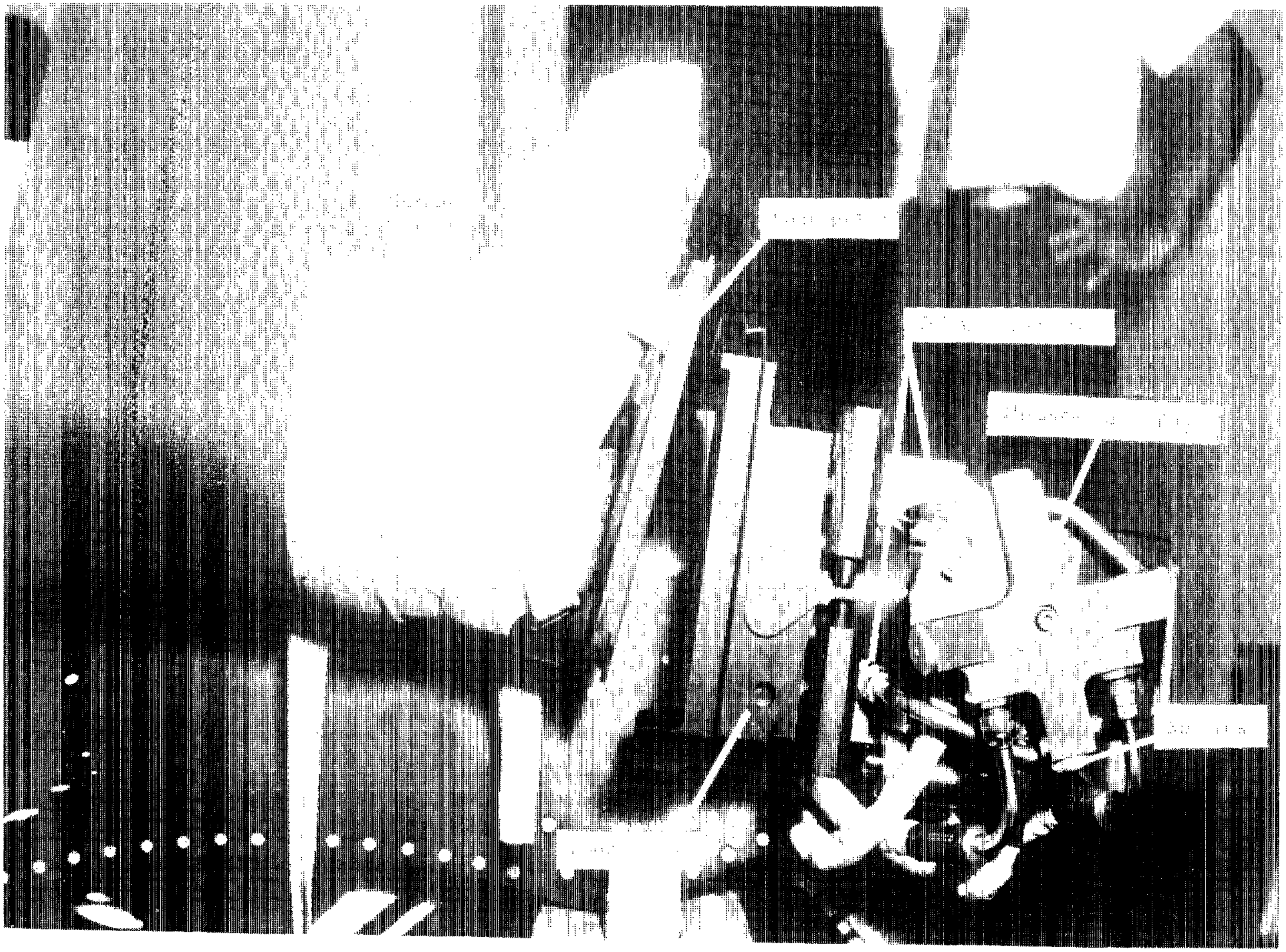


Figure 23.- Sketch of flight-hardware restraint harness.



L-70-5853.1

Figure 24.- Photograph of lower portion of the FCMU assembly showing the thruster and valve assemblies, the foot pedal, and the foot plate and straps. (Note that the foot plate strapped to the pressure-suit boot has been disengaged from the foot pedal.)

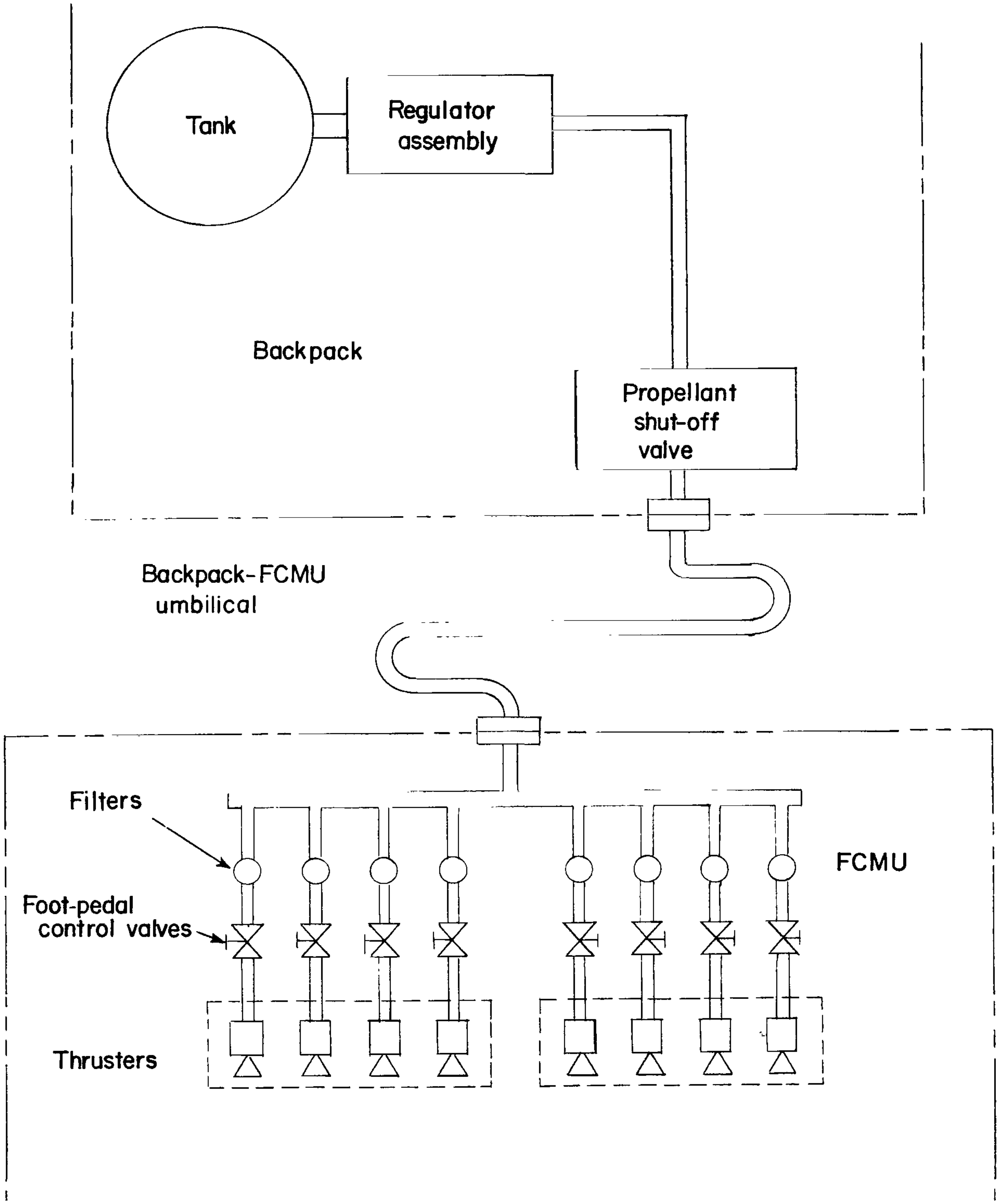


Figure 25.- Diagram of FCMU pneumatic system.

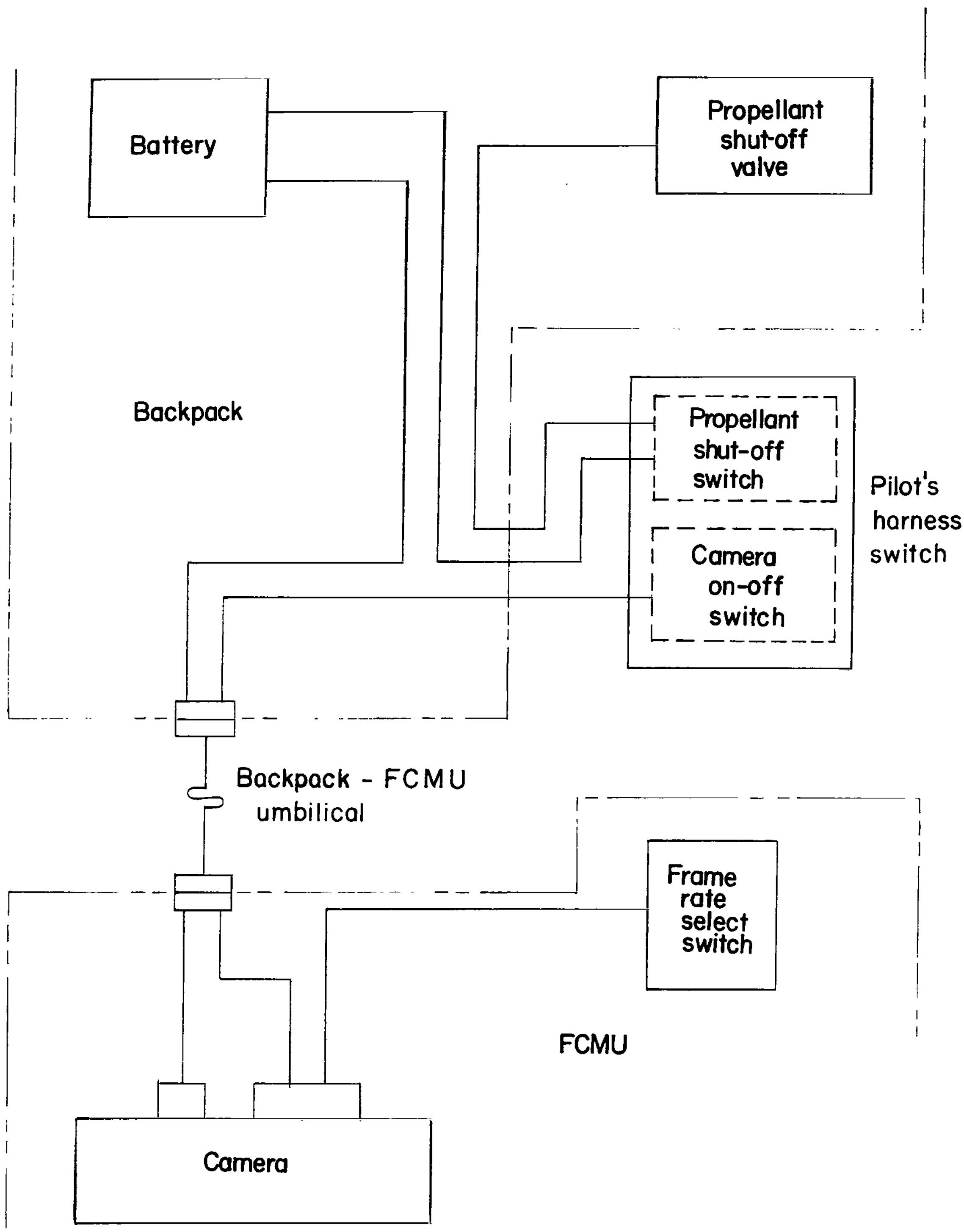
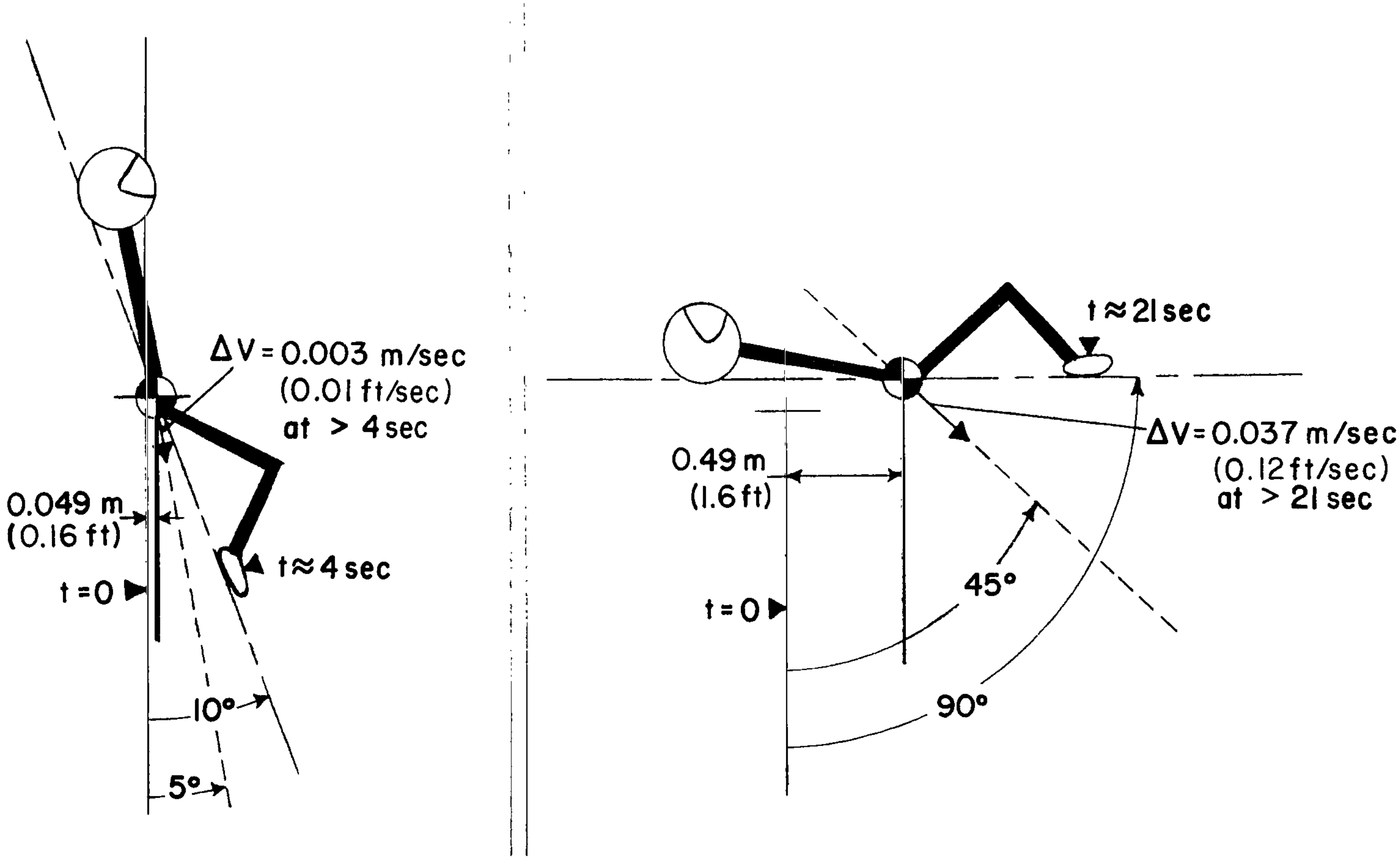


Figure 26.- Diagram of FCMU electrical system.



(a) Case 1; $\Delta\theta = 10^{\circ}$.

(b) Case 2; $\Delta\theta = 90^{\circ}$.

Figure 27.- Diagram showing results of calculated responses of the FCMU to commanded pitch attitude changes $\Delta\theta$ of 10° and 90°. (Based on 3 deg/sec^2 acceleration and 5 deg/sec angular velocity.)

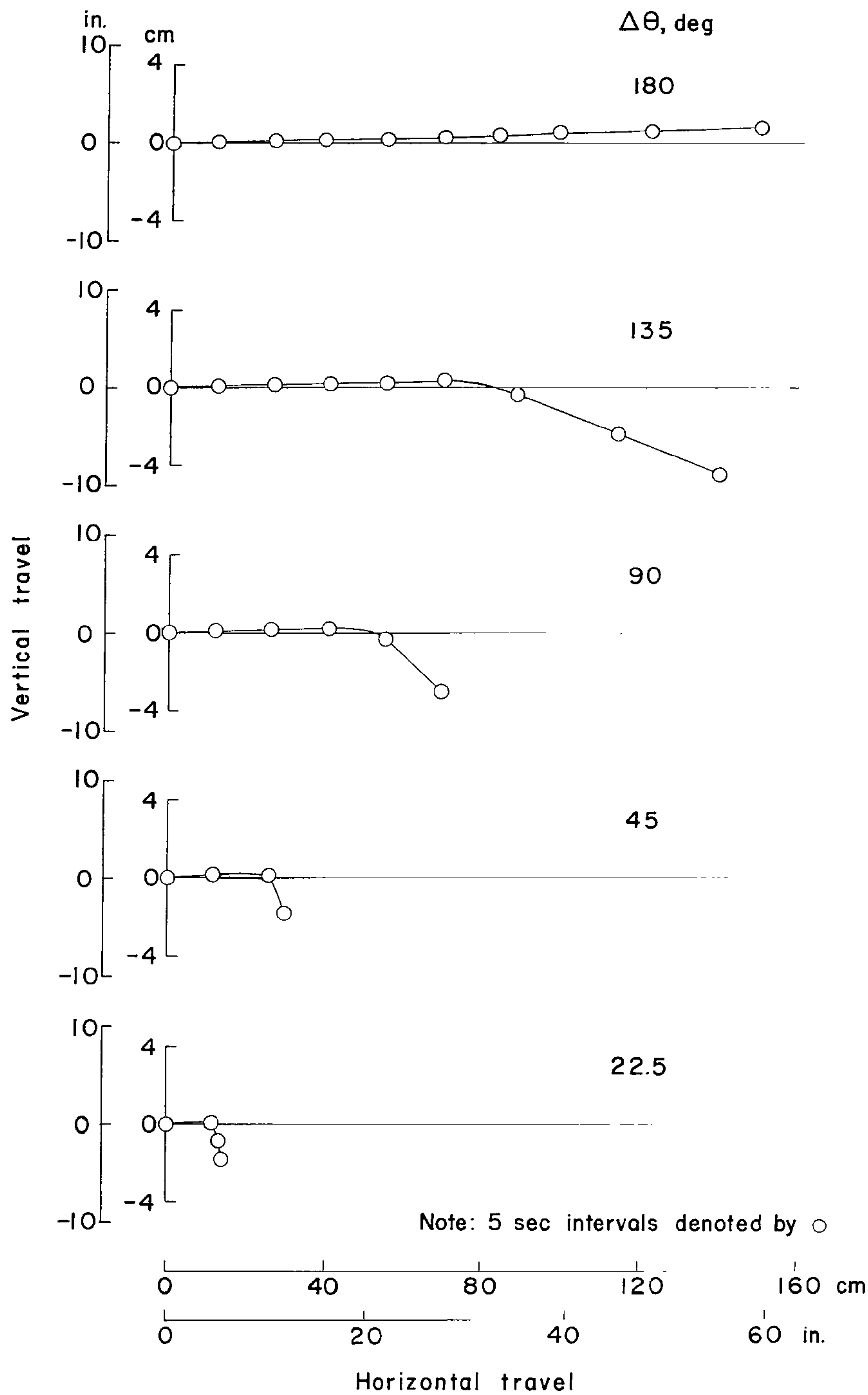


Figure 28.- Calculated trajectories in X_iZ_i-plane resulting from commanded pitch attitude changes using unbalanced thrusters.

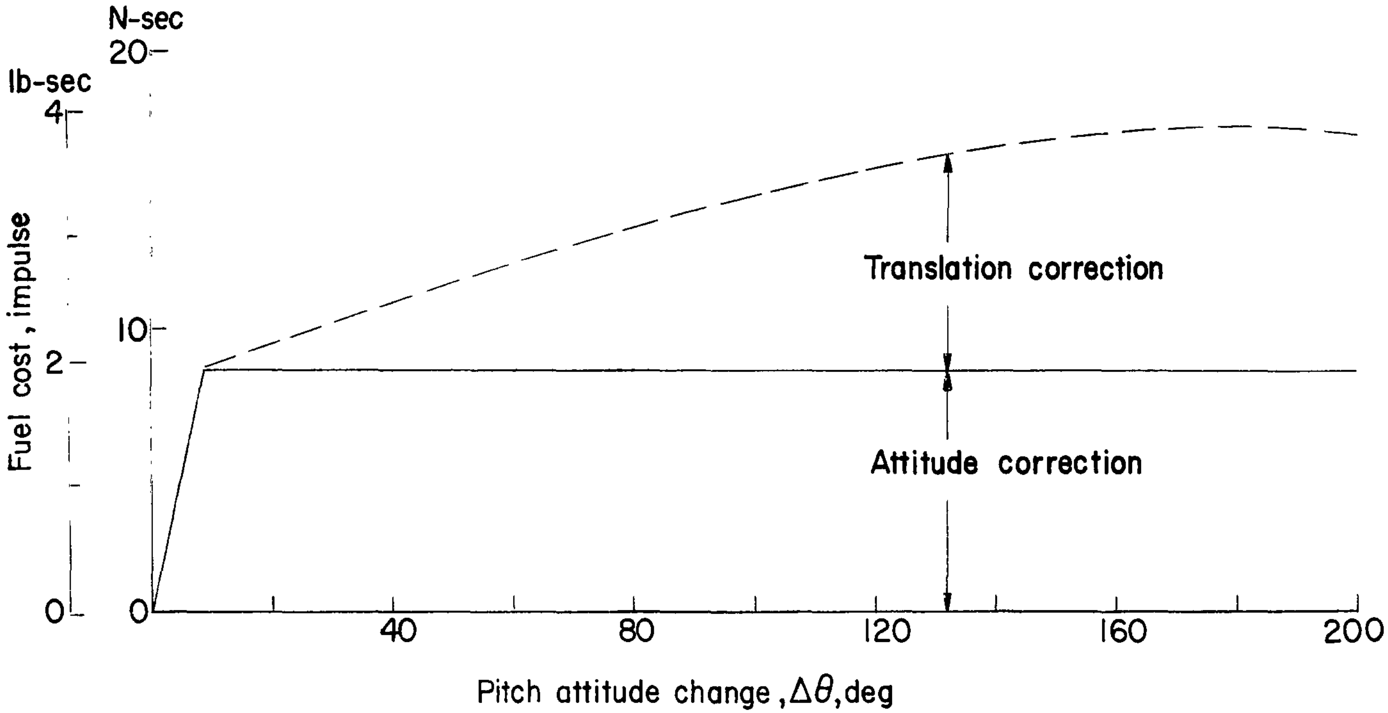


Figure 29.- Estimated fuel costs for making various pitch changes with and without translation correction. (Based on 3 deg/sec^2 acceleration and 5 deg/sec angular velocity.)

NASA-Langley, 1972 — 5 L-8045

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

U.S.MAIL

006 001 C1 U 05 720225 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LAB (AFSC)
TECH LIBRARY/WLOL/
ATTN: E LOU BOWMAN, CHIEF
KIRTLAND AFB NM 87117

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546