NASA TECHNICAL NOTE

NASA TN D-8055

NASA TN D-8055

THE FOOT-CONTROLLED MANEUVERING UNIT - SUMMARY REPORT ON SKYLAB EXPERIMENT T-020

Donald E. Hewes and Kenneth E. Glover

Langley Research Center
Hampton, Va. 23665

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1975

1. Report No. NASA TN D-8055	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THE FOOT-CONTROLLED MANEUVERING UNIT – SUMMARY REPORT ON SKYLAB EXPERIMENT T-020		5. Report Date November 1975
		6. Performing Organization Code
7. Author(s) Donald E. Hewes and Kenneth E. Glover		8. Performing Organization Report No. L-10348
		10. Work Unit No. 948-70-70-20
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23665		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

Supplements A and B (a film, L-1188) are available on request.

16. Abstract

Skylab experiment T-020 was conducted to study the maneuvering capabilities of astronauts using a relatively simple experimental self-locomotive device, referred to as the foot-controlled maneuvering unit, and to evaluate the effectiveness of ground-based facilities simulating the operation of this device in weightless conditions of space. This paper presents the final results of this experiment which includes comparison of the tests performed during missions SL-3 and SL-4 of the Skylab with those performed on the simulators. Furthermore, some of the results of this experiment and those of Skylab experiment M509, which employed an experimental hand-controlled maneuvering unit, are discussed in terms of the development of a possible future operational maneuvering system.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Foot-controlled maneuvering unit Space maneuvering Skylab experiment T-020 Astronaut maneuvering unit Astronaut maneuvering system	Unclassified – Unlimited Subject Category 16

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	60	$4.25

*For sale by the National Technical Information Service, Springfield, Virginia 22161

THE FOOT-CONTROLLED MANEUVERING UNIT – SUMMARY REPORT ON SKYLAB EXPERIMENT T-020

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

SUMMARY

The final results of Skylab experiment T-020 with the foot-controlling maneuvering unit (FCMU) are presented along with details of the experiment plan and procedures. The results of the in-flight tests performed by the two Skylab crewmen, who served as commanders during missions SL-3 and SL-4, are compared with similar results obtained by them with two zero-gravity simulators. Furthermore, some of these results are compared with those of experiment M509 and discussed in relation to possible future operational maneuvering systems.

The T-020 results indicated that the crewmen could successfully perform a series of relatively simple planned maneuvers which duplicated those performed in the ground-based simulators. The first subject experienced difficulties with the restraint system which attached the experimental equipment to the subject. This system was subsequently modified so that the second subject experienced no problems with the restraint system. Both crewmen considered that use of an attitude-stabilization system was desirable but was not necessary and that the use of only a single axis of translation control limited their performance capability with the FCMU. During a postmission simulation test session, this capability was found to be greatly improved by the addition of fore-aft and lateral translation control. The first subject was opposed to the possible application of foot controls to a future operational maneuvering system, whereas the second subject considered that the foot-control concept had significant merit and should overcome some problems that he had experienced with hand controls. The third Skylab crewman, who served as backup commander and participated in the premission simulation tests, generally concurred with the second subject.

The two simulators were considered to be very useful for training and research purposes but the two in-flight test subjects were divided as to which was the more useful. The air-bearing simulator having three-degrees-of-freedom motion was considered to offer a piloting task easier than that experienced in the actual zero-gravity tests. The visual task simulator imposed a task somewhat more difficult than that for the flight tests because of fewer visual cues and relatively poor television picture resolution.

INTRODUCTION

Two experiments conducted inside the Orbital Workshop (OWS) during the Skylab mission (ref. 1) were concerned with evaluation of design concepts for systems intended to provide locomotive capabilities for astronauts involved in various extravehicular activities (EVA) of space operations. One of these, the T-020 experiment, was research oriented and concerned with a new simplified approach referred to as the foot-controlled maneuvering unit (FCMU), shown in figure 1. This unit was mounted between the operator's legs and was controlled solely by his feet so that the operator's hands were left free for functions not necessarily related to operation of the maneuvering system. This system eliminated the use of gyro and power supply subsystems for attitude stabilization and control. The thrusters were operated by direct mechanical linkage to the foot pedals. The propellant gas was supplied to the unit from a separate assembly mounted on the subject's back to provide appropriate inertia characteristics for the tests. The other experiment, designated M509 (ref. 2), was concerned with various concepts of hand-controlled devices derived from astronaut maneuvering systems used in the earlier Gemini mission (ref. 3, pp. 91-146). The equipment used in experiment M509 was referred to as the astronaut space maneuvering unit (ASMU).

The purpose of this present paper is to present the final results of experiment T-020. This paper includes some comparisons with the results of experiment M509 and discusses some implications of these findings relative to future operational maneuvering systems. (See appendix A.)

Two supplements to this report are available and can be obtained by using the request form at the back of this report. Supplement A is a compilation of excerpts taken from the comments of the test subjects pertaining to various aspects of the experiment and to the FCMU design features and operating characteristics. Supplement B is a 16-mm motion-picture film which describes the general details of experiment T-020 and shows the operation of two FCMU simulators as well as a few scenes of an OWS test in progress. This film is in color with sound and is about 15 minutes in length.

ACRONYMS

ABS	air-bearing simulator
ASMU	astronaut maneuvering unit
DAC	data acquisition camera
EVA	extravehicular activity

FCMU	foot-controlled maneuvering unit
HHMU	hand-held maneuvering unit
IVA	intravehicular activity
JSC	Johnson Space Center
LSU	life support umbilical
OWS	orbital workshop
PCU	pressure control unit
PSS	propellent supply system
SOP	secondary oxygen pack
VTS	visual task simulator

EXPERIMENT OVERVIEW

Before presenting the results of experiment T-020, a brief outline of the total effort is presented to highlight some of the significant details and events involved. Additional information concerning these highlights are presented in references 4 to 7.

The experiment was initiated in early 1965 at the Langley Research Center with the stated objective of demonstrating a concept referred to as the "jet shoes." This concept was a simplified maneuvering system which provided hands-free operation by employing a single thruster attached to the bottom of each foot of the astronaut and controlled by switches inside the space suit boot. (See ref. 4.) This concept was of interest because it offered some promise for savings in cost, weight, system reliability, and procedural complexity. Performing the experiment inside the OWS enabled the tests to be carried out in zero gravity without exposing the operators to the hazards of actual extravehicular operations.

During the definition phase of the experiment, the original jet shoes concept was studied with the aid of various simulation techniques and the present FCMU configuration evolved as one way of overcoming some of the problems encountered with the jet shoes. The objectives of the experiment were restated in more definitive terms (ref. 5) as follows: (1) to add to the knowledge of the design of simple maneuvering devices and their limitations, (2) to obtain correlation between zero-gravity and ground-based simulation experiments, and (3) to obtain comparisons with other maneuvering devices. Two research simulators (ref. 6) were developed at the Langley Research Center to aid in further refinement of the FCMU design and to be used for providing baseline performance data for the maneuvers to be performed inside the Skylab Orbital Workshop (OWS). These simulators also aided in developing and refining the experiment procedures and timeline.

After development of the flight hardware and selection of the crewmen to conduct the experiment, a training program was carried out covering the design features and capabilities of the system and the procedures. The two research simulators located at Langley Research Center and other training facilities located at Johnson Space Center were used to support this training effort.

About 3 months prior to launch of each of the Skylab missions (SL-3 and SL-4), the crewmen, used as test subjects for each mission, completed a series of baseline data tests to be used for direct comparison with the in-flight tests. The in-flight tests were performed during the latter part of 1973 and early 1974, and a preliminary report of the results of these tests is given in reference 7. These same crewmen repeated some of the simulator baseline data tests after both missions were completed in the early part of 1974.

The results of the simulation phase of this experiment, which included both these postmission baseline tests and the previously mentioned premission tests, are presented in reference 6. The present report presents the final results of the T-020 experiment.

DESCRIPTION OF TEST EQUIPMENT

The test equipment, shown in figure 2, consisted primarily of the FCMU, a lightweight back-mounted frame, a removable and rechargeable propellant supply system (PSS), and an electrical storage battery. This equipment was used only to evaluate the FCMU concept under laboratory conditions within the Skylab Orbital Workshop (OWS) and was not intended as a prototype of an operational system. Additional equipment used for this experiment included two data acquisition cameras (DAC), and each crewman's extravehicular suit and life support system. This latter equipment was part of the normal operational support equipment carried on the Skylab spacecraft.

Backpack

The back-mounted frame was used to provide housing for the PSS and storage battery. The location of this equipment was selected primarily as a simple expediency to obtain an appropriate inertia distribution for the maneuvering system inasmuch as it was desired to have the principal axes of inertia alined as closely as possible with the reference axes of the system, as shown in the sketch of figure 3, in order to minimize attitude-control cross coupling. The backpack was equipped with a solenoid-operated propellant shut-off valve, a short electrical cable with a double switch assembly which clipped to the chest of the test subject, and outlet quick-disconnect receptacles for the propellant gas and electrical power supplied to the FCMU. One of the switches on the cable was used by the test subject for operation of the shut-off valve. The other switch was used for controlling a DAC located in the FCMU. The PSS was capable of storing approximately 5.8 kg (13 lb) of nitrogen gas at 2068 N/cm^2 (3000 lb/in^2) and supplying 86 g/sec (0.095 lb/sec) at a regulated pressure of 100 ± 7 N/cm^2 (145 ± 10 lb/in^2). The storage battery had a capacity of approximately 6 ampere hours at 28 volts.

Foot-Controlled Maneuvering Unit

The FCMU was equipped with two sets of four small thrusters. Each set was located just below and outboard of one of the test subject's feet. Two of the thrusters in each set were mounted in opposing directions and alined parallel with the fore-aft or X-reference axis. These thrusters generated approximately 1.3 N (0.3 lb) each when operated by action of both ankles in the toe-up and toe-down directions to produce pitch and yaw control accelerations. The other two thrusters of each set were alined in opposing directions with the up-down or Z-reference axis. These thrusters generated approximately 4.4 N (1.0 lb) each when operated by action of both feet in the up and down directions to produce translation and roll control accelerations. The logic used in controlling the system is given in table I.

The flow of propellant gas to the nozzles was controlled by a valve assembly mounted below each foot pedal. The foot pedals were provided with preloaded springs which held the pedals in their neutral positions until moved by the feet. The pedals moved about two-thirds of their travel before coming in contact with the stems of the poppet-type valves which required about 0.3 cm (0.1 in.) travel to be fully opened. The valves were spring loaded to their closed positions. Although the valves produced a proportional variation of thrust with displacement, the valves were normally actuated from full-off to full-on and return in a stepped manner. The spring preload was sufficient to force the pedals to return to their neutral position whenever the leg muscles producing the "on" action were relaxed.

The operating characteristics of the foot pedals are illustrated in figure 4, which shows the typical variations of the actuating force and torque required to move the pedals from their neutral positions to the stops and return. The test subject's feet were attached to the pedals by means of quick-disconnect plates attached to the feet by ankle and toe straps.

The length of the FCMU between the foot pedals and the seat was adjustable to accommodate different leg lengths. The adjustment was maintained by means of a spring-loaded locking pin and was sized to accommodate 10th to 90th percentile body sizes (ref. 8) in 10th percentile increments.

The upper part of the FCMU contained a mounting unit to support a 16-mm DAC and a mirror system used to produce a split image on the film frame as shown in figure 5. One-half of the image was the downward view along the Z-reference axis and the other half was the forward view parallel with the X-reference axis. The camera was operated through the remote control switch clipped to the test subject's chest and was equipped with an 8-mm lens focused at about 2 m (6 ft). A framing rate of 2 frames per second was used throughout the tests which provided over 14 minutes of filmed coverage for the test runs with each 43 m (140 ft) film magazine load.

Additional Camera Equipment

A second DAC with a 5-mm-wide angle lens was mounted near the hatch in the overhead dome area of the OWS and was aimed at and perpendicular to the OWS floor. For most of the experiment this camera was operated at a speed of 2 frames per second. In addition to this film coverage, some information concerning the experiment activities was obtained with the onboard television equipment. The TV camera was handheld by one of the crewmen located near the overhead DAC. A handheld 35-mm still camera was also used to document different aspects of the experiment.

Restraint System

The FCMU and backpack were strapped to the operator by a body harness, shown in figure 6, designed to provide a moderate degree of waist mobility. The harness was required to accommodate two conditions of test subject garb, a shirtsleeve mode as depicted in figure 1, and a suited mode as depicted in figure 7. Because of difficulties created by slippage and fitting of the harness during the first SL-3 experiment session, the harness was modified onboard the spacecraft by the addition of some straps as shown in figure 7. This harness was used for the second (shirtsleeve) and third (suited) test sessions of this mission.

Prior to the SL-4 mission, a new rigidized harness, shown in mockup form in figure 8, was developed on the basis of the improvised system of the previous mission. This harness incorporated a pair of aluminum tubes to minimize the relative motions between the upper torso, lower torso, FCMU, and backpack. The tubes fitted over the sides of the backrest on the FCMU seat and extended upward about 0.3 m (1 ft) to form a support to which the backpack was strapped. The tubes were bent 23° forward from the backrest to accommodate the natural relaxed position of the body which provided adequate downward visibility. The extended backrest restricted the operator's waist mobility and tended to make the man-machine system move as one rigid unit.

Pressure Suit and Equipment

The suited mode, as depicted in figures 3 and 7, consisted of the suit, a pressure control unit (PCU) at the waist, and a lightweight life support umbilical (LSU) used to supply the breathing and cooling oxygen to the subject from the spacecraft system. This lightweight LSU was improvised when prior experience in the M509 experiment sessions revealed that the standard umbilical was too stiff and massive for this type of experiment. Consequently, the crewmen stripped a standard EVA umbilical of the external wear-cover and the water-cooling and communication lines so that only the oxygen line remained.

For part of the suited mode tests, the umbilical was removed and replaced with a secondary oxygen pack (SOP) strapped to the subject's right leg. The SOP was a self-contained oxygen supply unit capable of providing a few minutes of suit pressurization without the umbilical. A second SOP which was depleted of gas was strapped to the other leg to provide a symmetrical loading condition and minimize control interactions. This arrangement is depicted in the photograph of figure 9.

IN-FLIGHT EXPERIMENT PLAN AND PROCEDURES

The basic plan of experiment T-020 for each of the missions was to have the participating crewman perform a series of both planned and free-style maneuvers within the OWS. He evaluated maneuvering performance, handling qualities of the system, piloting workload, and the differences between the actual zero-gravity conditions and those of the ground-based simulators. His replies to specific questions carried in his experiment checklist and additional comments were recorded after the tests were completed.

To conserve propellant gas and experiment time, the test subject was assisted by a second crewman who positioned him and the FCMU within the test area of the OWS prior to the start of each run and retrieved him after the run. The second crewman also functioned as operator for the OWS camera and observer of the maneuver activities. As observer, he recorded his own comments and relayed those of the test subject by use of the onboard OWS voice tape recording system. The recording system was operated continuously during the maneuvering phases of the experiment.

Planned Maneuvers

A description of each planned maneuver is given in appendix B. These maneuvers, which were the same as those performed in the simulators, were regarded as basic maneuvers employing the primary control actions of the FCMU system. These simple maneuvers were used because of the limited volume within the OWS and because of the need to maintain carefully controlled repeatable conditions that could be directly correlated with those of the ground-based simulators.

The first three maneuvers relate directly to the three basic attitude control commands: pitch, roll, and yaw. These maneuvers were concerned with the ability of the test subject to change selectively the orientation relative to a given reference axis by a specific amount while maintaining the orientation essentially fixed with respect to the other two axes. These three maneuvers were referred to as "attitude control and hold." The fourth maneuver, referred to as "single-axis," related directly to the fourth FCMU basic control command, that is, translation along the Z-reference axis. This maneuver was concerned with the ability of the test subject to change his position along his Z-axis while maintaining his attitude about all axes and minimizing drift along the other two translation axes. The last two basic maneuvers, referred to as "double-axis" and "dogleg," were concerned with the subject's ability to change his attitude and direction of translation while translating from one location to another. These latter two were concerned also with his ability to terminate his translation by use of his hands when arriving at the desired position.

A separate final maneuvering task, not included in the simulation phase of the experiment, was an attempt to recover from an initial condition of tumbling about all three axes. A successful recovery was considered to be achieved when the angular rates were all reduced below acceptable limits, although the translation rate was not necessarily stopped or minimized.

Free-Style Maneuvers

The test subjects were permitted to perform a series of maneuvers which they selected at their discretion. The purpose of this was to permit the subjects to evaluate the FCMU with maneuvers of a more complex nature for which they had not been previously trained.

Performance Guidelines and Data Measurements

Evaluation of the maneuvering capabilities for this investigation was a qualitative judgment, based on the comments of the individual operators and on some specific measurements obtained from the maneuvers. To support this judgment, some guidelines were established to define those elements of the planned maneuvers that were considered to be significant.

Guidelines.- The imposition of rigid performance requirements for the maneuver itself in terms of time limits or attitude and positional errors did not appear to be appropriate for most envisioned applications. Consequently, the approach taken was that the operator should be concerned primarily with moving from one position to another while maintaining his attitudes and velocities within reasonable limits and taking whatever time was required to perform the task with a reasonable amount of effort. The guidelines used throughout the training and experiment phases can be paraphrased as follows:

(1) No time limit is specified and the subject has the option as to how to use the available fuel.

(2) The subject should use his own judgment as to what maneuvers he has accomplished successfully and what translation and rotational rates he considers to be "comfortable" or "desirable."

(3) The subject may alter or adapt his previously developed piloting techniques as he judges necessary to satisfy conditions encountered in subsequent maneuvers or test sessions. However, in the repeat runs of a particular maneuver for data taking, he should attempt to be consistent.

(4) The subject should identify the initiation and termination of specific phases of each maneuver by use of the cue word "mark."

Performance criteria.- Criteria, based on the motions generated during different portions of each maneuver, were provided as a further guideline to assist the test subject in judging his performance of the individual maneuvers. These criteria, which were derived from experience with the ground-based simulators, are listed in table II. To apply these criteria, the subject was required to rely on his own estimates of his attitude, position, and rates inasmuch as no flight display instruments were available to him. However, he was given instruction during his training period to assist him in making these estimates.

Performance measurements.- The primary measurements of performance taken during the in-flight tests were the times required to perform the various phases of the specified maneuvers. These times consisted of the total time and the hold time. Total time for a given maneuver consisted of the time from the initiation of the test run to its completion as identified by the "mark" call-outs by the subject. The hold time consisted of that portion of the total time during which the subject was performing the attitude- or position-holding function, as specified for the particular maneuvers.

A secondary measurement, in the form of readings of the pressure gage located on the PSS, was taken to determine the average rate of propellant gas expenditure for the complete series of test maneuvers. The readings were taken periodically throughout the experiment. Film records of most of the test runs were taken with the two DAC's for the purpose of measuring the trajectories of typical runs.

Pilot ratings.- Subjective evaluation of the handling qualities of the FCMU system was performed by the test subjects. They assigned a pilot rating for each of the maneuvers at the completion of the tests by using the chart illustrated in figure 10. The rating system employed with this chart was based on that of reference 9. The format of this chart was altered considerably from that of reference 9 to facilitate the decision-making process with the intention of retaining the meaning of the rating values defined in the reference. These ratings apply only to those conditions under which the tests were conducted.

Test Subjects

The primary and backup commanders of Skylab missions SL-3 and SL-4 served as test subjects 1 and 2, and their backup crewman served as subject 3, respectively, for this experiment. They were also test subjects for the M509 maneuvering system experiment. Each subject had received about 30 hours of FCMU training in the ground-based zero-gravity simulators (ref. 6) and had participated in the collection of the baseline data obtained with these simulators. Each subject also had participated in procedures training sessions at the Johnson Space Center with his co-crewman who was to assist in carrying out the in-flight test sessions.

In-Flight Test Sessions and Conditions

The in-flight tests were scheduled to be carried out in two sessions during each of the two Skylab missions, the first was to be in the shirtsleeve condition followed a few days later by a pressure-suited session. At least two successful runs for each of the planned maneuvers in the specified sequence were requested for the shirtsleeve tests. Because of time constraints and operational complexities for the pressure-suited conditions, only one successful run each for a portion of the maneuvers was requested. However, runs were requested for both the suited conditions with and without the life support umbilical.

The in-flight tests were to be conducted inside the Orbital Workshop (OWS) generally in a plane about 2 m (6 ft) above and parallel with the gridded floor and within an area of about 2.5-m (7.5-ft) radius from the center line of the spacecraft. The orientation and position of the subject at the start of each run was specified for each of the maneuvers and corresponded to those used in the ground-based simulation tests. All runs were to start with the linear and angular rates relative to the OWS as near zero as practical.

The flight-test subjects were about the same size and stature and weighed approximately 73 kg (160 lb). A list of typical values for the physical characteristics of the maneuvering system, including the operator, is given in table III for both the shirtsleeve and suited conditions. All tests were performed at an ambient atmospheric total pressure of approximately 3.4 N/cm^2 (5.0 psi) in the OWS.

RESULTS AND DISCUSSION OF IN-FLIGHT TESTS

The test sessions were not carried out in the OWS as planned for various reasons; however, a total of five test sessions were completed, three of which were performed by subject 1 during mission SL-3, and the other two by subject 2 during mission SL-4. Subject 2 completed the tests for only the shirtsleeve condition. A schedule of these tests is given in table IV. The backup commander, who served as subject 3 for the simulation tests, was not required for either mission and therefore was unable to participate in the in-flight tests.

Each test session included the setup and checkout of the equipment, the performance of the test maneuvers, and the stowage of all equipment. These sessions generally lasted 4 to 5 hours each and provided between about 20 and 30 minutes of actual maneuvering time for each session. Consequently, a total of about 140 minutes of maneuvering time for the FCMU was obtained in actual zero-gravity conditions. Most of this time was obtained in the shirtsleeve mode and provided experience directly comparable with that of the ground-based simulator. Because of scheduling problems for the last mission, subject 2 was unable to carry out the suited tests; consequently, the total suited time of 22 minutes was obtained only by subject 1.

A listing of the time measurements for each of the maneuvers in terms of the mean and standard deviation values is given in table V. The values given in this table for the two subjects are compared in figure 11. Plots of the readings taken from the PSS pressure gage are presented in figure 12 as a function of accumulated test time for each session. The pilot-rating values assigned by the test subjects to the various maneuvers are given in table VI.

Major Experiment Anomalies

There were several changes made in the planned tests because of anomalies that occurred during the mission. Two of the anomalies were associated with test equipment problems. The others were more of a procedural nature that resulted from these equipment problems. The anomalies had a direct impact on the results of the test runs that were completed, as will be discussed.

Although a significant amount of effort, including underwater simulated zero-gravity tests, was involved in the development of an adequate restraint harness, the original harness (fig. 6) was the major source of equipment difficulty for the actual zero-gravity tests because the harness allowed the backpack to wobble excessively and did not hold the FCMU securely between the operator's legs. During the first session, subject 1 reported that this arrangement caused great difficulty in making the desired control inputs. He also reported that the equipment was extremely uncomfortable to wear. Part of the discomfort was produced by the excessive tightening of the body straps in repeated attempts to secure the FCMU and backpack. The bending of the subject's body at the waist, as permitted by the harness, was an additional source of discomfort.

Although the scheduled test maneuvers of this session were completed successfully, the subject stated that his performance was generally not within the performance criteria (table II) and he made recommendations for improving the harness system. A modified harness based on these recommendations was used for both the second shirtsleeve and the pressure suit tests. There was a noticeable improvement; however, the degree of body restraint desired by the subject was not achieved. The subject considered his performance to be still outside the criteria and he noted a restricted field of view in the downward direction, particularly for the suited test.

Analysis of some of the photographic records revealed that at least part of the subject's problem with his restricted field of view was due to adjustment of the harness. The straps at his back were tightened excessively in attempts to secure the equipment on the subject more securely, as noted previously. Unfortunately, these tight straps forced him to lean backward on the FCMU further than the intended position which would have provided adequate visibility downward past his feet. This leaning is illustrated by the sketches of figure 13 which were traced from photographs taken during both ground and in-flight tests. As indicated by the angles drawn on the sketches, the subject during the in-flight tests was leaning backward from the position used in the ground tests by more than 10°.

This problem also accounts for some minor difficulties that subject 1 had with fitting his feet into the foot pedals during the suited run. Because he was forced to lean back on the FCMU, the natural position of the legs in the pressurized suit was forward of the foot pedals. Consequently, the legs had to be forced backward in order to place the feet in the pedals. This posture caused the boots to be in a slight toe-down position relative to the neutral position of the pedals. In this position the heels could not be pulled down against the pedals by the foot straps. This arrangement, by itself, apparently did not cause the subject to have too much difficulty in making the proper control inputs. However, the tendency of the suit legs to move forward did cause the boots to disengage inadvertently a few times from the pedals because of a quick-release feature which had been built into the pedals. When this condition did occur, however, the subject was able to reengage the pedals without seriously affecting the test runs.

The second source of equipment problems was the life support system used for the SL-3 suited tests. The original plan was to use the standard life support umbilical (LSU), which was quite stiff and bulky, for a short period to permit the subject to carry out some familiarization runs in the suited mode. He was then to perform the data runs with the umbilical removed and the SOP unit used for pressurizing the suit to eliminate any influence of the standard umbilical on the motions of the FCMU. Unfortunately, because of launch weight constraints and mission priorities, only a portion of one SOP supply was available for the T-020 tests and this quantity was insufficient to carry out the complete set of planned runs. The crewmen were, therefore, requested to perform most of the data runs with the umbilical and to perform only a few additional exploratory runs with the SOP.

Fortunately, the modification of the LSU to reduce its stiffness and weight resulted in very little apparent influence of the umbilical on the FCMU motion. However, this modification also resulted in the loss of direct voice contact between the test subject and the observer during the test runs. Consequently, the two crewmen were unable to communicate effectively during the tests and considerable confusion resulted in trying to work with the unfamiliar revised test plan. As a result, some of the intended runs were not attempted and some of the camera records and run time measurements were not obtained. The communications problem coupled with the previously mentioned visibility problem apparently created a sense of helplessness that was reflected in several of the subject's debriefing comments pertaining to the suited tests.

For the SL-4 mission, the details of the new rigidized harness system (fig. 8) and modified test procedures were reviewed with the crewmen prior to the launch and the additional equipment was carried with them to the OWS at that time. Unfortunately, there was no opportunity for them to receive pertinent familiarization training prior to the flight. Consequently, they were forced to perform the first shirtsleeve session with inadequate preparation. The test subject observed that his initial performance was relatively poor but improved markedly as he progressed through the various maneuvers. He concluded that the results of the first session were not valid and, therefore, requested that a second shirtsleeve session be scheduled. This was carried out a few days later in place of the planned suited run.

Because of other mission priorities and schedule constraints the suited run could not be rescheduled for a later time. Therefore, the second subject was unable to evaluate the FCMU for the suited condition in the OWS.

The rigidized system proved to be successful and subject 2 stated that he was able to perform practically all the planned maneuvers within the performance criteria. He subsequently attempted a few maneuvers with this restraint system without the tubular braces to duplicate the modified system used by subject 1, and he found the same problems with control inputs and discomfort that were encountered by subject 1.

Maneuvering Performance

Essentially all the planned maneuver runs attempted by the two subjects were completed successfully but not always within the guideline performance criteria given in table II. The few instances in which a run was aborted after being initiated were attributed primarily to minor equipment or procedural problems, such as entanglement of the FCMU with stray cables in the test area or bumping by the observer as he repositioned himself during the test run.

Analysis of the DAC 16-mm film records indicates that both the shirtsleeve and suited in-flight maneuvers followed closely the preplanned motions.

Both subjects were able to recover from the tumbling conditions initiated by the test observer. They each reported that there was no problem of spatial disorientation or lack of adequate control authority to overcome the fairly high angular rates about all axes that were encountered.

No attempt has been made to analyze in detail the free-style maneuvers that were performed by the subjects. Review of the DAC records, which covered portions of these tests, reveals that the subjects apparently were able to perform some phases of these maneuvers successfully. However, the subjects commented that they were unable to perform successfully other phases of these maneuvers.

Performance time.- Comparison of the mean performance time values, shown in figure 11, for the planned maneuvers of the two subjects reveals that with the exception of the first two attitude maneuvers, each subject performed the same maneuver within about 10 seconds of the time taken by the other. Subject 2 generally took somewhat longer to complete the attitude maneuvers than subject 1 did. Also, his variations from run to run for these maneuvers were somewhat higher than those of subject 1. Both subjects tended to take longer than the specified total hold times of 20 seconds to stabilize their motions for the holding phases of all the attitude maneuvers. By contrast, the performance times of the two subjects for the subsequent translation maneuvers were very similar.

The somewhat erratic performance of subject 2 for the first few runs is attributed primarily to an unusual difficulty he experienced in coordinating the motions of his left foot and ankle. He initially found that left toe-up inputs were difficult to make without raising the left foot at the same time. However, as the runs progressed, he noted that he was able to overcome the difficulty. He also had experienced this same problem to a lesser degree during the simulation training and data sessions. He concluded that this problem was a peculiar physical characteristic and should not be considered as being typical for other operators. In fact, this subject was the only one of numerous individuals who had operated the FCMU simulator to have experienced this particular problem.

Expenditures of propellant gas.- The amount of gas used from the propellant supply system (PSS) could be determined from the pressure changes in the supply pressure; however, it was not possible to determine the specific amount used for each maneuver because of the low reading resolution of the gage and because readings were not taken continuously throughout the session. The average expenditure for the complete series of maneuvers was determined from the plots given in figure 12 showing the variation of the actual pressure readings taken during each session with accumulated maneuvering time. The accumulated time represents only those time intervals during which the subject was actually performing specific maneuvers. The time intervals for the planned and free-style maneuvers performed by the two subjects are indicated in this figure.

These plots for the shirtsleeve test sessions (sessions 1 and 1A) indicate an average change in pressure reading of 44 N/cm^2 per minute (62 psi per minute) which corresponds to the propellant gas being used at an average rate of about 5.9 kg/hr (13.6 lb/hr). There does not appear to be a substantial difference between gas expenditure rates for the planned and free-style maneuvers inasmuch as the same straight line has been drawn with a reasonable matching of all data points. In all shirtsleeve tests, the gas charges, which were less than the full capacity of the PSS, provided in excess of 25 minutes of continuous maneuvering.

For the suited tests of the first subject, the gas expenditure was about 50 percent greater as would be expected because of the greater mass and inertia of the system. However, a total maneuvering time in excess of 20 minutes was obtained with the partially filled PSS.

Comparisons of In-Flight and Simulation Test Results

Analysis by photogrammetric techniques of the DAC 16-mm film records taken during both the in-flight and the premission simulation tests showed a close similarity of the trajectories. This similarity is illustrated in figure 14 which shows a side-by-side comparison of the dogleg maneuver as performed by subject 2 in the air-bearing simulator (ABS) prior to the mission and in the OWS during his second shirtsleeve session. The figure shows plots of the two trajectories in the maneuver plane parallel with the OWS floor. The dots represent the position of the subject at 0.5-second intervals as determined by photogrammetric techniques from the DAC film records. The stickmen represent the approximate body attitudes at about 10-second intervals. The additional degrees-of-freedom motion for the OWS tests are evidenced by the small amounts of roll and yaw attitudes depicted by the legs of the stickmen. There was a small amount of out-of-plane lateral motion in the OWS which resulted in the subject being about 0.3 m (1 ft) to his left of the original plane of motion at the termination of this maneuver. The pitch attitudes at the corresponding trajectory positions and the translation velocities, as depicted by the spacing of the dots, are very similar for the two test conditions.

Performance time for individual maneuvers.- A comparison of the mean time values, based on the two flight subjects taken together for each individual maneuver in OWS with those for the premission and postmission tests, is shown in figure 15. This figure reveals that, in general, the subjects took slightly longer to perform the first two maneuvers in the OWS than they did in their premission simulation runs. For the subsequent maneuvers, however, they took somewhat less time. For the postmission tests, all time values were noticeably less than those for the comparable premission tests and were either equal to or slightly less than those of the in-flight tests. The dog-leg maneuver, which was the last of the sequence and was considered to be the most difficult, as reported in reference 6, was completed in each succeeding session in considerably less time than in the preceding session. Increasing familiarity and improved skills with the FCMU as well as the accumulation of experience in an actual zero-gravity environment are considered to be the factors accounting for these trends.

Propellant supply pressure readings.- The variations of the pressure readings for the sequence of planned maneuvers for each of the subjects during the second shirtsleeve sessions (1A) are shown in figure 16 and compared with the corresponding values that were determined from the simulation baseline data. The maneuvering time intervals and the total number of runs for each of the maneuvers are also indicated in this figure. The pressure reading values and maneuvering time intervals for the baseline tests were based on the data given in tables VI(a) and VI(b) of reference 6 for the two specific subjects. (The ABS data for the maneuvers as performed in the OWS were used except in the case of the yaw maneuver for which the visual task simulator (VTS) data were used.) The total impulse values of table VI(b) of reference 6 were converted to equivalent pressure readings on the basis of the assumption that the initial pressure was the same as that for the OWS tests. Note that the total number of maneuvers performed by each subject was different, 12 for subject 1 and 16 for subject 2.

These comparisons reveal that although there were some differences between the actual and calculated data, there was reasonable agreement in terms of the total interval for the complete sequences of maneuvers and the total gas expended.

In the case of subject 1, the differences between actual and calculated data are attributed primarily to the greater expenditure of gas and the much shorter times to perform the yaw maneuver in the OWS than in the simulator. Subject 1 made specific note of this maneuver during his in-flight debriefing comments and referred to it as a "real gas waster" because of the large amount of roll-due-to-yaw cross coupling involved. In the case of subject 2, the differences can also be attributed, at least in part, to the roll-due-to-yaw cross-coupling problem. The other contributing factors, however, are considered to be differences in piloting technique for the dogleg maneuver and the difficulty subject 2 had with his left foot control inputs, as mentioned previously. This latter problem introduced considerable unintentional disturbances in right roll and up translation that had to be countered by additional left foot-down inputs. This problem was much more dominant for the in-flight tests and resulted in additional fuel expenditure and time to complete the in-flight pitch and roll maneuvers.

With regard to the dogleg piloting technique, subject 2 commented at the time of the simulator runs that he was varying his technique somewhat from run to run. It appears that most of these runs must have been "real gas wasters" inasmuch as he used over twice as much as did subject 1 for this same maneuver. Evidently, the technique he ultimately used for the in-flight tests was much more conservative. As shown in figure 11, he did take slightly longer to complete the in-flight runs than those of the simulator.

Discussion of Subjective Evaluations

The test subjects were requested to perform their subjective evaluations by first giving consideration to the operation of the FCMU under the specific conditions and defined guidelines for the tests without regard to other factors or considerations. Having done this, they were then requested to make comments relative to such other factors as they considered important such as assumed requirements for extravehicular operations. The following discussion is based primarily on the comments pertaining to the in-flight tests, some of which are given in supplement A of this report.

Pilot rating.- For most of the maneuvers, both subjects assigned ratings in the 3 to 4 range for the conditions of operating inside the OWS, as shown in table VI. These ratings correspond closely to those that were assigned by the subjects during the premission tests for all the maneuvers as reported in reference 6 and also shown in this table. For the yaw and dogleg maneuvers, subject 2 assigned poorer ratings of between 6 and 5 because of the previously mentioned ankle-foot coordination problem he was experiencing with his left foot during the test session. This problem made it difficult for him to execute these particular maneuvers as well as he desired. He noted, however, that as the test progressed, the problem appeared to be abating and therefore he considered that with additional time he could have given a better rating.

In extrapolating his evaluation to actual extravehicular conditions, subject 1 significantly down-rated this experimental system by assigning ratings of 9 and 10. This rating was based primarily on his concern over specific features of the experimental system, the lack of translation control for all three axes, and the inadequacies of the body restraint systems utilized for his tests. Subject 2 declined to extrapolate his rating beyond the

OWS test conditions but did state that he considered the basic concept of foot controls to have significant potential for a system intended for EVA operations.

Performance criteria.- The criteria listed in table III were generally considered to be pertinent and reasonable for the purposes of evaluating a maneuvering system. Subject 1 judged that most of his maneuvers were outside these values. Subject 2 noted that all values were achieved for most of his maneuvers with use of the rigidized restraint system. However, he had to work very hard during the yaw maneuver to overcome the rotational cross-coupling problem and was unable to hold his translational position within the 0.3-m (1-ft) criteria value. He estimated that his position varied about twice that amount.

FCMU design features and characteristics.- The primary design feature of the FCMU, the foot controls, was the most controversial aspect of this experimental system. Initially, the first subject stated that he considered the foot controllers to be a useful feature. Subsequently, he noted that the controller deflections and forces were much too large and that the foot controller was not as precise as the more conventional hand controllers. In his final opinion, use of foot controls in place of hand controls provided no benefits in the design of a maneuvering system. In contrast to this judgment, the second subject considered the forces and travels of the controllers to be satisfactory. He concluded that the use of the foot controllers was a very useful feature of the FCMU and appeared to offer significant advantages over the type of hand controllers used with the ASMU.

It appears evident that personal preference is a strong factor involved in these opposing views of the two flight subjects. However, it is believed that the problems encountered by the first subject with the body harness and the design changes incorporated in the harness for the second subject account to a significant degree for the differing judgments.

In other respects, the two subjects were in close agreement in that both considered that the logic of the control inputs presented no serious problem. Also, both considered the single-axis translation control capability to be a major deficiency of the system because of the inability to permit fore-aft and lateral drift corrections to be made without changing attitude. This deficiency was compounded by the undesirable fore-aft translation produced whenever the pitch controls were used to change attitude. Consequently, when the subjects changed their pitch attitude so as to be able to correct for a drift in one direction with the single-axis translation thrusters, a drift would be generated in another direction. Each subject stated that translation control of all three axes was necessary in any maneuvering system to achieve desired performance with a reasonable workload.

Both subjects judged the direct operation of the attitude thrusters that provided an acceleration command type of control system to be acceptable for operation within the OWS. However, they considered the incorporation of some form of attitude stabilization for attitude-holding tasks as being very desirable.

The angular accelerations were satisfactory in pitch, somewhat low in roll, and too high in yaw. The cross coupling in the roll axis due to yaw control inputs was also considered to be somewhat high and to be causing a significant part of the pilot workload. This rotational cross coupling resulted from misalinement of the principal inertia axes from the control reference axes.

The linear accelerations along the Z-axis were satisfactory although the first subject considered that the accelerations were slightly low when attempting to stop the higher translation velocities he used in the OWS maneuvers.

Pressure suit effects.- Subject 2 was unable to carry out his evaluation of the pressure suit in the OWS, as mentioned previously; however, he did some preliminary evaluation during a suited training session carried out on the air-bearing simulator at JSC. In that case, he judged the influence of the suit as being not particularly disturbing although it did reduce the "feel" for the system and restricted his field of view to some extent.

In the case of subject 1, although he experienced considerable difficulty during the suited session in the OWS, as mentioned previously, he successfully performed most of the maneuvers he attempted. He stated that he was able to make appropriate control inputs although his feet did not fit snugly in the boots which also were not tight on the pedals. He commented that his ability to reposition himself with his hands and arms was limited by the additional straps of the improvised restraint system which restricted his arm and shoulder motions.

The lightweight umbilical used for these tests was found to have no noticeable effect on motions of the FCMU system.

Simulation.- There were significant differences in the opinions of the two subjects concerning the ground-based simulators used for training and obtaining baseline performance data.

Subject 1 considered that although the visual cues provided in the air-bearing simulator were more than adequate, the lack of complete freedom of motion and the influence of the air-bearing drag on the FCMU motions were serious deficiencies. He considered that these factors resulted in the tasks being very easy to perform and were not realistic. The pilot workload was considered to be very low when compared with the other simulator and the zero-gravity conditions in the OWS.

On the other hand, subject 2 considered the air bearing to be a very good approximation of the OWS situation, although he did recognize that the task was made easier by the absence of the additional degrees of freedom. He noted that the differences between the air-bearing simulator and the OWS were what he had expected and that the additional workload to cope with the increased degrees of freedom for the OWS conditions were reasonable. He concurred with subject 1, however, concerning the adequacy of the visual cues in the air-bearing simulation but differed on the influence of bearing friction. He considered this to be detectable only in the occasional runs when the bearings became fouled with foreign particles. Otherwise, he stated that the drag was undetectable and had no noticeable influence on the FCMU motions or on his maneuvering tasks.

Subject 2 stated that he found very little value in the six-degree-of-freedom visual task simulator primarily because of the inadequacy of the visual cues used to depict the extravehicular conditions. He attributed this inadequacy to lack of picture resolution and three-dimensional qualities, as well as to lack of earth and sky features useful for determining azimuth and cross-range information. He did appreciate the ability to experience dynamic responses of the FCMU with six-degrees-of-freedom motion but considered this to be a relatively minor feature. The opposite position was taken to some extent by subject 1 who considered this motion capability to be the most important aspect of the visual simulator and thereby it was much more useful than the air-bearing simulator. He concurred, however, with subject 2 on the deficiencies of the visual presentation.

In defense of these two differing opinions, it should be noted that each subject was relating to a different set of conditions for the in-flight tests. In the first case, subject 1 used only the original flight restraint harness which was found to be deficient and was not truly represented in the simulators. Subject 2, however, completed most of his tests with the rigidized harness which was found to be much superior to the original and closely matched the conditions of the simulators.

Both subjects commented on the favorable aspect of being able to hear the audio cues associated with the thrusters firing which were provided with the air-bearing system but not with the visual task simulator. These cues appeared to give the subjects confidence that the system was responding to their control inputs although the subjects could not necessarily distinguish which thrusters were firing. They both recommended that if the thrusters could not be heard inside the pressure suit under actual extravehicular conditions, simulated thruster audio cues should be provided to them through their earphones to ease their task.

Training.- As noted in reference 6, the training received by the two flight subjects prior to the mission was considered by them to be adequate for developing their basic skills of controlling the FCMU and to accomplish the in-flight tests. However, they had not fully developed their proficiency in performing the maneuvers in the visual task simulator because of its particular limitations and artifacts. Subject 1 noted that a few short sessions with a break of several hours in between was preferable to a long, continuous session. Subject 2 noted that the VTS seemed to have "a personality of its own" due more to its limitations and artifacts than to workload of controlling six-degrees-of-freedom motion; consequently, he spent considerable time in each session adapting to the simulator.

Both subjects commented on the desirability of a simulation technique combining the major attributes of the two simulators, that is, providing six-degrees-of-freedom motion within a full-scale three-dimensional mockup of the OWS.

Discussion of Additional Design Features

Because both flight subjects were in agreement concerning the desirability of three-axes translation but differed strongly on the subject of the foot-control concept after completing the in-flight tests, it was considered desirable to undertake a brief study of a refined version of a foot-controlled system incorporating the additional two axes of translational capability with the aid of the visual task simulator. This was done to determine the extent to which the undesirable aspects of the single-axis translation capability of the FCMU might have influenced the evaluation of the foot-control concept by the two subjects.

The very brief exploratory study was carried out during the postmission simulation session by using the visual task simulator as discussed in appendix C. This study utilized a different foot controller which delegated the attitude and translation control functions to the right and the left foot, respectively. This feature eliminated the somewhat undesirable FCMU feature of requiring paired or coordinated inputs from both feet for all control commands. A third axis of control was added to each foot pedal to accommodate the additional features.

Both subjects agreed that this refined system was a marked improvement over the FCMU because of the inclusion of the additional control capability. However, they appeared merely to have reinforced their original divergent opinions concerning the applicability of the foot-control concept to future maneuvering systems.

Because of this disagreement between the two flight subjects concerning the merits of this control concept, it is considered pertinent to introduce the comments of the third crewman, who served as the backup commander and participated in the premission simulation phase of this experiment as subject 3. (He was not utilized as a replacement for either space mission and had not participated in the postmission tests.) During a postmission discussion, subject 3 stated that based on his premission experience with both the T-020 and M509 experiments, he considered that the basic concept of foot control had merit but that the foot controller as implemented on the FCMU was not applicable to an operational system. His primary concerns with the FCMU were the limited translation capability and the need for coordinating both feet. He noted that the feet were not as precise as the hands but he also expressed concern over problems with the hand controller of the ASMU as well. His recommendation for the foot-control concept was the same as the approach taken in the study of the refined system using the six-axes foot controller. It appears, therefore, that subject 3 was generally in accord with the comments of subject 2.

CONCLUDING REMARKS ON EXPERIMENT T-020

In summary, this experiment has demonstrated that trained operators could successfully perform various maneuvers with a relatively simple unstabilized foot-controlled maneuvering system in the zero-gravity environment of the Orbital Workshop. Furthermore, it is believed that the results of this experiment and the generally favorable views of two of the three Skylab crewmen involved in the experiment have established the desirability of hands-free operation and the feasibility of applying the foot-control concept to future operational maneuvering systems. However, it is recognized that this experiment has not established the practicality of such an application inasmuch as the experiment was not oriented toward the many operational requirements that must be considered for a practical application. In view of some of the problems encountered in this experiment and the comments of all three subjects, it is evident that further research effort will be required if the foot-control concept is to be implemented.

Although actual experience in the pressure-suited mode was very limited for this experiment, neither subject expressed serious concern about the influence of the pressurized suit itself. In view of the fact that most of the difficulties appeared to be caused by factors other than the pressurized suit, it appears reasonable to conclude that these tests demonstrated that operation of a future operational system employing foot controls probably would not be seriously encumbered by the pressure suit. It is obvious, of course, that close attention would have to be given to providing proper integration of the suit with the maneuvering system and to providing a proper fit of the suit to the operator.

Although the test maneuvers could be successfully performed with the single-axis translation system, both flight subjects were in agreement that a full three-axes capability should be incorporated in any future operational maneuvering systems in order to provide a reasonable pilot workload and to permit the system's use for maneuvers other than those used in the tests. Likewise, both subjects concurred that the system could be operated satisfactorily without the aid of attitude stabilization but that such stabilization was highly desirable from the standpoint of reducing pilot workload.

Although there were significant differences in the personal opinions of the flight-test subjects as to the relative importance of one simulator compared with the other, the results indicated that the two simulators employed were useful research and training tools. The simulators generally demonstrated the dynamic characteristics of the FCMU and the performance capabilities of the astronauts with a reasonable degree of accuracy. The pilot workload experienced in actual zero-gravity conditions appeared to fall somewhere between the workloads imposed by the two simulators. From an overall standpoint, the results achieved with the visual task simulator when compared with the in-flight results were conservative whereas the air-bearing simulator results were somewhat optimistic.

In view of the strongly differing opinions of the two subjects and the somewhat differing results of the two simulators, it appears that the use of two different types of simulators was beneficial to obtaining a balanced representation of the actual zero-gravity experience.

Although effective in other respects, the simulation studies failed to reveal the problems associated with the original restraint harness. This result suggests that the use of simulators cannot completely replace the use of actual zero-gravity tests in the development of future maneuvering systems, particularly in the area of man-machine integration.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Va. 23665
July 31, 1975

APPENDIX A

COMPARISON WITH RESULTS OF EXPERIMENT M509

It is pertinent to the objectives of this experiment to make some comparisons of the results from both Skylab maneuvering system experiments and to comment on how these results might apply to possible future operational systems. This discussion is based on the results of experiment T-020 as covered in this report and the results of experiment M509 as reported in reference 2.

Restraint Harness

Considerable effort, including special simulated zero-gravity tests, had been directed toward suitable body restraint harnesses for both systems during their development phases prior to the flight missions. However, both maneuvering systems experienced difficulties with these systems during the actual zero-gravity test runs. In both cases, the subjects found that relative motion between their bodies and the equipment was very distracting and at times uncomfortable. Although some fixes were worked out for each system during the missions, these were considered only stop-gap measures and did not necessarily represent the ultimate solutions to the problem. It is evident, therefore, that in the future very careful attention must be directed toward the mounting of any type of equipment to the astronaut's body when operation of a maneuvering system is involved. It is very likely that special developmental efforts for future systems will be required to be carried out in actual zero-gravity conditions.

Control-System Response Characteristics

A comparison of the static responses (linear and angular accelerations) and related physical characteristics of the two maneuvering systems for the shirtsleeve condition is given in table VII. It is evident that the inertial characteristics of the FCMU and ASMU systems differed significantly. This is due primarily to the different locations of the various pieces of equipment and to the extra equipment carried in the ASMU. Furthermore, the thruster levels for the ASMU were from about 2 to 8 times higher than those of the corresponding thrusters for the FCMU. These higher thrust levels, coupled with the generally smaller moment arms of the ASMU, resulted in the static control responses of the ASMU being from about 1.5 to 4 times larger than those of the FCMU.

In spite of these seemingly large differences in response characteristics for the two systems, neither of the two subjects who operated both systems in the OWS considered that most of these differences were particularly significant relative to the handling qualities of the systems. One subject had noted that the control harmony for the ASMU was better than that for the FCMU. This was attributed to the fact that the yaw acceleration for the FCMU was about three times that for pitch and roll, whereas those for all three axes of the ASMU were very nearly the same. The yaw acceleration was generally considered to be too high for the FCMU although, as shown in the table, it was actually somewhat less than that for the ASMU. From this result it is judged that fairly satisfactory control responses may be achieved anywhere in the range of about 3° to 13° per second^2 provided the responses about all three axes are fairly close to the same value.

Expenditure of Propellant Gas

As noted previously, the thrust levels for the FCMU were generally much smaller than those of the ASMU. This would seem to indicate that the propellant expenditure for the FCMU would be correspondingly smaller than that for the ASMU. However, as shown by the comparison in figure 17, the expenditure rates of the two subjects for the two systems, in terms of weight of propellant used per hour of operation per total system weight, were almost identical. The explanation for this condition is attributed primarily to the fact that the subjects tended to use the same maneuvering velocities with both systems. Thus, differences in thrust levels only resulted in the thrusters of the two systems being fired for different periods of time. Although the longer thruster moment arms for the FCMU could be shown to have a favorable effect on the propellant expenditure for controlling rotational motions, this factor should be relatively minor because most of the propellant gas for this system was used to control the translational motions.

In comparing the propellant expenditure rates for the two systems, the differences in thruster moment arms might account for the slightly lower rate of subject 2 shown in figure 17. Also, the fact that the rate for subject 1 with the FCMU was slightly higher than that for subject 2 could be attributed to the restraint-harness problems that subject 1 encountered. However, it is doubtful that the accuracy of the values for the expenditure rates were determined to the degree of accuracy required to make these differences significant.

Perhaps the most significant point to be drawn from this comparison is that insofar as propellant utilization was concerned, the type of system controller employed and the relative degree of precision with which command inputs could be made was relatively insignificant.

Attitude Stabilization Systems

Both experiments clearly demonstrated that by controlling the thrusters directly, the operators were able to stabilize satisfactorily their attitudes and complete the desired maneuvers without resorting to use of an automatic stabilization system. This result emphasizes the point that an attitude stabilization system serves primarily to reduce the operator's piloting workload and, furthermore, that loss of such a system should not necessarily inhibit the operator's ability to perform successfully most general maneuvering tasks. These findings are particularly important when analyzing system failure modes and the requirements for component redundancy in subsequent development efforts for an operational system.

Translation Control Capability

When compared with the three-axes translation control capability of the M509 system, the single-axis capability of the FCMU was generally considered to be inadequate by the test subjects. However, the ability to successfully perform some primary tasks with the FCMU does serve to demonstrate that in an emergency condition involving loss of one or possibly two axes of translation control of a fully implemented operational system, the operator should be able to accomplish a safe return to his spacecraft with the remaining translation control. This situation, of course, assumes that the attitude-control capability of the system remains intact.

System Controllers

Although it is believed that the feasibility of the foot-control concept has been demonstrated by the results of experiment T-020, the application of foot controls to an operational system appears to be an open question partly because of the lack of agreement between the two test subjects. It should be noted, however, that there also were some problems encountered with the hand controller of the ASMU. There were problems of gripping the controller, of maintaining inputs for long periods of time, of maintaining system control while using the hands and arms to carry objects, and of obstructing the operator's working envelope. It is evident from both experiments, therefore, that more effort should be devoted to the development of suitable controllers.

Consideration should be given to the combination of hand and foot controls as a means of overcoming some of the shortcomings of using a single type of controller. The combination of foot and hand controls is, of course, in very common usage for most complex ground and airborne vehicles in use today. One possible arrangement for a future maneuvering system is one in which the feet are used to control translation in the three axes and the right hand is used to control attitude. It appears appropriate to delegate the translation control functions to the feet inasmuch as they generally have no other useful function in space activities and, therefore, could be used full time to make the necessary translation commands and corrections throughout the maneuvers. The hand controller could be located near the operator's right leg, outside the normal working envelope of the operator. The left hand would be free at all times to carry equipment or to act as a bumper or an anchor during the docking maneuver. In the event that attitude stabilization was incorporated, control inputs by the right hand would not be required continuously and, therefore, the right hand also could be free during some of the maneuvering activities.

APPENDIX B

DESCRIPTION OF TEST MANEUVERS

The following are descriptions of each of the test maneuvers given in the sequence in which they were performed.

Pitch-Attitude Change and Hold

Starting from initial conditions of essentially zero rotation and translation, the operator's primary task was to perform a 90° change in pitch attitude by using whatever rate was considered to be desirable or comfortable. Upon reaching the 90° position, the operator was to hold that position for a period of at least 10 seconds during which time he held his estimated pitch attitude and rate within about $\pm 10^\circ$ and $\pm 1^\circ$ per second, respectively. When these were firmly established, he then was to repeat the maneuver in the opposite direction. Throughout the complete maneuver, the operator's secondary tasks were to maintain the roll and yaw attitudes and rates within the same limits as pitch and also to maintain his position within 1 m (0.3 ft) of his starting position.

Roll- and Yaw-Attitude Change and Hold

The roll and yaw maneuvers were the same as for pitch except that they were performed separately about the roll and the yaw axes rather than about the pitch axis.

Single-Axis Translation and Position Hold

Starting from initial conditions of essentially zero motion with the thrust axis alined with the target position, the operator's primary task was to perform a translation maneuver directly to the target position by using whatever rate was considered to be desirable or comfortable. Upon reaching the target position, the operator was to maintain that position for a period of at least 10 seconds during which time he was to hold his translational position and rates within about ±0.3 m and ±0.03 m/sec. Throughout the complete maneuver, the operator's secondary tasks were to maintain the pitch, roll, and yaw attitudes within the previously prescribed limits except as was required to control spatial drift rates.

Double-Axis Translation

Starting from the zero-motion initial condition with the thrust axis pitch about 10° down from the target position, the operator's primary task was to aline the thrust axis with the target and initiate translation toward it at the desired rate; pitch 90° down so as to be able to make cross range corrections; and finally to complete the maneuver by grasping the target and braking his translational and rotational rates with his arms and hands. (In the case of the VTS where direct contact with the target was not possible, the run was merely terminated at the appropriate distance with no braking action.) The operator's secondary tasks were to maintain the roll and yaw attitudes within the specified limits. In this case, the FCMU was not used to alter the translational rate as the target was approached.

Dogleg Translation

Starting from the zero-motion initial conditions at some distance from the target with the line of sight to the target pitched up approximately 45° from the down-thrusting axis (+Z-reference axis), the operator's primary task was to initiate a translation in the direction of the thrust axis; and then to pitch down about 30° to be able to thrust toward the target by firing the up-direction thrusters. The upward thrusts, applied at intervals, redirected the FCMU to the target with a somewhat reduced translational rate. The operator terminated the maneuver as he grasped the target. The secondary tasks were similar to those previously defined for the other maneuvers.

APPENDIX C

AN EXPLORATORY EVALUATION OF AN IMPROVED FOOT-CONTROLLED MANEUVERING SYSTEM

As an adjunct to the formal experiment with the FCMU, an exploratory study was carried out by using the participating T-020 flight subjects to evaluate a refined version of the foot-control concept incorporating translation control capability along the longitudinal and lateral axes. This version had been considered during the definition phase of the experiment but had not been pursued because of scheduling and funding limitations. The evaluation was performed at the conclusion of the postmission session at the Langley Research Center by use of the visual task simulator with the foot controls modified to represent the proposed version. Some of the same maneuvers used for evaluation of the original FCMU were performed, and the subjects were requested to comment on the influence of the refinements. No attempt was made to obtain quantitative data for these tests.

The Improved Maneuvering System

The visual task simulator as used for the FCMU experiment (ref. 6) was modified by installing a new foot controller and by utilizing an alternate computer program.

Foot controller.- The new foot controller was referred to as a six-axes controller inasmuch as it employed a set of two independently operated three-axes controllers, one for each foot. This arrangement permitted the operator to command longitudinal and lateral translation responses as well as to command pitch, roll, yaw, and vertical responses as in the case of the original FCMU. The right foot was used to command the three specific attitude responses and the left foot to command the three translation responses. This was in contrast to the original four-axes system which required the use of both feet for any specific command input. The control logic used with this system is shown in table VIII. This logic was somewhat similar to that for the four original control functions and minimized the time required by the subjects to adapt to the revised system.

The additional control axis for each foot pedal was obtained by using a vertical pivot at the heel of each foot plate which thereby permitted lateral rotation of the lower leg at the knee joint to be used by the operator as the command input. Switches to provide the control signals to the computer were activated near the limits of travel which corresponded to about ±9-mm (±3/8-in.) lateral movement at the toes. The foot plate incorporated preloaded springs to provide a positive centering action to the neutral position for the foot plate.

Computer program.- The alternate program used for this study was the same as that used for a concurrent study of the M509 maneuvering system mentioned briefly in reference 2. The foot controller was merely substituted for the hand controller and the program for the direct mode was used. In this mode, the controller essentially operated the thrusters directly without use of the stabilization systems provided in the M509 unit. This mode corresponds to the on-off operation of the thrusters in the T-020 FCMU. The orientation and thrust levels of the thrusters were the same as those of the M509 unit. The reference axes for the refined system were the same as those for the M509 and therefore were rotated about 20° in the pitch-down direction from those for the original FCMU, that is to say, the vertical thrust axis was alined essentially parallel with the operator's back rather than inclined about 20° forward at the feet.

A comparison of the control responses in terms of acceleration for the original and the refined foot control systems is given in table VII. As noted, the latter values are the same as those for the M509 system.

Results and Discussion

Both subjects were able to satisfactorily perform the test maneuvers with this new system and considered the tasks much easier and the workload considerably reduced from that for the original FCMU system. The subjective evaluations for this study, however, reflected the strong differences in the personal opinions of the two subjects as brought out in the main body of this report and in reference 6. The first subject was still of the strong opinion that foot controls in any form were not acceptable as a substitute for hand controls. He restated the opinion that hand control was precise and an intuitive function, whereas foot control was not; and consequently, he contended that use of foot controls could lead to serious problems under conditions of stress. In direct opposition to this opinion, the second subject was still strongly convinced that the use of foot controls could overcome some of the problems experienced with hand controls. He found that with his prior hand and foot control experiences, he had easily adapted to the refined system. Furthermore, he did not encounter the somewhat unusual toe-foot coordination problem that he had experienced with the original system. He was of the opinion that a person learning to use the foot controls should require about the same time as a person learning to use the hand controls and that a person already experienced with hand controls would find little difficulty in adapting to the foot controls.

The following are excerpts taken from tape recordings of the comments made by these subjects during this study from which these points were drawn. To improve readability, the excerpts have been edited by the addition and deletion of various words and phrases, as denoted by the brackets and the dots, respectively. The letters "PI" refer to a question or comment posed by the principal investigator and "S" refers to the response of the subjects. The following is taken from the discussion with subject 1:

PI: Are the problems . . . with the controllers and the travels fairly reasonable?

S: I would say that the travels are good in this configuration. If (I) were at zero g, I would think that (I) would want the forces less. But sitting in here (in the simulator), they seem acceptable.

PI: Less travel or forces?

S: Both, but here they are okay. The task is much better, of course, with the six degrees (of control response) we have here . . . It can be taught but it isn't natural. There is nothing intuitive about the way this is flown, whereas hand controller operations are very intuitive.

PI: As far as the dynamics are concerned, (the system) is . . . operating like the direct mode (of the M509) unit, isn't it?

S: It seems to. The fact that (foot control) is not intuitive is a huge disadvantage but (the system) seems to have the (same) dynamics. When I put (a command) in now . . . with my feet, I never am as sure of exactly what I put in . . . compared to what I did with my hands, so that is another drawback.

PI: I take it (that) a few times you did tend to use the other foot?

S: That is true. What happens, I have noticed, if I am trying to get a command in on one foot and (the system doesn't respond) fast enough, then I tend to (use) my other foot the same way . . . but the moment I do, of course, I recognize it; but that means I have got some additional (commands) in (that) I have got to do something about.

PI: Does the attitude (and translation control) seem more logical?

S: This seems better logic and everything than the T-020 did, but once again, it is very artificial. There is nothing natural about it . . . I will tell you another thing I think is true. You are going to have a more difficult time ever convincing anybody that flies it to take a foot-controlled maneuvering unit outside. They will do a lot of things inside the workshop where it isn't a big deal than they ever would think about accepting (for outside activities).

(I) made a lot of squawks long ago about the T-020 but all the time in the back of (my mind) was the fact that (I knew) even if we ended up (in difficulty we) still probably weren't going to get hurt. So, the level that you disagree with the concept of something, you don't work at it as hard. You just say okay, we will go ahead and do it because we probably won't get killed doing it. Then the minute it gets a little bit tougher, then we start squawking a little bit more.

The following are taken from the discussions with subject 2:

PI: Can you give me some general impressions?

S: Well, I think this is a very good mode. I think it could be utilized very nicely, particularly if you had (an) attitude-hold phase. Sorting out my line-of-sight rates from attitude rates is a very, very demanding task (in this simulator), but with an attitude-hold mode you would be able to work out your line-of-sight rates, and I think you can fly a pretty precise trajectory.

PI: (Did you have any problems) as far as the logic and coordination aspects of it?

S: It isn't too bad, it's just (that) you have to think about it for awhile. You know, since we are (conditioned) to using the foot controllers in a different mode, I have to be careful. I have thrown in a couple of two-foot (control inputs) -- realized it as soon as I did it and took the (wrong inputs) back out.

PI: It's no big transition?

S: No, it isn't.

PI: Do you find a three-axes function for each foot a bit demanding?

S: No, I don't think so, particularly, again, if you have got attitude hold, you are not really working (your) feet in six directions (at the same time).

PI: (Is it any problem) as far as muscles having to (coordinate the) toe-up, toe-down, toe-left, toe-right, foot-up, and foot-down (inputs)?

S: No, I don't think it is any problem.

PI: Having one foot (to control) attitude and one foot (to control) translation, does that seem better to you than like we did for the T-020?

S: Oh yes, that way you don't have as much of a chance of putting in the wrong input.

PI: You can accept this new reference axis fairly easily?

S: Oh yes, once you get it in your mind as to where your maneuvering axis is.

The biggest problem is getting the attitude squared away so that your line-of-sight rates mean something. You have to really keep the horizon in sight here and keep it just exactly where you want it, then consider your line-of-sight rates and that is the beauty of the attitude-hold mode.

PI: You flew the M509 with the reference axis along your backbone and the T-020 reference along your feet and I think you said it really didn't make too much difference in rotation. What about the fact that your feet are sticking out there . . . Sometimes you are maneuvering and the target gets pretty close to being cut off by your feet. Does that seem to be bothersome?

S: Only (with) the T-020, but if you fly (with) the six-degree-of freedom foot control, you won't ever have to fly (with the target) down there.

PI: (The problem with T-020 is due more to) the fact that it is limited to single-axis translation than . . . to the fact that you will fly (with the target) down there?

S: Yes, I think so.

PI: You know (that) you can always "get out of the box" with three-axes translation as opposed to single-axis translation?

S: Right.

PI: I am afraid the single-axis translation tended to add a negative flavor to the other (FCMU) features that you had (to evaluate in the OWS experiment. The FCMU) might have been more acceptable if we had (provided) more axes of translation control.

S: Yes, I think so. I have always felt that if you could take the foot control pedals and make them easier to use (than for T-020) and put them on the M509, . . . you would have a real going combination.

PI: What's your impression of the amount of training effort that it would take to learn the use of the six-axes foot controls?

S: My assumption will be . . . that the guy has had training with the six-axes hand controller system in . . . some sort of simulator and now you are going to ask him to use the six-axes control . . . on a foot-controlled maneuvering unit. I do not think it will be a difficult transition for him at all. I think it will take – oh, I cannot even guess how long. It is an individual thing. The two are enough alike that it will be a fairly natural transition and it won't take too much time.

I think if you are asking him to go from six-axes hand controller to the regular FCMU (four-axes controller) that we have in the T-020 system, I think that it will take some time just like it did for us.

PI: So, you would think that the training time for a six-axes foot controller would be (about) the same . . . as a hand controller?

S: Yes . . . . Well, like I say, if he already knows how to use the hand controller, then I don't think it will be much. If he has never used the hand controller before, it would be a different ball game.

REFERENCES

1. Skylab Program Office. MSFC Skylab Mission Report – Saturn Workshop. NASA TM X-64814, 1974.

2. Whitsett, C. E., Jr.; and McCandless, B., II: Skylab Experiment M509: Astronaut Maneuvering Equipment Orbital Test Results and Future Applications. Paper 74-137, 20th Annual Meeting, American Astronaut. Soc., Aug. 1974.

3. Gemini Summary Conference. NASA SP-138, 1967.

4. Thomas, David F., Jr.; Bird, John D.; and Hellbaum, Richard F.: Jet Shoes – An Extravehicular Space Locomotion Device. NASA TN D-3809, 1967.

5. Hewes, Donald E.; and Glover, Kenneth E.: Development of Skylab Experiment T-020 Employing a Foot-Controlled Maneuvering Unit. NASA TN D-6674, 1972.

6. Hewes, D. E.; and Glover, K. E.: Premission and Postmission Simulation Studies of the Foot-Controlled Maneuvering Unit for Skylab Experiment T-020. NASA TN D-7963, 1975.

7. Hewes, D. E.: Skylab Experiment T-020 Preliminary Results Concerning a Foot-Controlled Maneuvering Unit. Paper No. 74-138, American Astronaut. Soc., Aug. 1974.

8. Webb, Paul, ed.: Bioastronautics Data Book. NASA SP-3006, 1964.

9. 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	
Axis	Direction	Left	Right
Pitch	Up	Toe up	Toe up
	Down	Toe down	Toe down
Yaw	Right	Toe up	Toe down
	Left	Toe down	Toe up
Translation	Up	Foot up	Foot up
	Down	Foot down	Foot down
Roll	Right	Foot up	Foot down
	Left	Foot down	Foot up

TABLE II.- MANEUVERING PERFORMANCE CRITERIA

Requirements	Initial conditions	Maneuvering conditions	Final conditions
Responsibility	Observer	Test subject	Test subject
Trajectory or position	$<\pm 0.3$ m (1.0 ft)	$<\pm 0.3$ m (1.0 ft)	$<\pm 0.3$ m (1.0 ft)
Translational rates	<0.03 m/sec (0.1 ft/sec)	Desirable, comfortable	<0.03 m/sec (0.1 ft/sec)
Rotational attitude	$<\pm 10^{\circ}$	$<\pm 10^{\circ}$	$<\pm 10^{\circ}$
Rotational rates	$<\pm 1^{\circ}$/sec	Desirable, comfortable	$<\pm 1^{\circ}$/sec

TABLE III.- CALCULATED CHARACTERISTICS OF FCMU SYSTEM

[Typical values for shirtsleeve conditions]

	SI Units	U.S. Customary Units
Weight	139 kg	307 lb
Principal moments of inertia:		
Roll	47 kg-m^2	35 slug-ft^2
Pitch	43 kg-m^2	32 slug-ft^2
Yaw	4.9 kg-m^2	3.6 slug-ft^2
Thruster size:		
Pitch-yaw	136.1 g	0.3 lb
Translational-roll	453.6 g	1.0 lb
Inclination of principal axes from reference axes	7°	7°
Control accelerations:		
Roll	3.0°/sec^2	3.0°/sec^2
Pitch	3.8°/sec^2	3.8°/sec^2
Yaw	9.4°/sec^2	9.4°/sec^2
Translation (Z-axis)	6.2 cm/sec^2	0.20 ft/sec^2

TABLE IV.- SCHEDULE[a] FOR IN-FLIGHT TEST SESSIONS OF MISSIONS SL-3 AND SL-4

Mission	Session	Condition	Time period
SL-3 (Subject 1)	1	Shirtsleeve, original nonrigid restraint	[b]231-[c]20-[d]37 to 231-22-20
	1A	Shirtsleeve, modified nonrigid restraint	241-22-37 to 241-23-45
	2	Pressure suit, modified nonrigid restraint	256-21-49 to 257-00-15
SL-4 (Subject 2)	1	Shirtsleeve, revised rigid restraint	[e]015-14-39 to 015-16-33
	1A	Repeat of 1, also revised nonrigid restraint	024-13-17 to 024-14-59

[a] Based on the time periods that the OWS voice recorder was operated for experiment T-020.

[b] Calendar day 1973.

[c] Hour, Greenwich Mean Time.

[d] Closest minute.

[e] Calendar day 1974.

TABLE V.- SUMMARY OF MEAN AND STANDARD DEVIATION VALUES OBTAINED FROM IN-FLIGHT TESTS OF SUBJECTS 1 AND 2

Maneuver	Subject	Number of runs	Mean	Standard deviation
Shirtsleeve condition[a]				
Pitch	1	4	68	13
	2	4	97	18
Roll	1	4	84	3
	2	4	100	14
Yaw	1	3	62	4
	2	6	73	10
Single	1	4	47	10
	2	4	42	4
Double	1	5	49	7
	2	7	46	8
Dogleg	1	4	41	8
	2	8	42	7
Pressure suit condition[b]				
Pitch	1	2	62	15
Roll	1	2	63	1
Yaw	1	2	50	1
Single	1	4	45	1
Double	1	5	45	11
Dogleg	1	2	55	1

[a] Includes both sessions 1 and 1A.

[b] Includes only runs made with the life support umbilical in session 2A.

TABLE VI.- PILOT RATING FOR IN-FLIGHT AND CORRESPONDING SIMULATOR TEST CONDITIONS

Maneuver	Subject 1		Subject 2	
	Simulator [a]	In-flight	Simulator [a]	In-flight
Pitch	3	[b] 3	3	4, [c] 3
Roll	3	3	3	4, 3
Yaw	---	3	---	[d] 6, [e] 8
Single axis	3	$3\frac{1}{2}$	3	3, 3
Double axis	3	$3\frac{1}{2}$	3	3, 3
Dogleg	3	$3\frac{1}{2}$	3	[d] 5, 5

[a] From reference 6 for ABS, IVA condition.

[b] From session 1. Also, subject subsequently extrapolated his evaluation to EVA conditions and assigned 9 for all attitude maneuvers and 10 for all translation maneuvers.

[c] First value is for session 1; second value is for session 1A.

[d] Subject subsequently extrapolated his evaluation to account for his unusual left foot coordination problem and assigned 4 for yaw and 3 for dogleg.

[e] Subject continued to have foot coordinate problems which resulted in excessive rotational cross-coupling and translational drift.

TABLE VII.- COMPARISON OF TYPICAL STATIC CONTROL RESPONSE CHARACTERISTICS OF FCMU AND ASMU FOR SHIRTSLEEVE CONDITIONS

	FCMU		ASMU	
	SI Units	U.S. Customary Units	SI Units	U.S. Customary Units
Total system weight[a]	139 kg	307 lb	186 kg	410 lb
Moments of inertia:				
Pitch	43.4 kg-m^2	32 slug-ft^2	28.7 kg-m^2	21.2 slug-ft^2
Roll	47.5 kg-m^2	35 slug-ft^2	25.1 kg-m^2	18.5 slug-ft^2
Yaw	4.9 kg-m^2	3.6 slug-ft^2	15.2 kg-m^2	11.2 slug-ft^2
Accelerations:				
Fore-aft	[b]0.02 m/sec^2	[b]0.06 ft/sec^2	0.11 m/sec^2	0.37 ft/sec^2
Up-down	0.06 m/sec^2	0.20 ft/sec^2	0.10 m/sec^2	0.34 ft/sec^2
Side-side	-----------	-----------	0.10 m/sec^2	0.34 ft/sec^2
Pitch	3.8°/sec^2		9.6°/sec^2	
Roll	3.0°/sec^2		12.8°/sec^2	
Yaw	9.4°/sec^2		13.1°/sec^2	
Thrust levels[c]:				
Fore-aft and pitch	0.13 N	0.6 lb	1.06 N	4.7 lb
Up-down and roll	0.45 N	2.0 lb	0.97 N	4.3 lb
Side-side	-----------	-----------	0.97 N	4.3 lb
Yaw	0.13 N	0.6 lb	0.56 N	2.5 lb
Moment arms:				
Pitch	1.06 m	3.48 ft	0.46 m	1.50 ft
Roll	0.594 m	1.95 ft	0.29 m	0.96 ft
Yaw	0.576 m	1.89 ft	0.29 m	0.96 ft

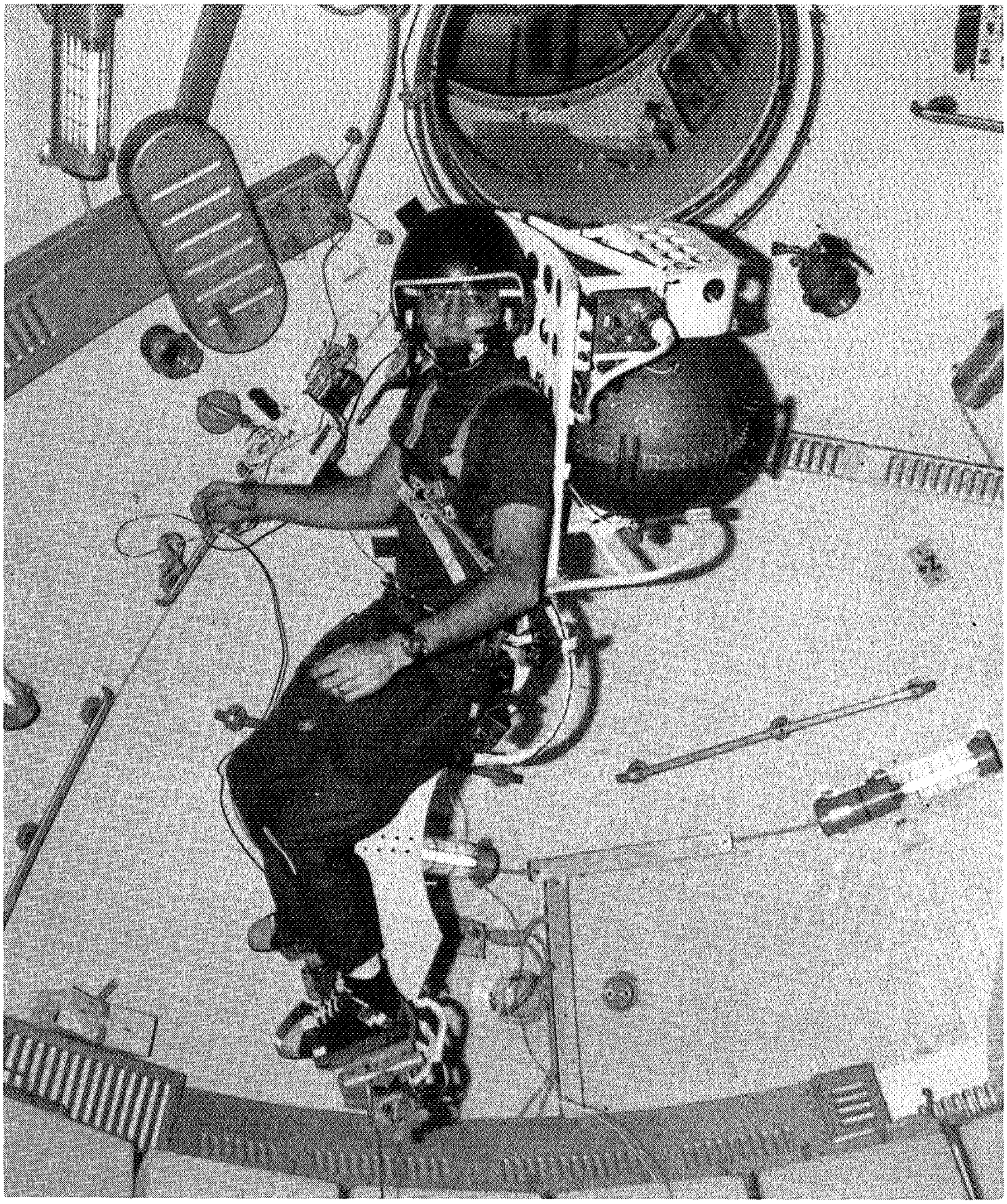
[a] Including 726 kg (160 lb) test subject.

[b] Produced by pitch thrusters.

[c] Values for thruster pairs.

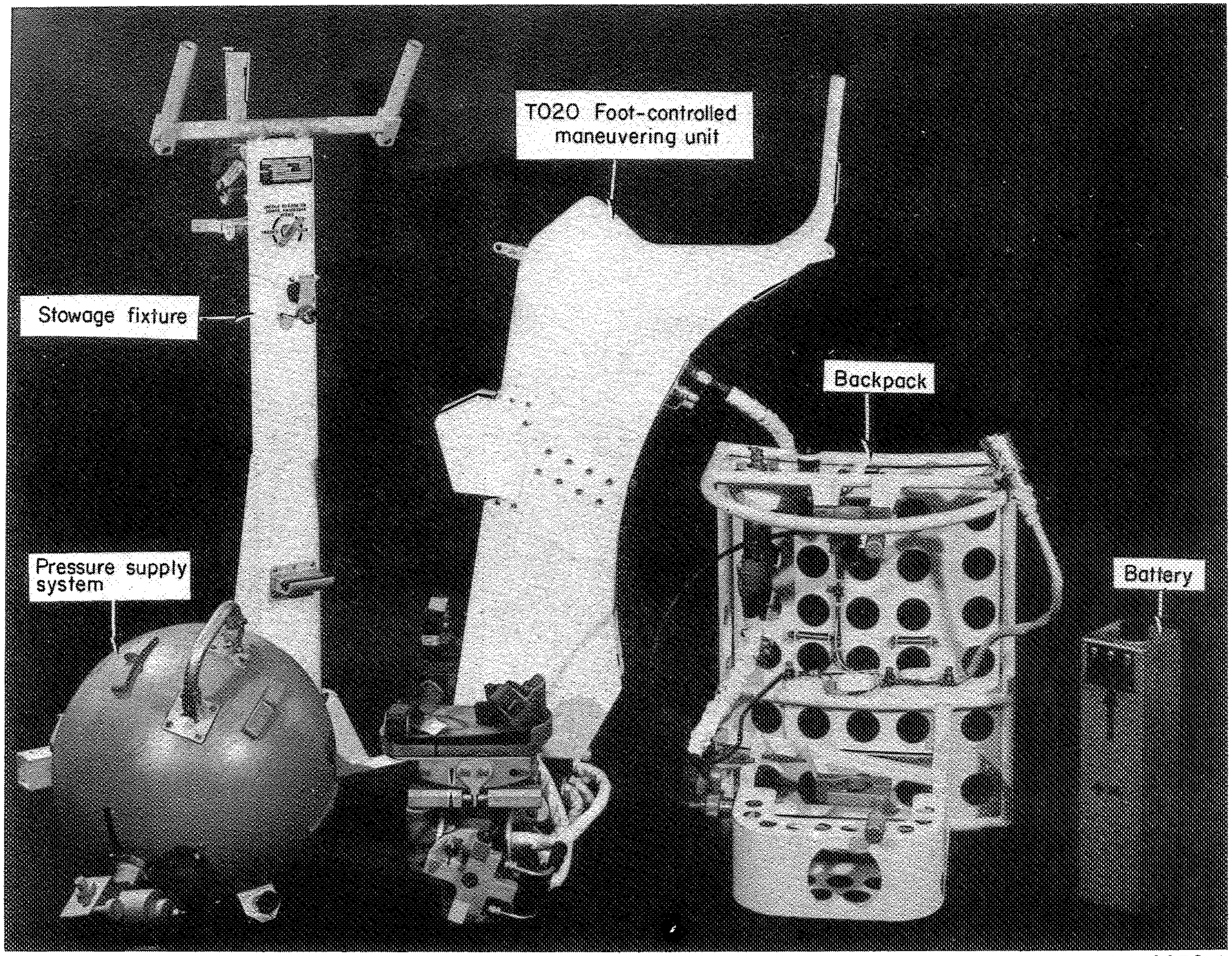
TABLE VIII.- FOOT CONTROL LOGIC FOR SIX-AXES FCMU

Commanded acceleration		Control input	
Axis	Direction	Left	Right
Pitch	Up	---------	Toe up
	Down	---------	Toe down
Yaw	Right	---------	Toe right
	Left	---------	Toe left
Roll	Right	---------	Foot down
	Left	---------	Foot up
Translation (X-axis)	Fore	Toe down	---------
	Aft	Toe up	---------
Translation (Y-axis)	Right	Toe right	---------
	Left	Toe left	---------
Translation (Z-axis)	Up	Foot up	---------
	Down	Foot down	---------



L-75-170

Figure 1.- Photograph of SL-3 test subject performing test maneuvers in the Skylab Orbital Workshop.



L-71-9352.1

Figure 2.- Experimental foot-controlled maneuvering unit components.

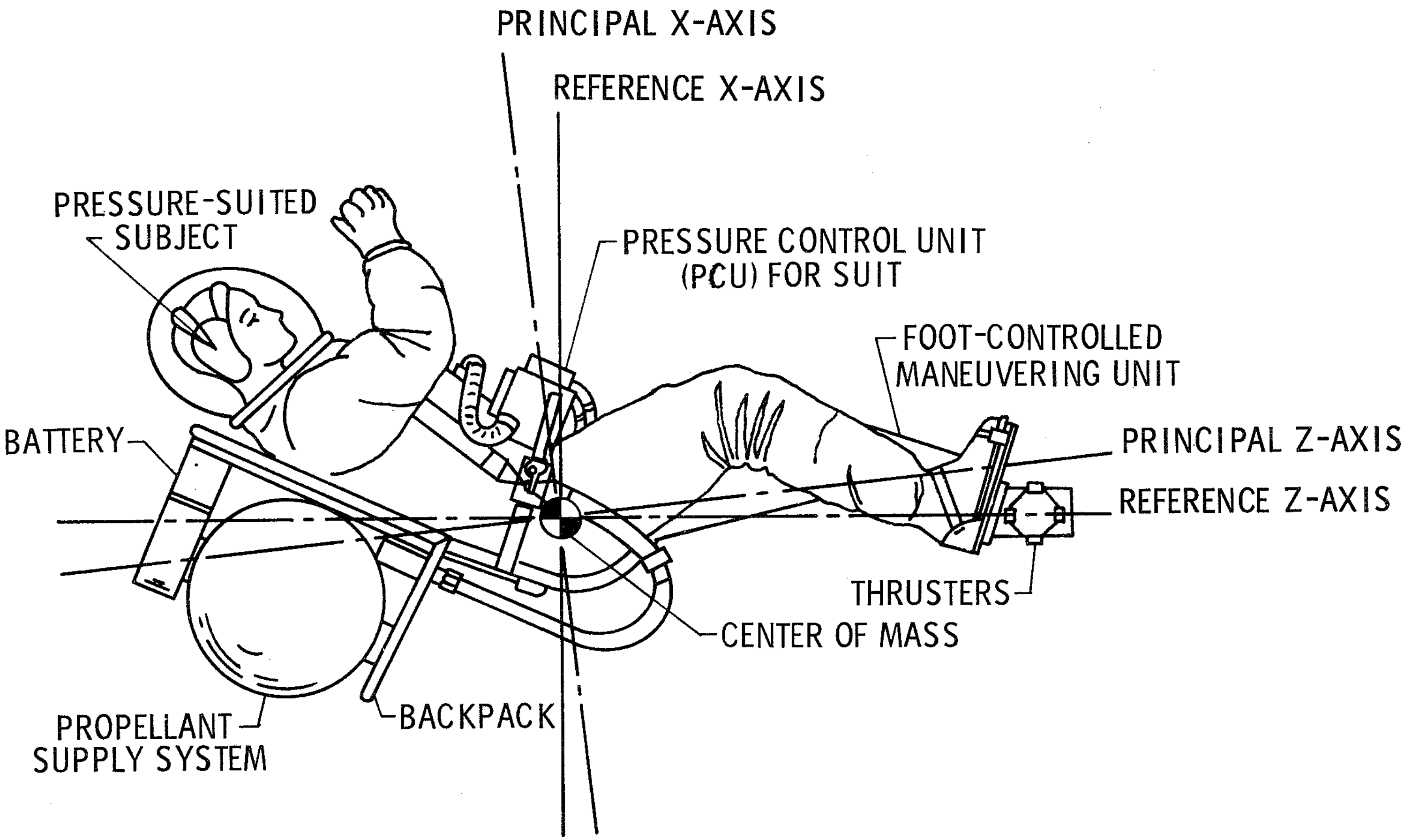


Figure 3.- Sketch of foot-controlled maneuvering unit for the pressure-suited condition.

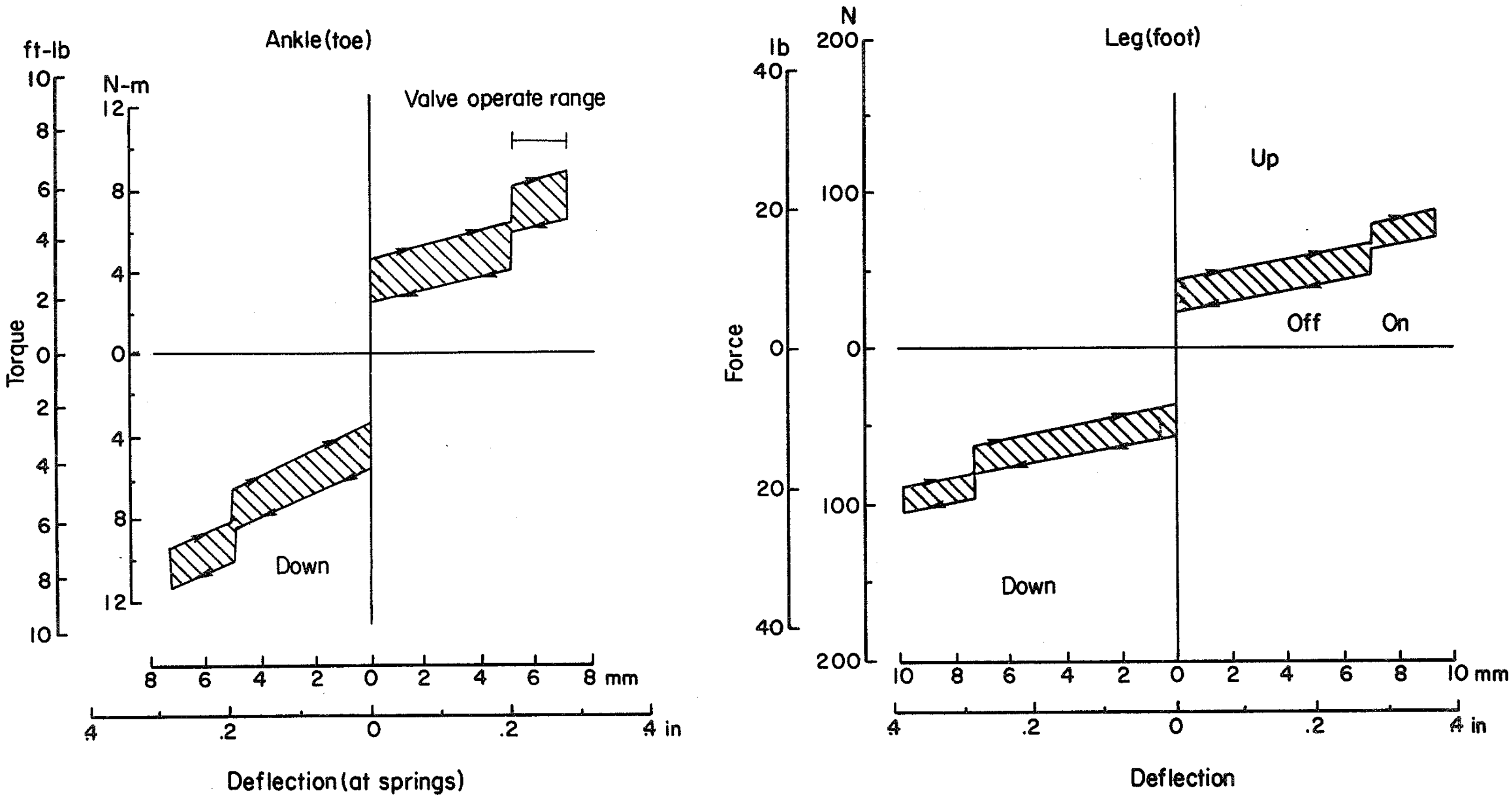


Figure 4.- Typical variations of torque and force with deflection of FCMU foot controller.

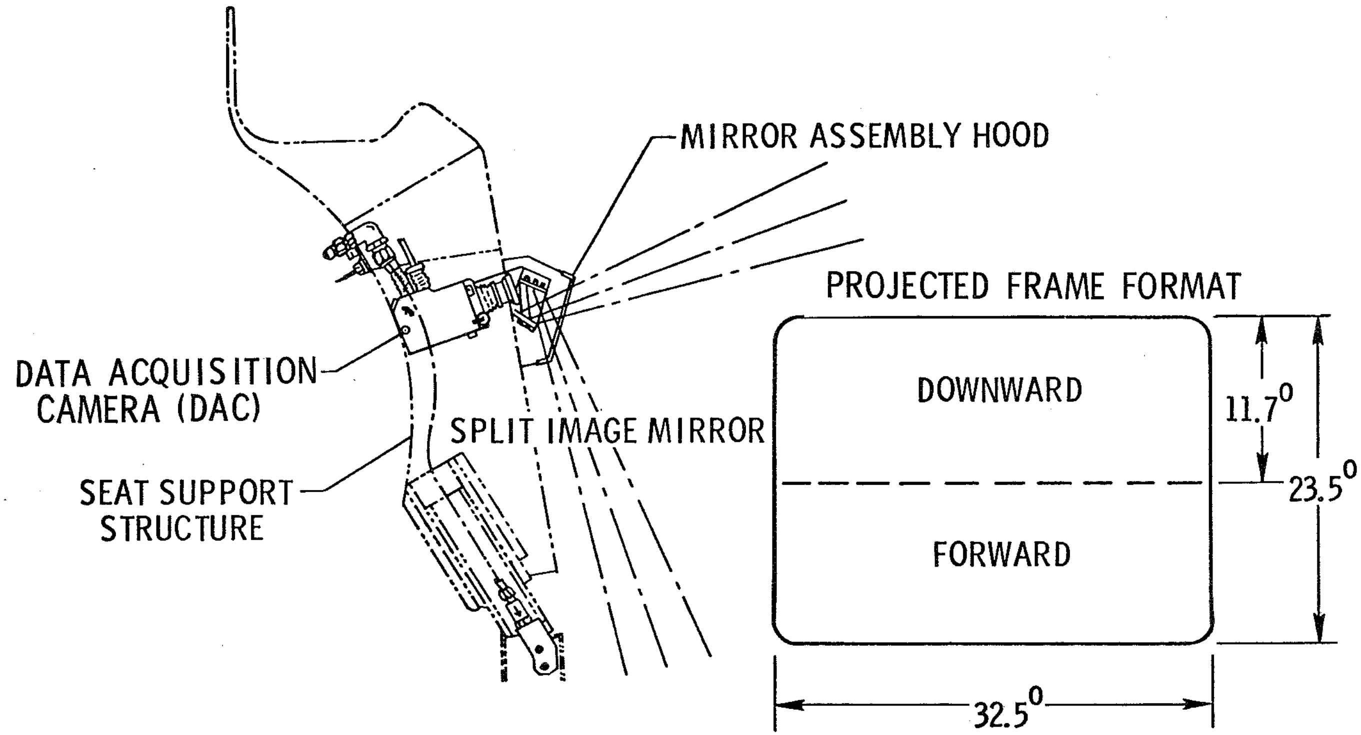


Figure 5.- Sketches of the data acquisition camera installation and the format for the projected split-frame film image.

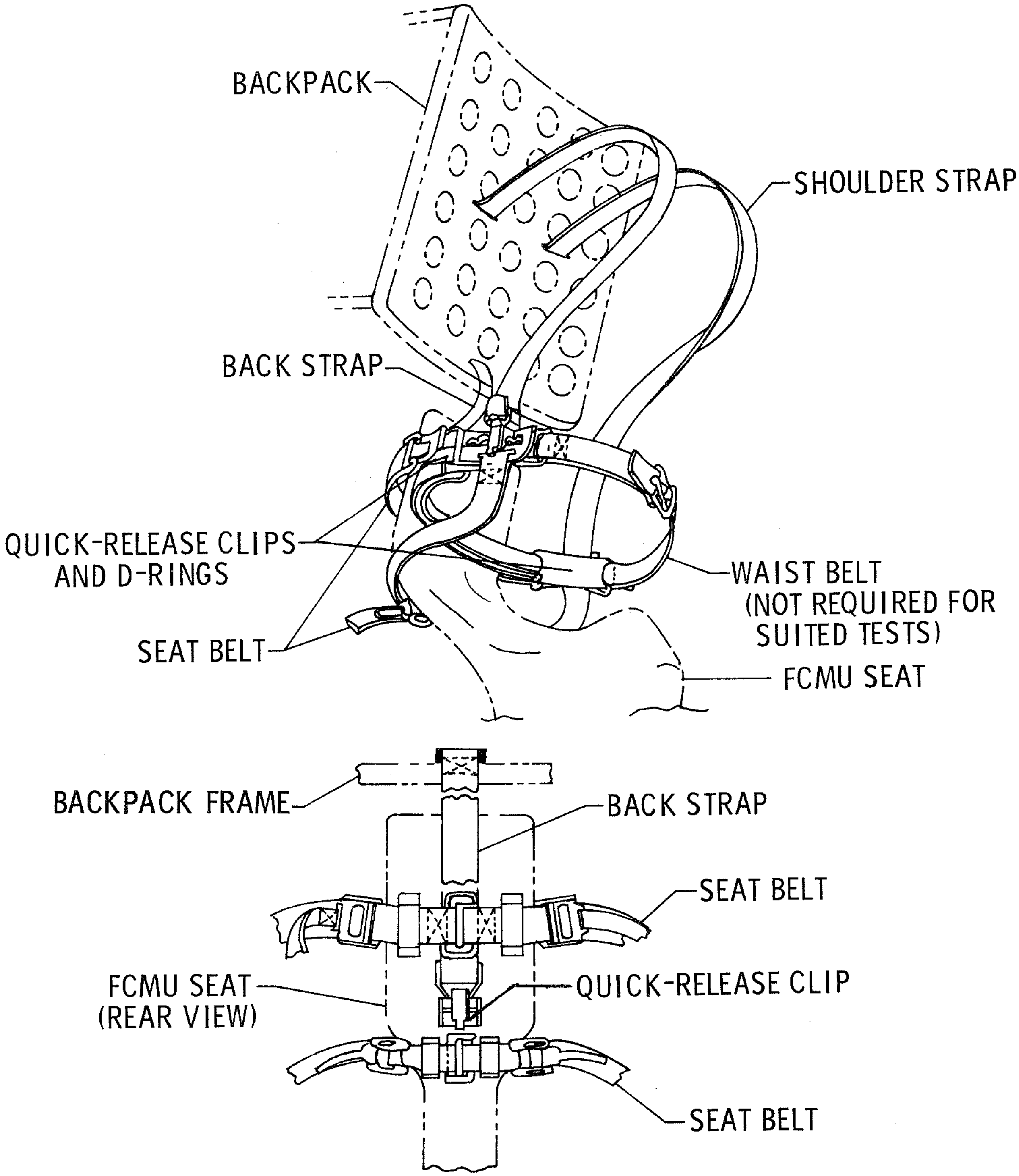
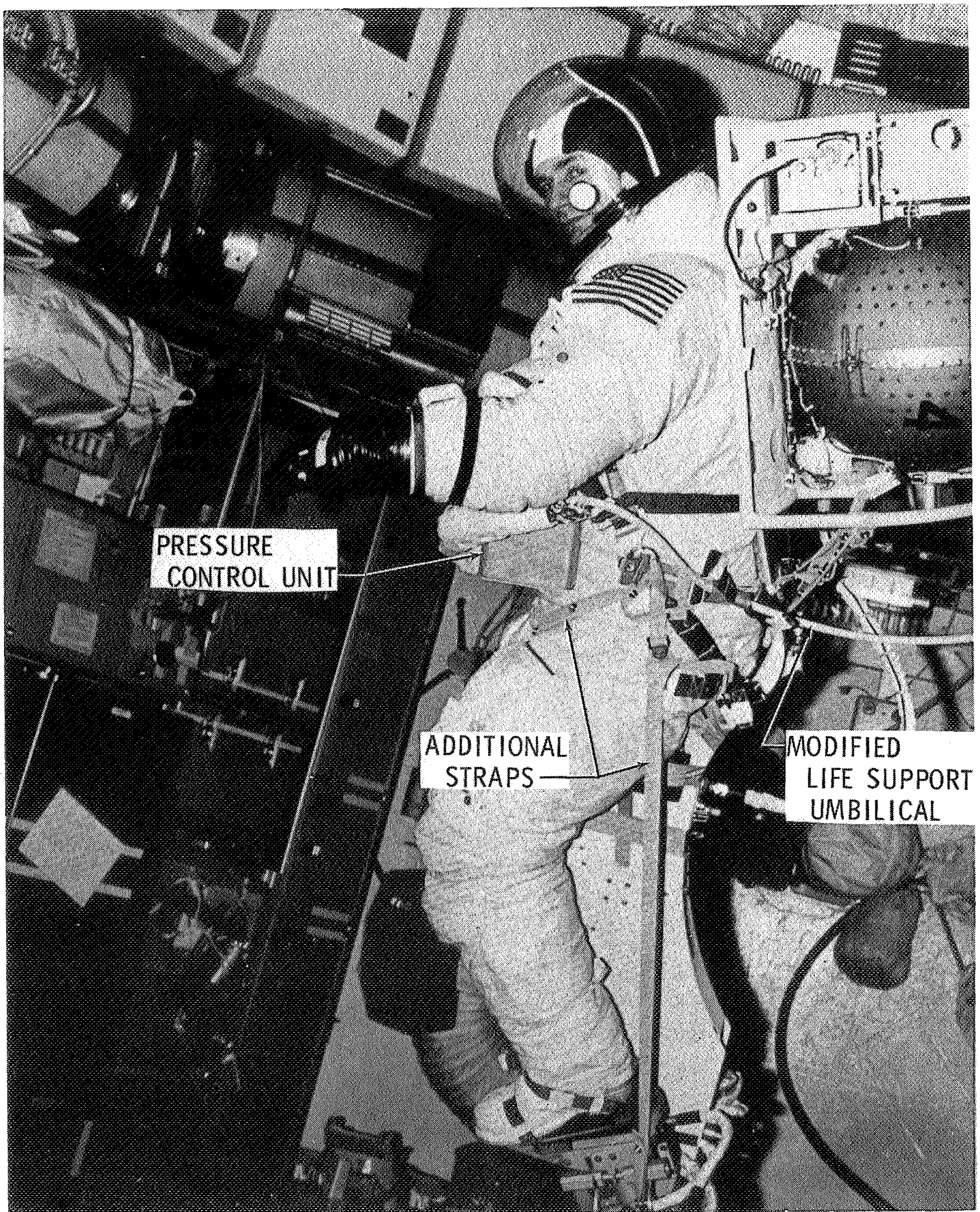
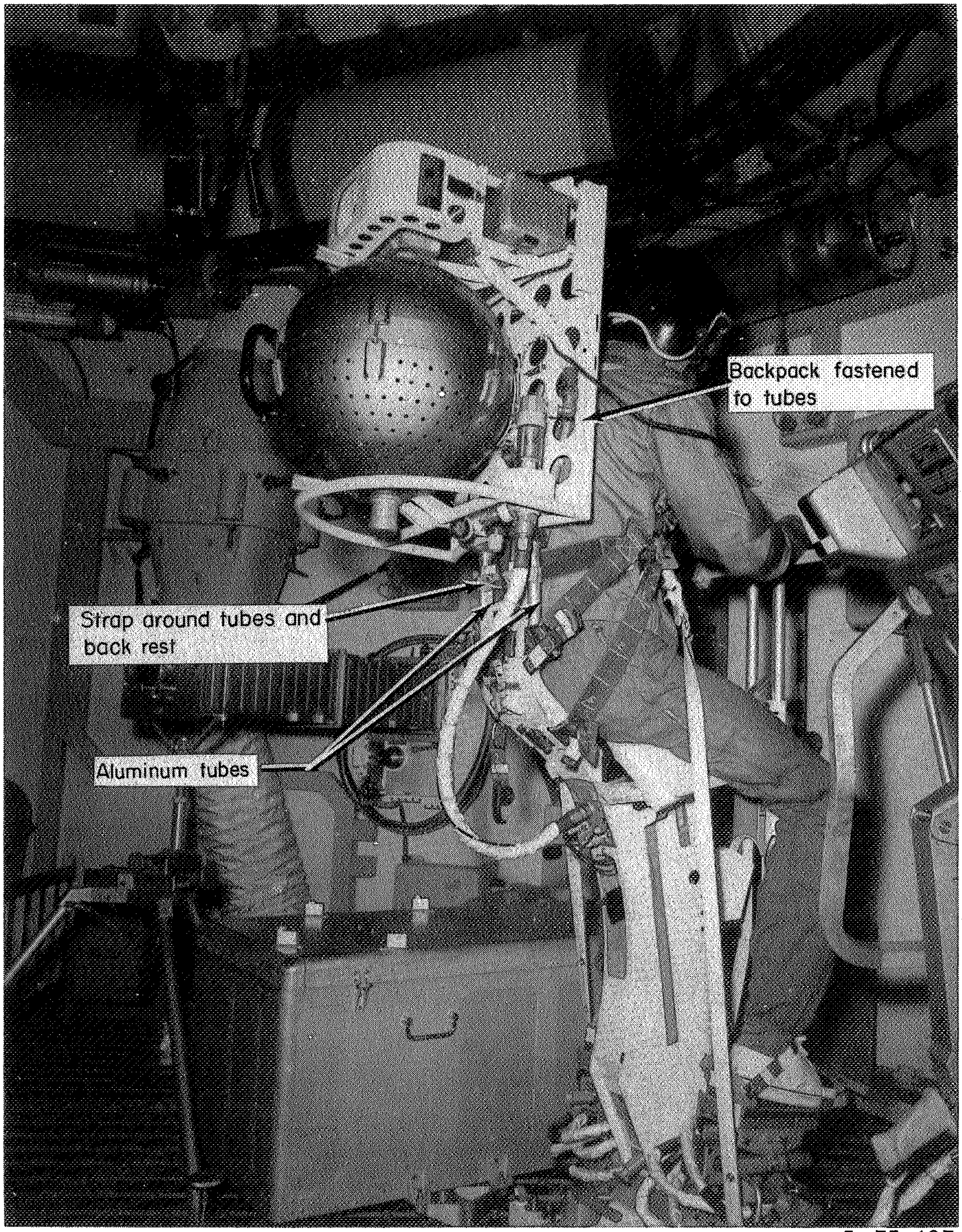


Figure 6.- Sketches of the original harness system used to attach the FCMU and the backpack to the test subject.



L-75-169

Figure 7.- View showing the SL-3 test subject in the pressure-suited condition with the modified harness system.



L-75-197

Figure 8.- Photograph taken in ground-based OWS mockup showing the rigidized harness used for the SL-4 mission by subject 2. The actual tubes (not shown here) used to rigidize the system were bent forward 23° to accommodate the natural position of the subject's body.

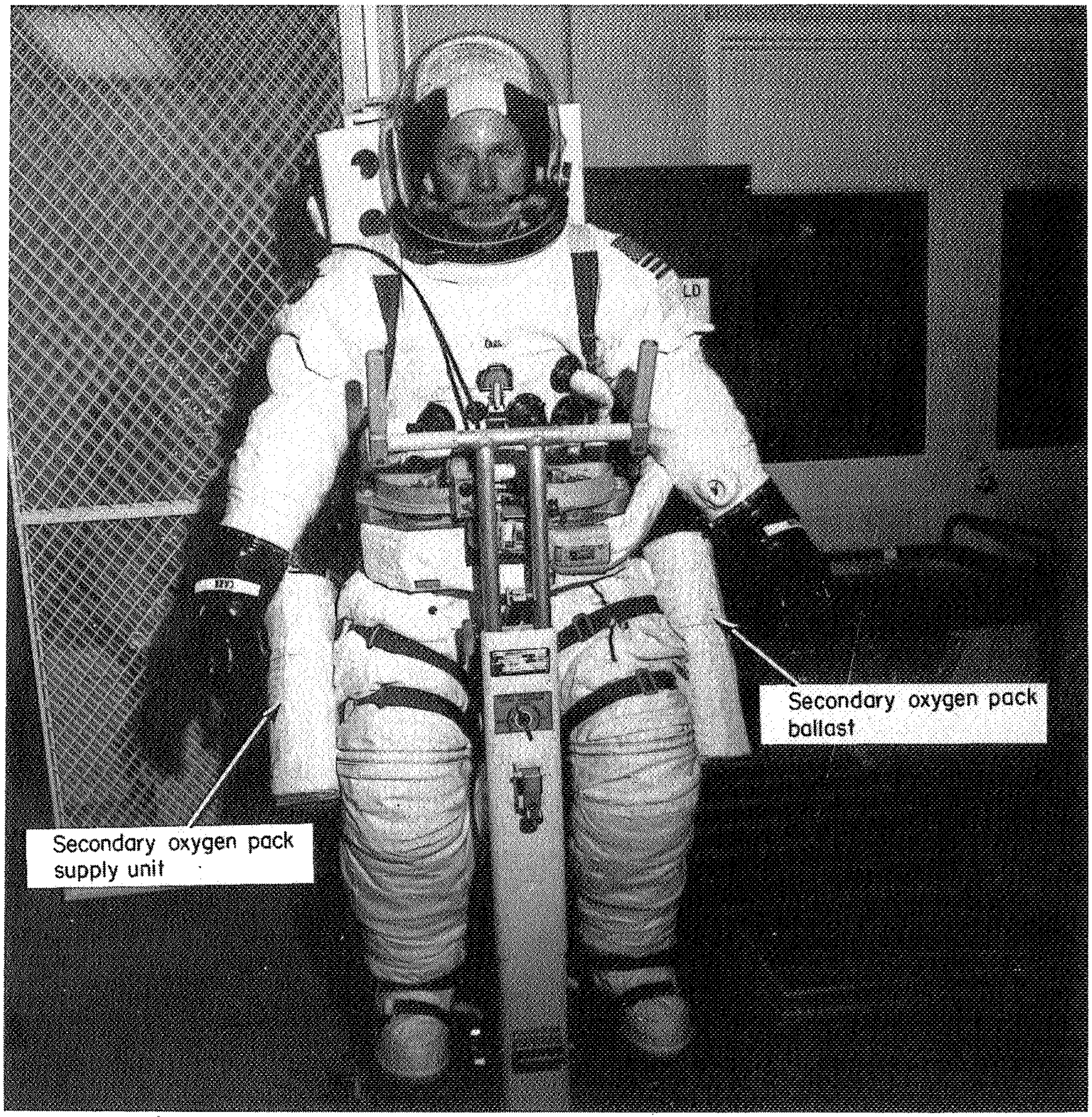


Figure 9.- FCMU with operator in pressurized space suit configured for operation with oxygen supply from secondary oxygen pack. Photograph taken during premission fitting tests.

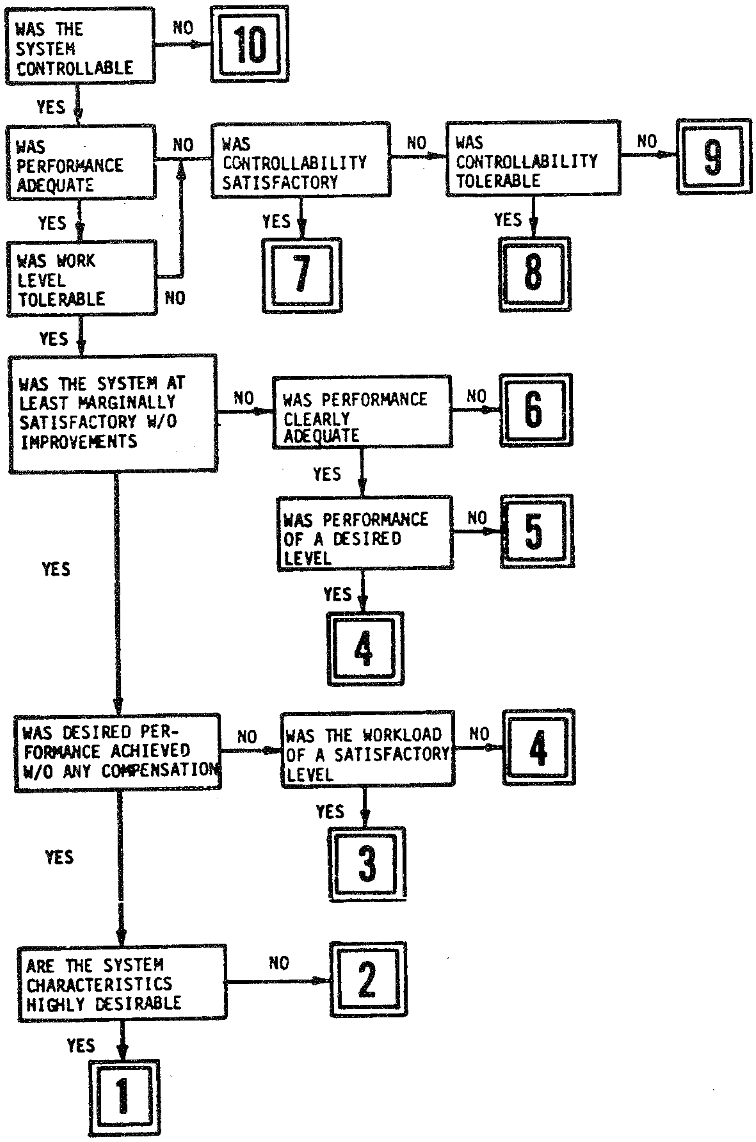


Figure 10.- Chart used as aid in assigning pilot rating values for the FCMU test maneuvers. Based on the rating system of reference 9.

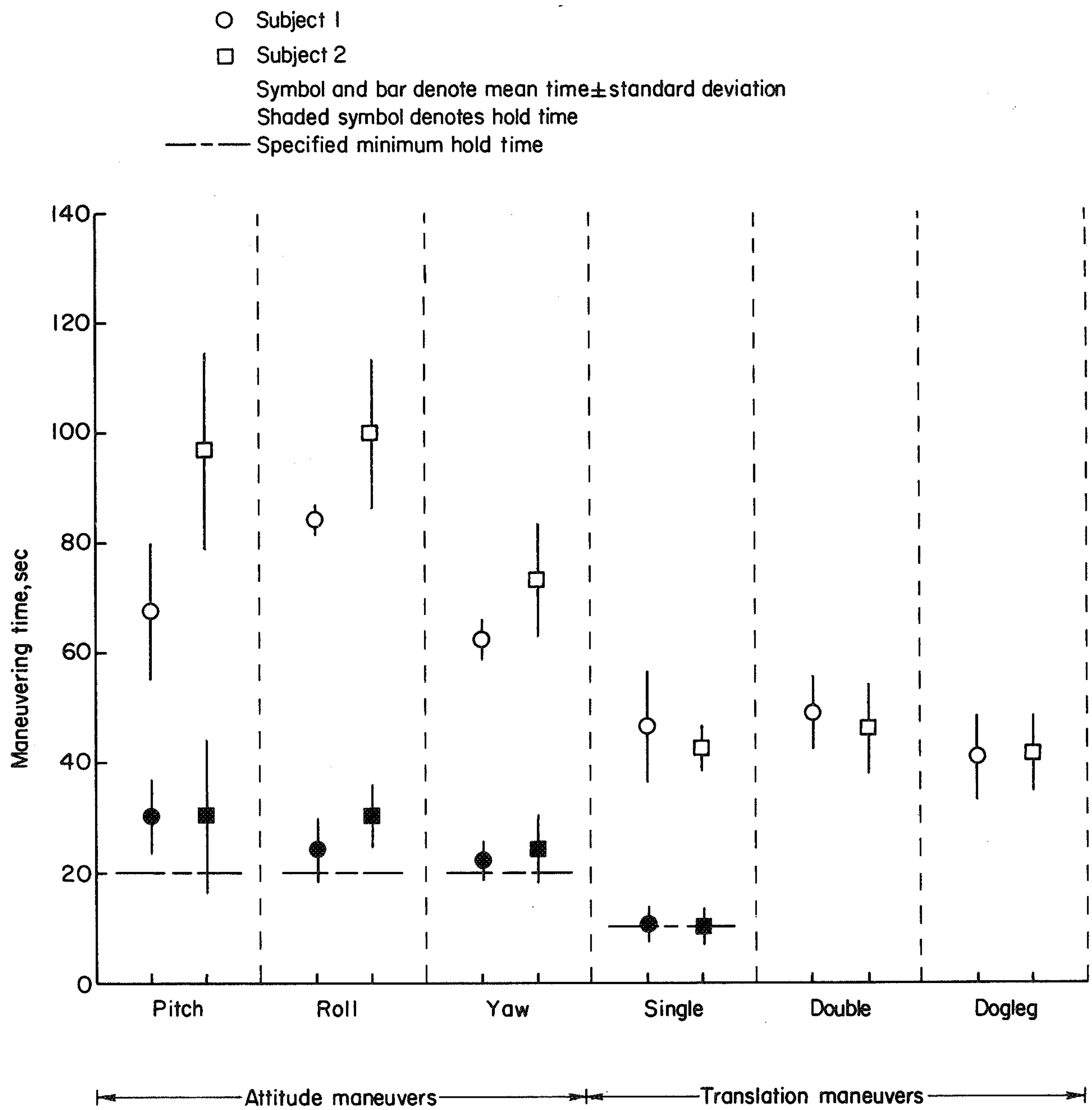


Figure 11.- Comparison of mean and standard deviation values for total maneuvering and hold times for the maneuvers performed by the two flight subjects in the OWS during sessions 1 and 1A.

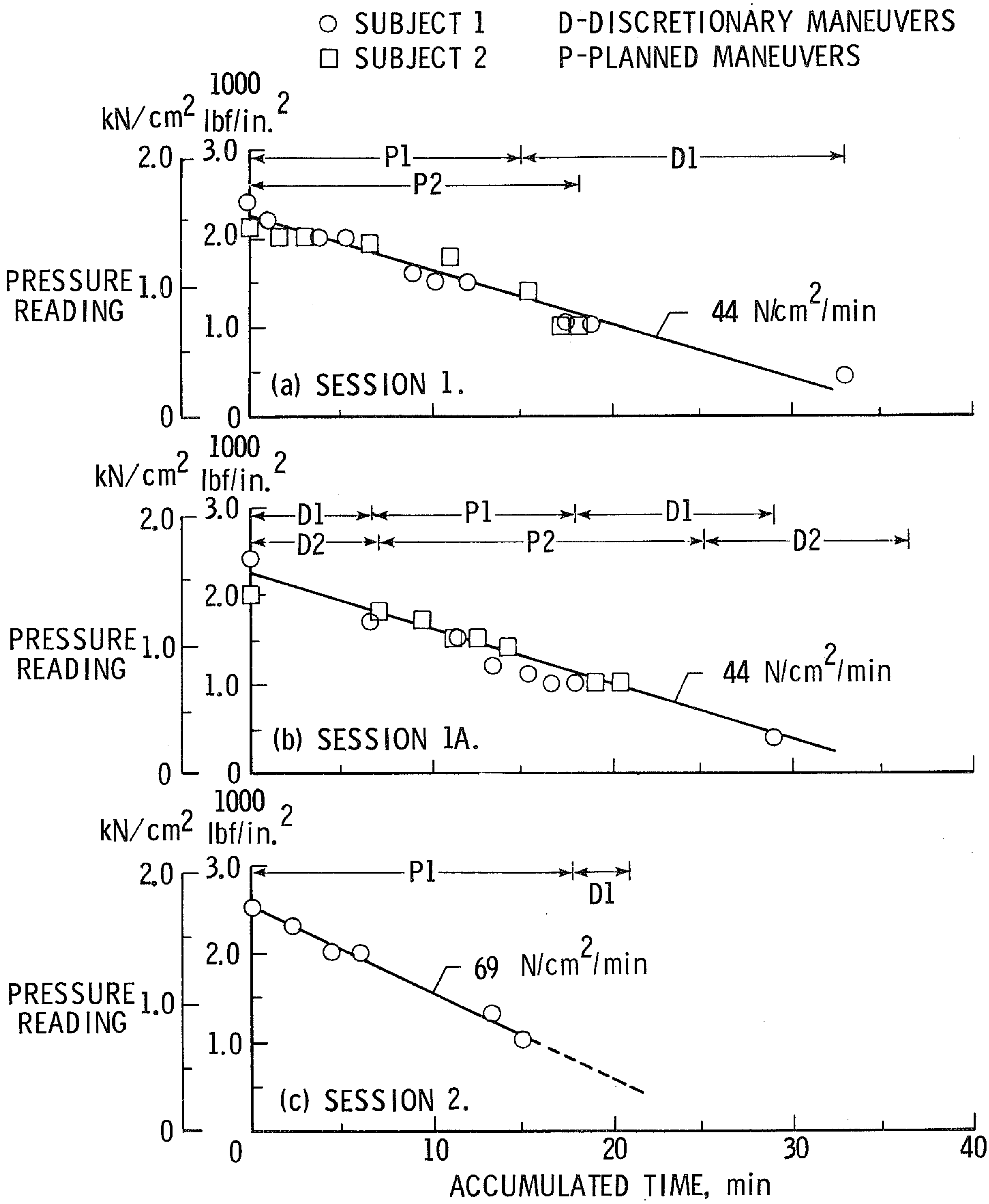


Figure 12.- Variations of the propellant supply pressure readings with the accumulated maneuvering times for each of the test sessions of SL-3 and SL-4 missions.

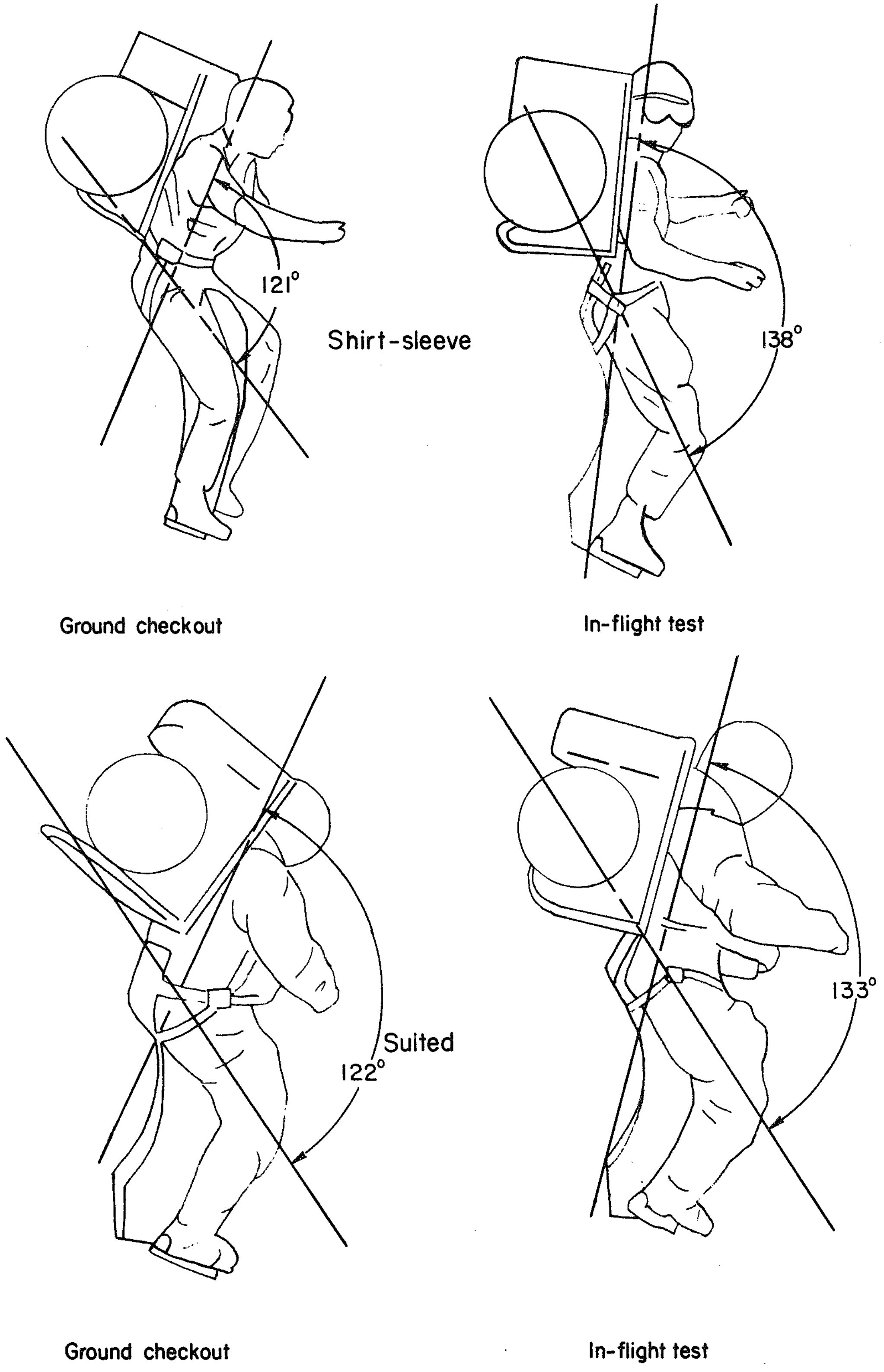
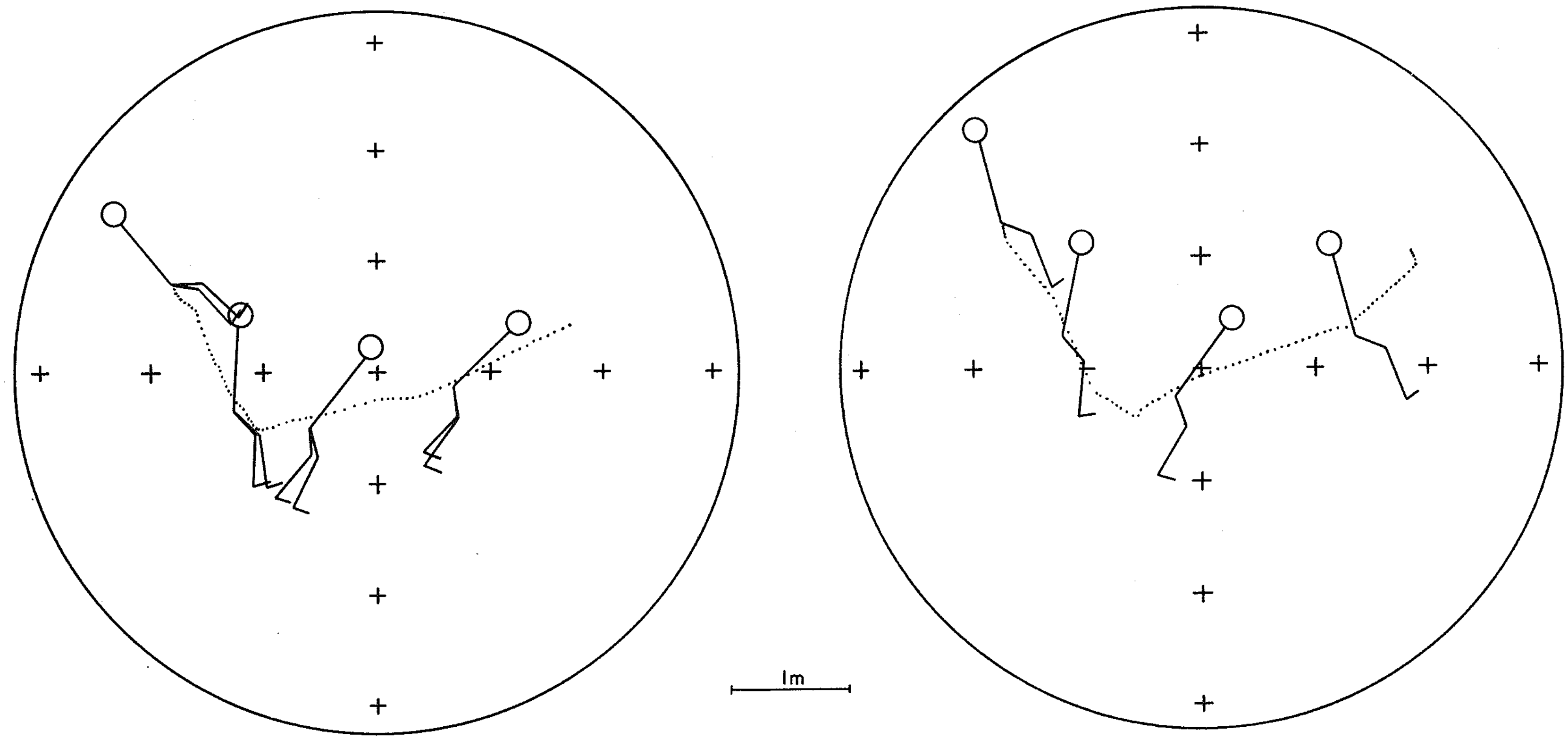


Figure 13.- Sketches showing body positions during ground-based and in-flight tests with the FCMU. The differences in body position are attributed to adjustments of the restraint harness.



OWS

Air bearing simulator

Figure 14.- Comparison of trajectories for the dogleg maneuver as performed by subject 2 in the OWS and the air-bearing simulator. Trajectories were obtained by photogrammetric analysis of the 16-mm films. Spacing of data represents 0.5-second interval.

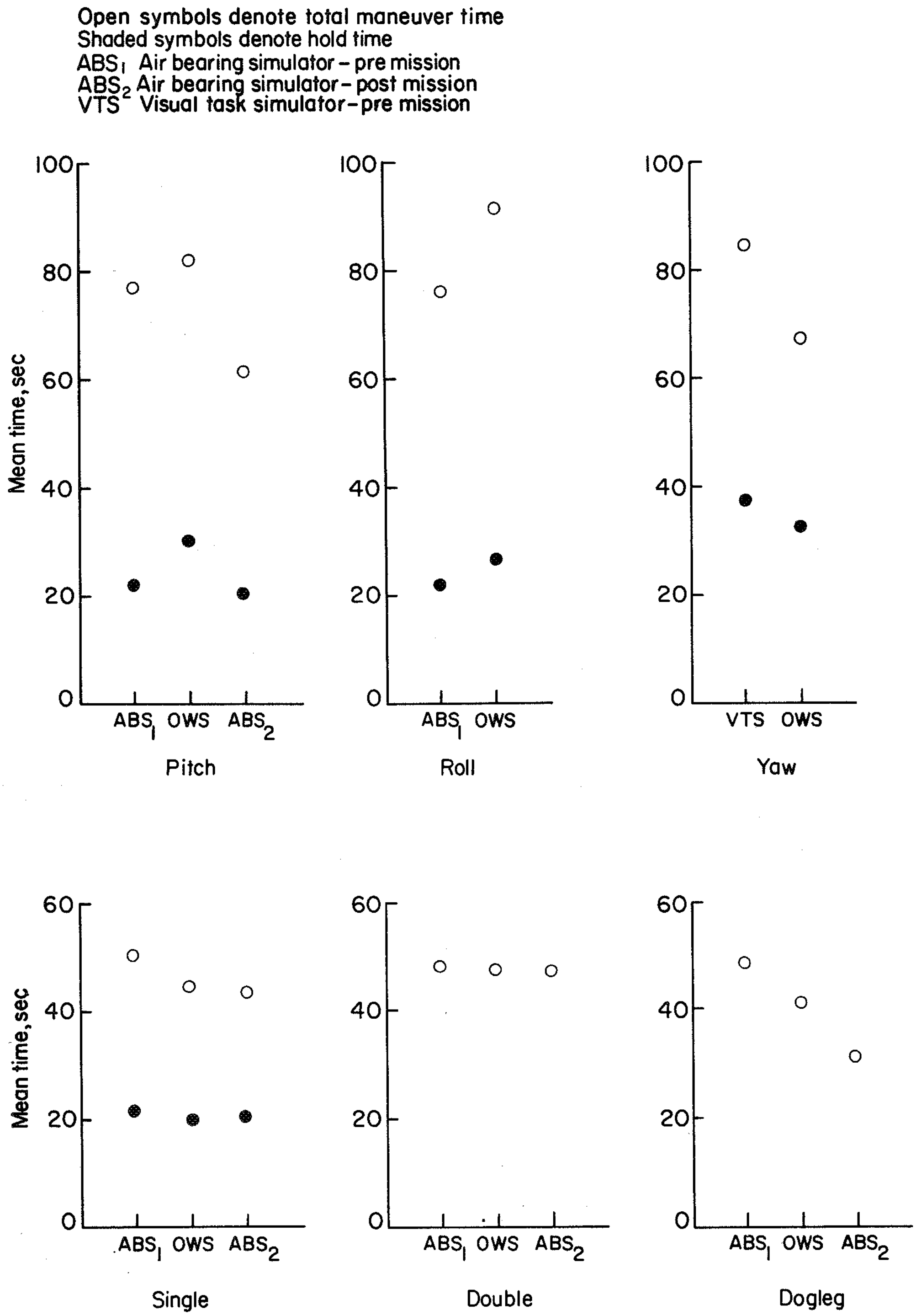
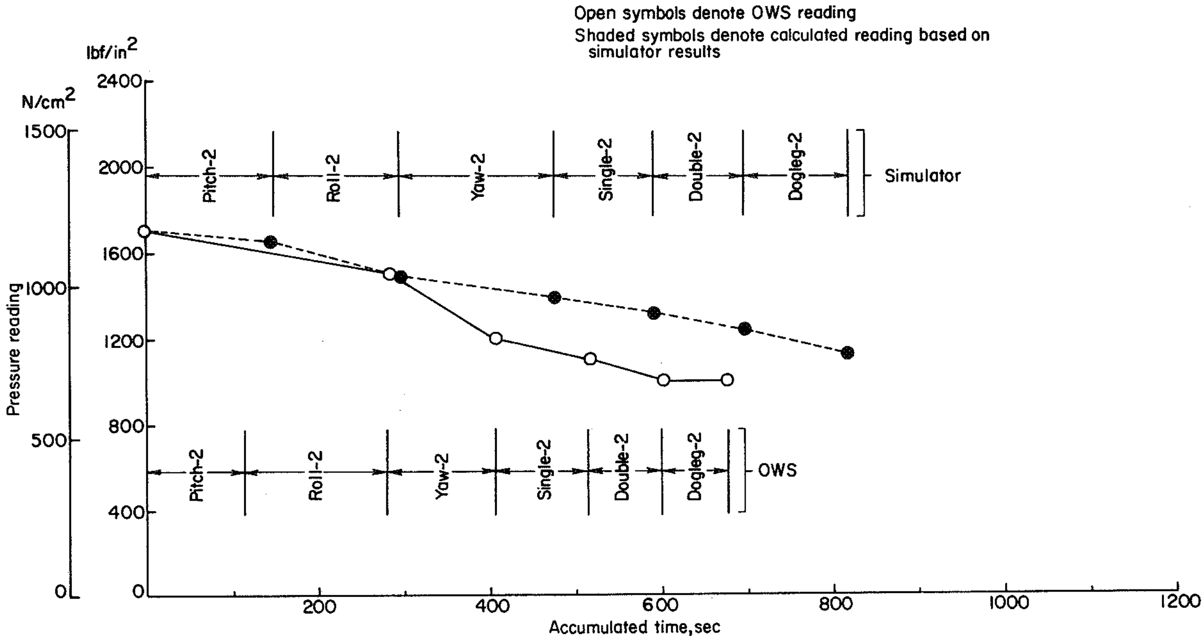
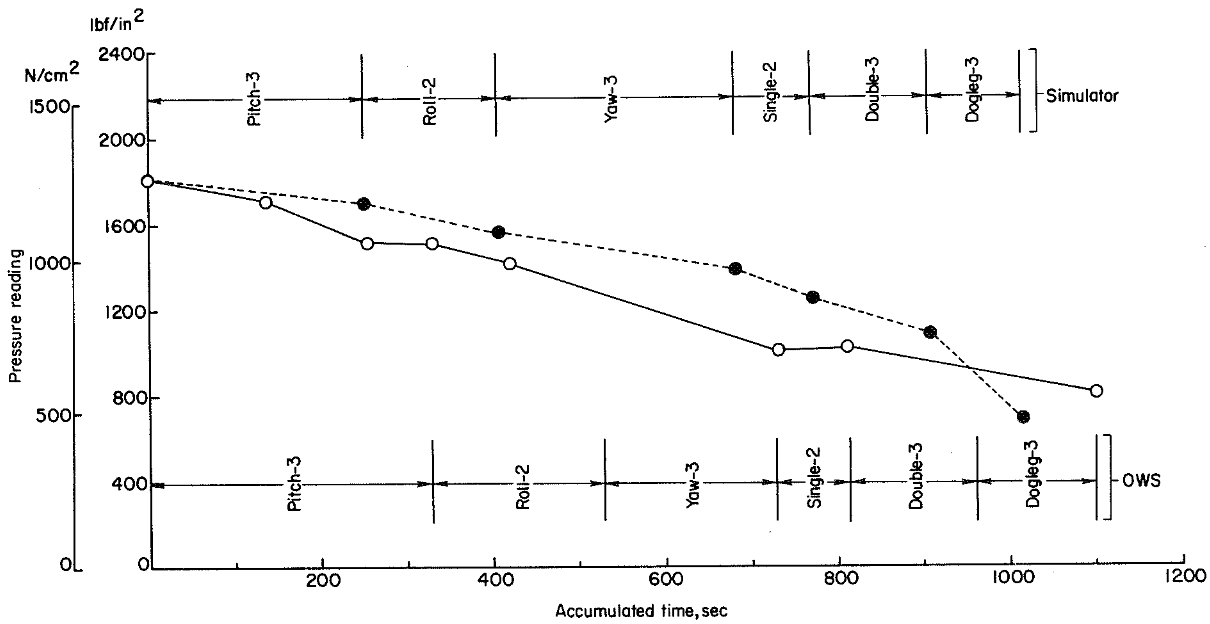


Figure 15.- Comparison of mean values of the times for the two subjects to perform the individual maneuvers during the premission, in-flight, and postmission tests. Postmission roll and yaw maneuvers were not performed.



(a) Subject 1.



(b) Subject 2.

Figure 16.- Variation of actual propellant supply pressure readings with accumulated maneuvering time for sessions 1A compared with calculated variation of readings based on premission simulator results for subjects 1 and 2.

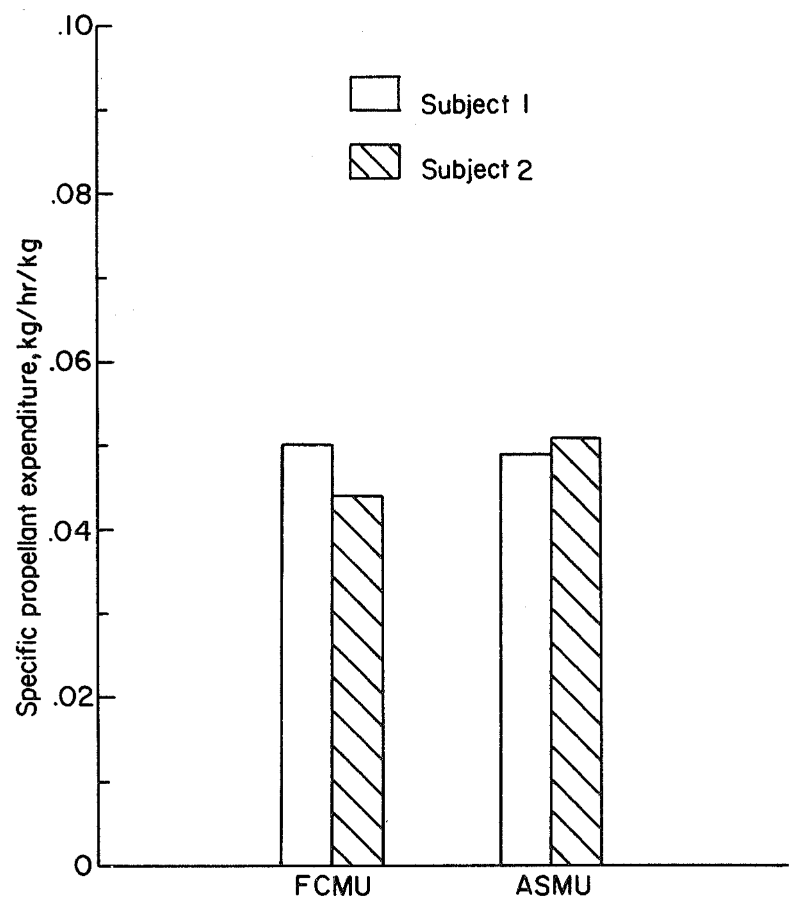


Figure 17.- Comparison of specific propellant expenditure values for the FCMU and ASMU (ref. 2) derived from in-flight tests by subjects 1 and 2.

NASA-Langley, 1975 L-10348

Two supplements to NASA TN D-8055 are available. The film supplement (L-1188) is available on loan and requests will be filled in the order received. You will be notified of the approximate date scheduled.

Supplement A presents excerpts taken from comments of the test subjects pertaining to the experiment, the foot-controlled maneuvering unit (FCMU) design features, and the operating characteristics.

Supplement B is a film (16 mm, color, sound, 15 min) which describes the general details of the experiment T-020 and shows the operation of two FCMU simulators as well as a few scenes of an OWS test in progress.

Requests for the supplements should be addressed to:

Flight Dynamics and Control Division
National Aeronautics and Space Administration
Langley Research Center
Hampton, Va. 23665

CUT

Date ________________

Please send

☐ Supplement A of NASA TN D-8055

☐ Supplement B of NASA TN D-8055 (film L-1188) on loan

____
Name of organization

____
Street number

____
City and State Zip code

Attention: Mr. ________________________

Title ________________________

CUT

Place
Stamp
Here

Flight Dynamics and Control Division
National Aeronautics and Space Administration
Langley Research Center
Hampton, Va. 23665