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A Study Of Man's Physical Capabilities On The Moon

VOLUME I, PART 1

LUNAR GRAVITY SIMULATION FACILITY

By W. Kuehnegger

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for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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A STUDY OF MAN'S PHYSICAL CAPABILITIES

ON THE MOON

ABSTRACT

A study was made to compare man's energy expenditure and gait characteristics, during self locomotion at various rates, in earth and in simulated lunar gravity conditions. The tests were made for the subject walking and running on the level and on grades up to 30° while in shirt sleeves and while wearing a suit pressurized to 3.5 psig. The results, presented in four volumes, may be useful for the design of space suits and life support systems and the planning of lunar exploration missions and their logistics.

FOREWORD

This report describing the lunar gravity simulation facility was prepared by Northrop Space Laboratories (NSL), Hawthorne, California under NASA Contract NAS 1-4449 entitled "A Study of Man's Physical Capabilities on the Moon". This program was administered by Langley Research Center with Mr. W. Letko as NASA Technical Monitor.

The study reported herein was performed by Northrop Space Laboratories in association with Case Institute of Technology, Cleveland, Ohio. Dr. Walter Kuehnegger served as Principal Investigator for NSL. Professor James B. Reswick, Director of the Case Institute Engineering Design Center, guided and directed the work conducted at Case under subcontract.

In view of the complexity and scope of the work performed under this contract, the final report has been organized in four separate volumes (numbered I thru IV). Since the work itself was broken down into phases it was possible to treat each phase individually and document them correspondingly. The four volumes which comprise this report are identified as follows.

CR-66115	Volume I, Part 1 - Lunar Gravity Simulation Facility
CR-66116	Volume I, Part 2 - Instrumentation
CR-66117	Volume II, Part 1 - Biomechanics Research Program
CR-66118	Volume II, Part 2 - Biomechanics Research Program Appendices
CR-66119	Volume III - Work Physiology Research Program
CR-66120	Volume IV - Investigation of Lunar Gravity Simulation Techniques

Volumes I thru III were produced by NSL and have been assigned Northrop Space Laboratories' document number NSL 65-153. Volume IV was prepared from material contributed by Case Institute and reports on their portion of the contract effort. The total report (all four volumes) summarizes the performance during the contract period from 2 November 1964 to 30 September 1966.

The author of this report (Volume I, Part 1) wishes to express appreciation to Mr. J. Felder for his assistance in design of the Lunar Gravity Simulation Facility and to Messrs G. Branch and L. Christian for its realization. Appreciation is also due to the Northrop Facilities Section for their general responsibility of installing the simulator.

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A STUDY OF MAN'S PHYSICAL CAPABILITIES ON THE MOON

VOLUME I, PART 1 – LUNAR GRAVITY SIMULATION FACILITY

By W. Kuehnegger
Northrop Space Laboratories

SUMMARY

One of the primary prerequisites for conduct of "A Study of Man's Physical Capabilities on the Moon" was a suitable lunar gravity simulator. Work in this area actually began prior to contract initiation with design and fabrication of a small scale (20-foot (609.6 cm) walkway) simulator at NSL. Use of this facility also continued through the early stages of the study contract as a test bed and feasibility demonstrator for the techniques to be applied to the design, construction, and operation of the full scale simulator.

The Lunar Gravity Simulator (LGS) which served as the basic test facility for the study program was designed after a concept developed at Langley Research Center. Although based on this concept, the complete facility at NSL is unique in that it incorporates all the specific requirements dictated by the study program. These included capability for testing of both shirtsleeve and pressure suited subjects, highly accurate measurements of biomechanics motion and work physiological parameters, and a wide variety of test devices such as an adjustable platform, an adjustable walkway, stairways, and a treadmill, etc.

The Lunar Gravity Simulator was erected outdoors against the west wall of an office structure in the Northrop Hawthorne Complex. Its major components include a 100-foot (3,048 cm) walkway parallel to the side of the building, a backdrop, a dolly for subject suspension attached to a 250-foot (7,620 cm) rail near the upper edge of the building wall, and a test control center building located near the starting end of the walkway.

The LGS has been in constant use since becoming operational and, with the exception of minor shakedown modifications, has functioned successfully in its original design. Continuing and expanded use of the facility is planned.

INTRODUCTION

The rapidly approaching event of man's mission to and exploration of the Moon appropriately keynotes this report. When the first astronaut sets foot on the Moon's surface he will be surrounded by an alien environment. To cope with this environment, especially in the performance of work, he must be prepared and equipped to function with maximum physical efficiency. During a lunar mission this work will range from activities within his base such as its assembly, maintenance, and repair, to external scientific exploration and material retrieval. How will man be able to perform such work on the lunar surface? Will he be able to locomote himself along this surface similarly to that on Earth? How will a gravitational force one sixth that which he is used to affect his stability and what velocities and acceleration will he experience in the conduct of his activity? These are typical questions which arise in planning the functional use of man on a lunar mission.

Man's physiological reactions in the performance of his work under subgravitational stress will be directly reflected in his life support requirements including the environmental control equipment which must be taken into consideration in the design of his lunar base and protective garment. If man is expected to perform certain work activities assigned to him within the mission objective of the combined man-machine system, they must be based on prior knowledge to ensure that he neither over-exerts himself nor his supporting subsystems.

These thorough considerations are a prerequisite to any manned lunar mission. They will directly contribute to successful completion of the mission and the survival of man.

The Lunar Gravity Simulator discussed in this report has played a most important part in a study program aimed at answering some of the questions raised earlier. This facility and a similar one at NASA Langley Research Center will continue to serve as vital tools in the effort to prepare man for exploration in space.

METHOD

The lunar gravity simulation technique by Hewes and Spady (1) was used in the design of the Lunar Gravity Simulator (LGS) at Northrop. The basic principle of this technique is illustrated in Figure 1, where the subject was suspended on his side at an angle of 9° 36' through his center of gravity. The one g down vector in this position produced a corresponding one sixth g vector towards the subject's walkway, simulating lunar gravity.

The geometry of this angle is explained by the relationship of

$$\sin \alpha = \frac{1/6}{1} = .1667 \text{ and } \alpha = 9.6^\circ = 9^\circ 36'.$$

This "inclined plane" simulation technique enables the test subject to locomote and to perform tasks in one plane.

The experiments conducted during the study program resulted in data which depended greatly on the lunar gravity simulation technique. This technique was carefully investigated early in the program (see Appendix A). The results of this analysis indicated a high degree of accuracy for horizontal locomotion experiments.

This determination made it unnecessary to correct the experiments to predict results for an actual lunar operation. However, a completely definite verification of this simulation technique and its predictions cannot be made until man actually reaches the lunar surface. Lunar experiments conducted on the surface will then provide a direct comparison with those conducted on the LGS. Such verification experiments under the true environment will further indicate the necessary changes to be incorporated to improve the accuracy of simulation and training devices for lunar missions in general.

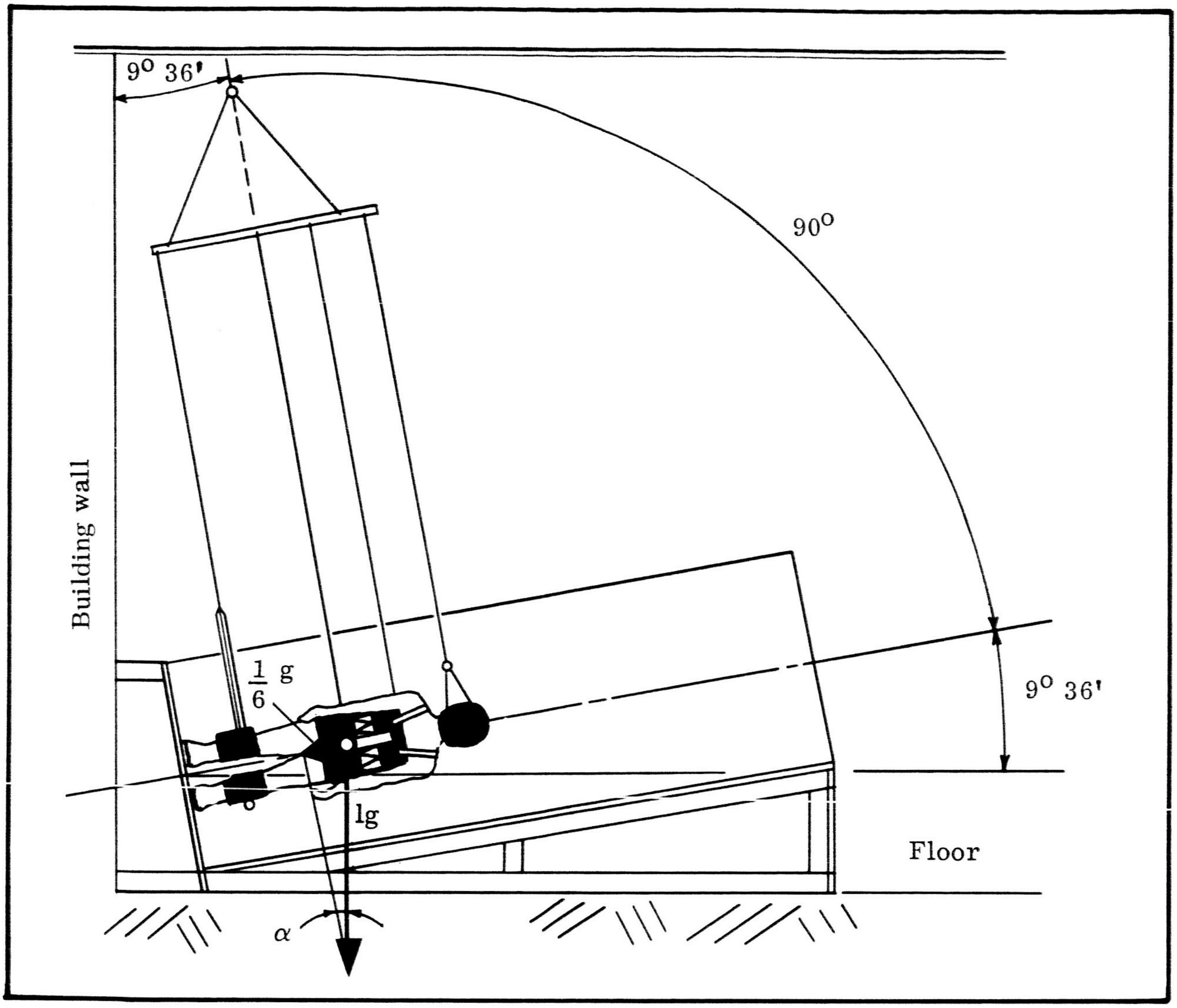

Figure 1. - Lunar gravity simulation technique

THE LUNAR GRAVITY SIMULATION FACILITY

This facility consists of a number of major components. These are:

- Suspension System
- Walkway
- Inclined Treadmill
- Backdrop
- Test Devices
- Test Control Center

- Environmental Control System
- Instrument Packs

An overall view of the complete facility is shown in Figure 2.

Each of the listed major components is subsequently discussed in their sequence.

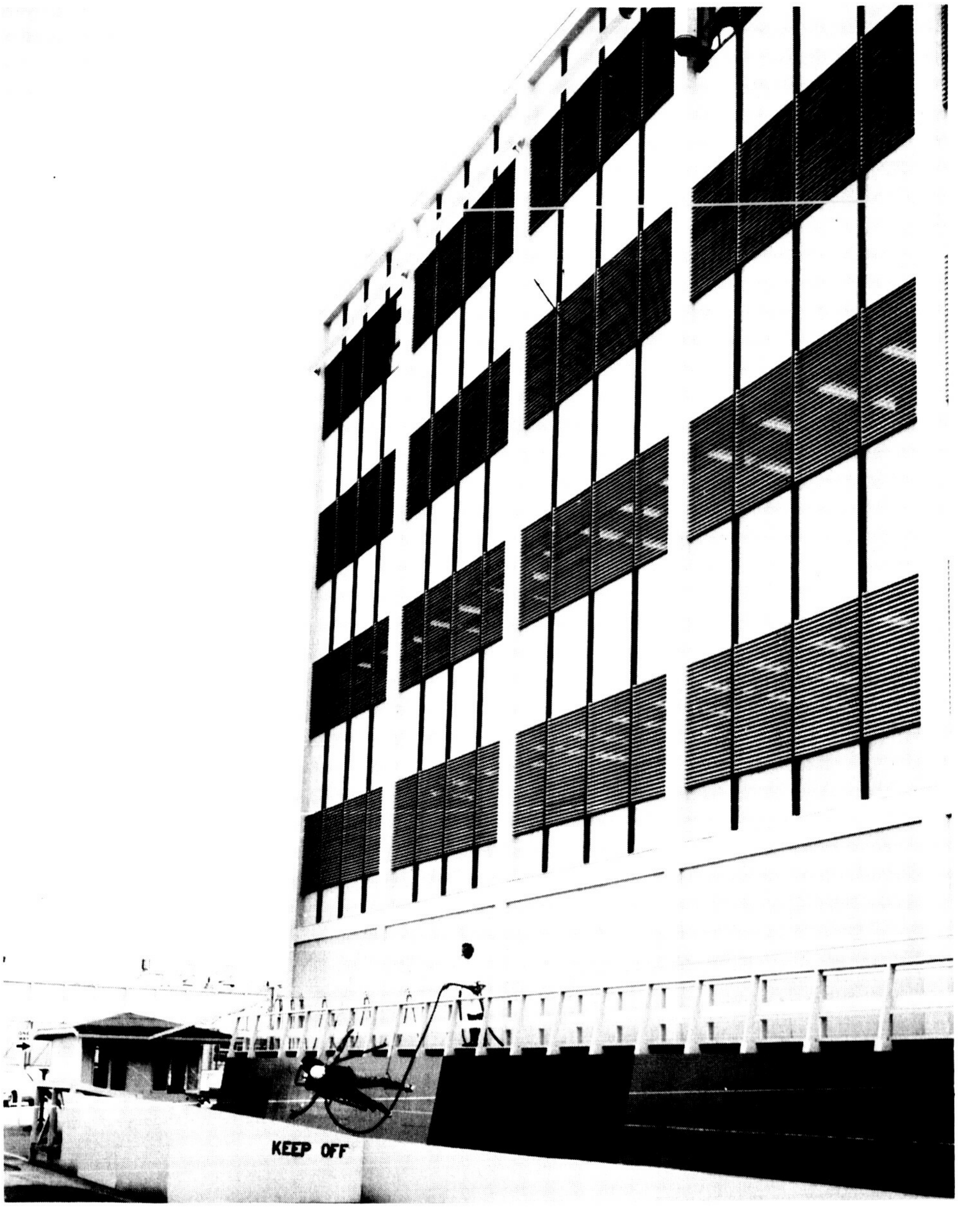

Figure 2. - The lunar gravity simulation facility

Suspension System

The suspension system consists of the rail installation, dolly, spreader bar with suspension cables, and body suspension gear. These components are described individually in the paragraphs that follow.

Rail installation. - The dolly rail was installed along the west side of the Northrop Space Laboratories high rise building just slightly above the fifth floor windows at an elevation of 69' -4" (2,113.28 cm) above the first floor level. The design was performed by a registered Professional Engineer (specializing in structural engineering) and the installation reviewed with the original building contractor. Bids were received by several steel companies for staging of the building, manufacture, and installation of the rail. The steel contractor selected then redrew some of the installation details, fabricated, erected and installed the rail in 40- and 20-foot (1,219.2 and 609.6 cm) sections. A typical rail attachment to the building column is shown in Figure 3. The rail extends 250 feet (7,620 cm) from the north to the south end of the building.

Stainless steel liner sections were welded together on site and ground to fit. The liner was placed in the structural rail section and held in place by clips. This provided a continuous running track surface for the dolly wheels.

A safety flange was welded on the rail sections before erection. The purpose of this flange was to prevent the dolly from swinging out too far and leaving the track.

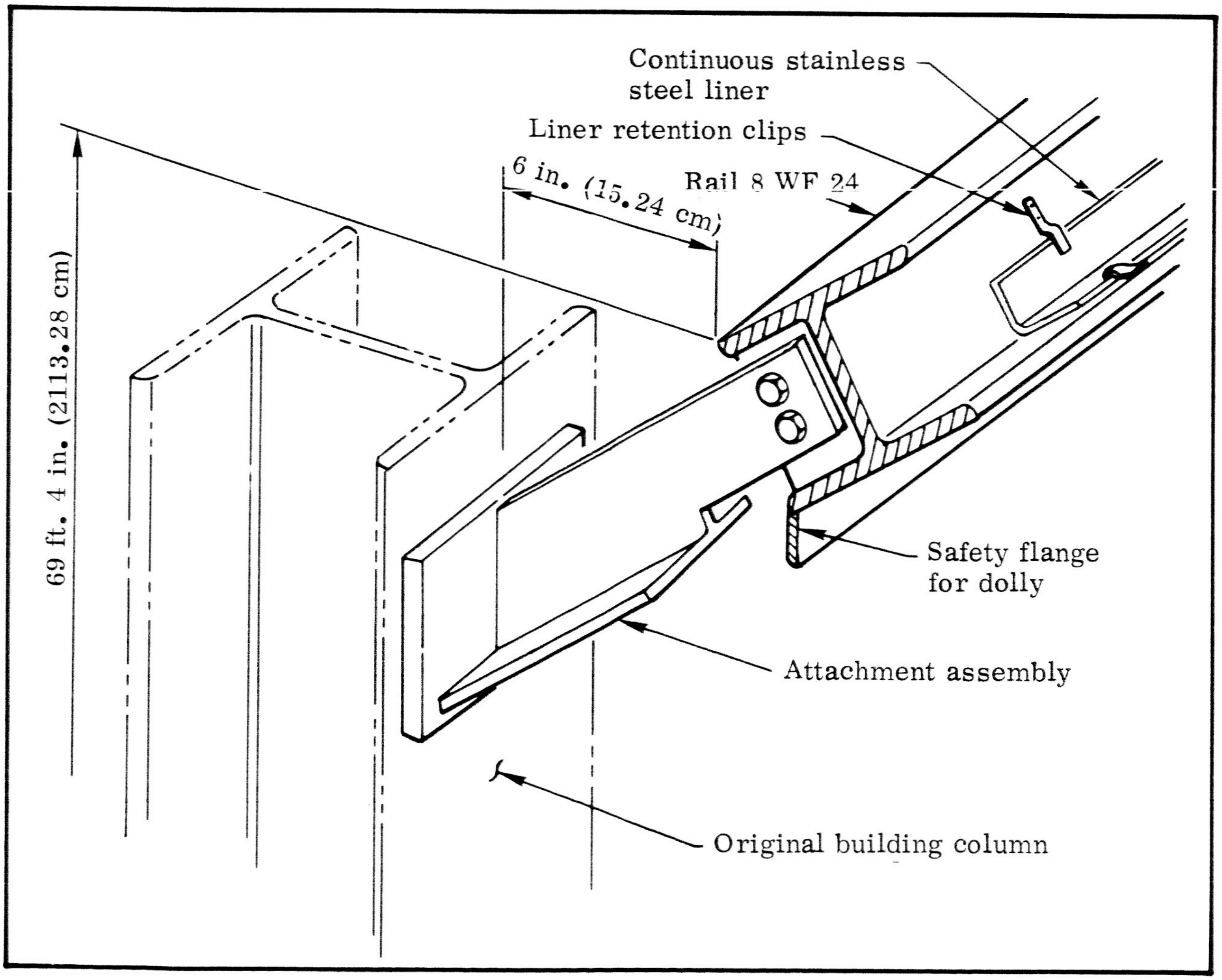

Figure 3. - Typical rail attachment

Dolly. - To achieve minimum weight, magnesium was used in fabrication of the dolly structure. The 6 in. (15.24 cm) diameter wheels were made from 7075 aluminum and hard anodized for minimum friction and wear. Bearings were installed in the wheels which were held in position by one bolt each. Two views of the dolly are given in Figures 4 and 5. The total weight of the assembled dolly was 9.2 lbs (4.49 kg). A cross-sectional view of the dolly and supporting rail is given in Figure 6.

Spreader bar with suspension cables. - The suspension point for the master cable from the dolly can be seen on Figure 5. This master cable extends 18 ft. 4 in. (558.cm) to hold the spreader bar. The 1.12 0/D x .058 wall spreader bar made from SAE 4130 steel in turn holds the suspension cables through adjustable clips over the various body segment supports. The total suspension length from the dolly track to the subject's center line is 66 ft. 4.7 in. (2,023.87 cm). The geometry and dimensions of this assembly are given in detail in Figure 7. The master cable diameter was 3/16 in. (.476 cm) while the diameter of the segment suspension cables was 3/32 in. (.238 cm).

All suspension cables were proof tested. Turnbuckles for subject alignment were installed at the lower end and can be seen on Figures 8 and 9. The weight of the spreader bar with clips and cables was 10.79 lbs (4.893 kg).

Body suspension gear; head and neck support. - In the shirt sleeve mode the head and neck were supported by a three-point attachment through the flight helmet as shown in Figure 8. The attachment through three points was necessary to make the suspension cable align with the mass center and thereby avoid torsion about the neck of the subject. A chin strap with a preformed chin cup was installed to prevent spreading of the helmet sides. The weight of the shirt sleeve helmet including the communication system was 2.5 lbs (1.134 kg).

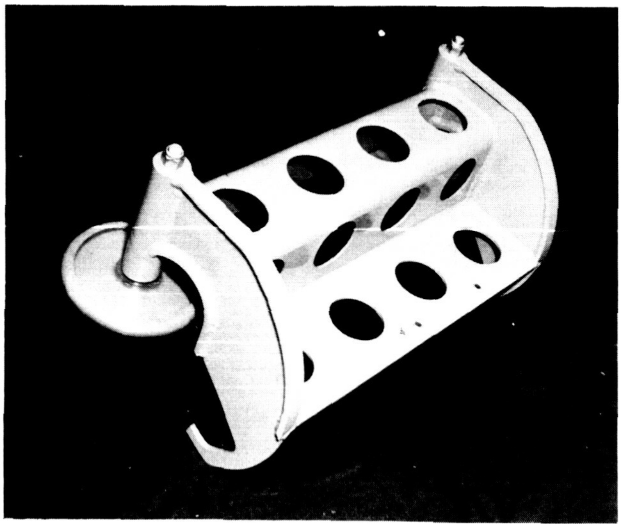

Figure 4. - External view of dolly

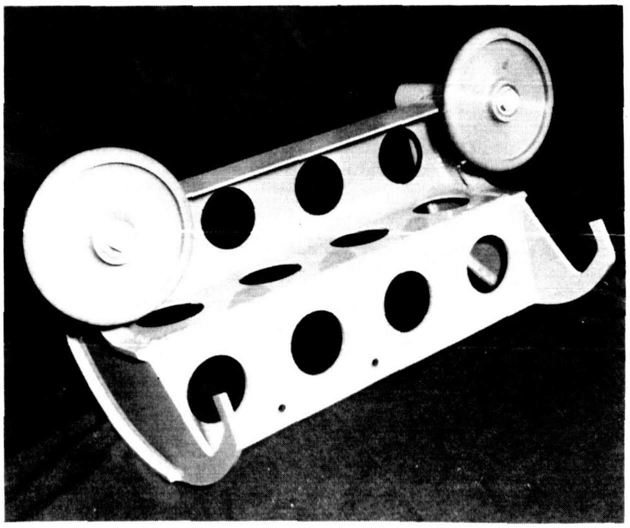

Figure 5. - Internal view of dolly

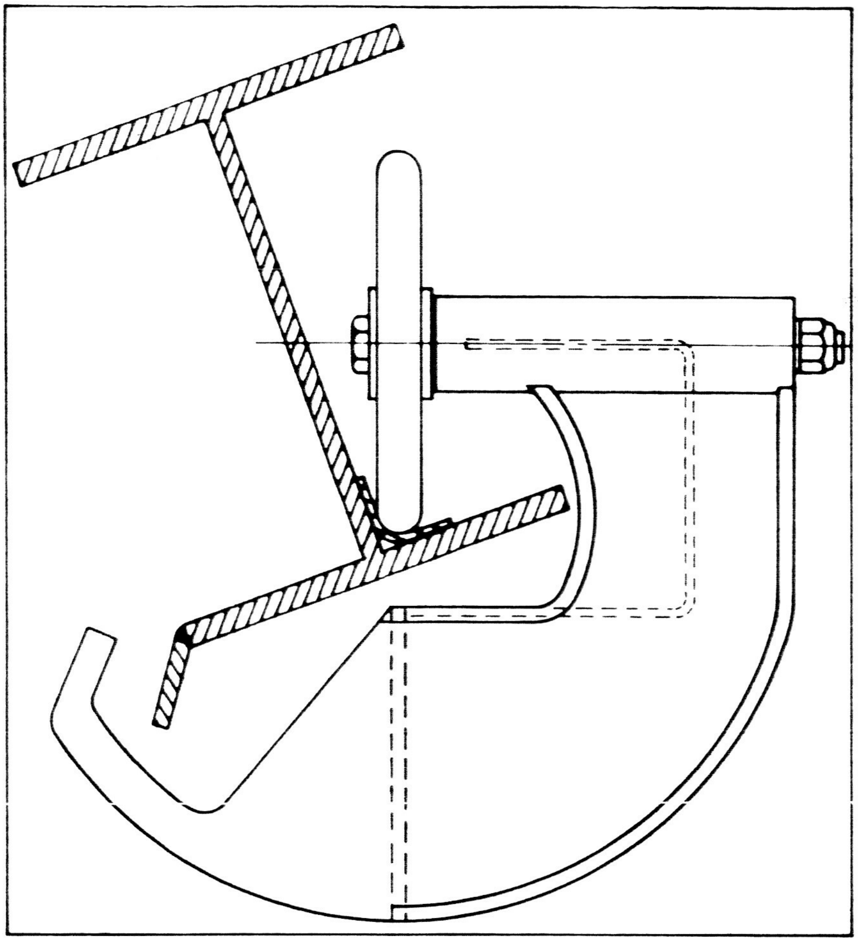

Figure 6. - Dolly installation

In the pressure suit mode the subject's mass distribution indicated that it was possible to provide a single point suspension through the pressure suit helmet. By coincidence this mass center fell directly into the release button center for the helmet visor. This button was removed and replaced by a machined fitting with an eyebolt attachment as is visible in Figure 10. The attachment to the suspension cable was then achieved by pip pin.

The pressure suit helmet had to be modified further for the compression support of the lower ear. During preliminary tests it was found that the lower headset produced pressure points on the subject's ear with resulting discomfort. It was further observed that since the lower ear was resting slightly against the cup, the original pressure would remain trapped in the lower outer ear, producing great discomfort during pressurization and depressurization. The lower headset was then disconnected and the ear cup removed while the upper headset remained in position to serve for communications. The lower ear cup was replaced by a contoured foam insert providing a more comfortable support area in addition to permitting more rapid pressure changes due to the permeability of the foam structure. The installation of this removable foam insert can be seen in Figure 11. The weight of the helmet is found listed under pressure suit data in Volume II.

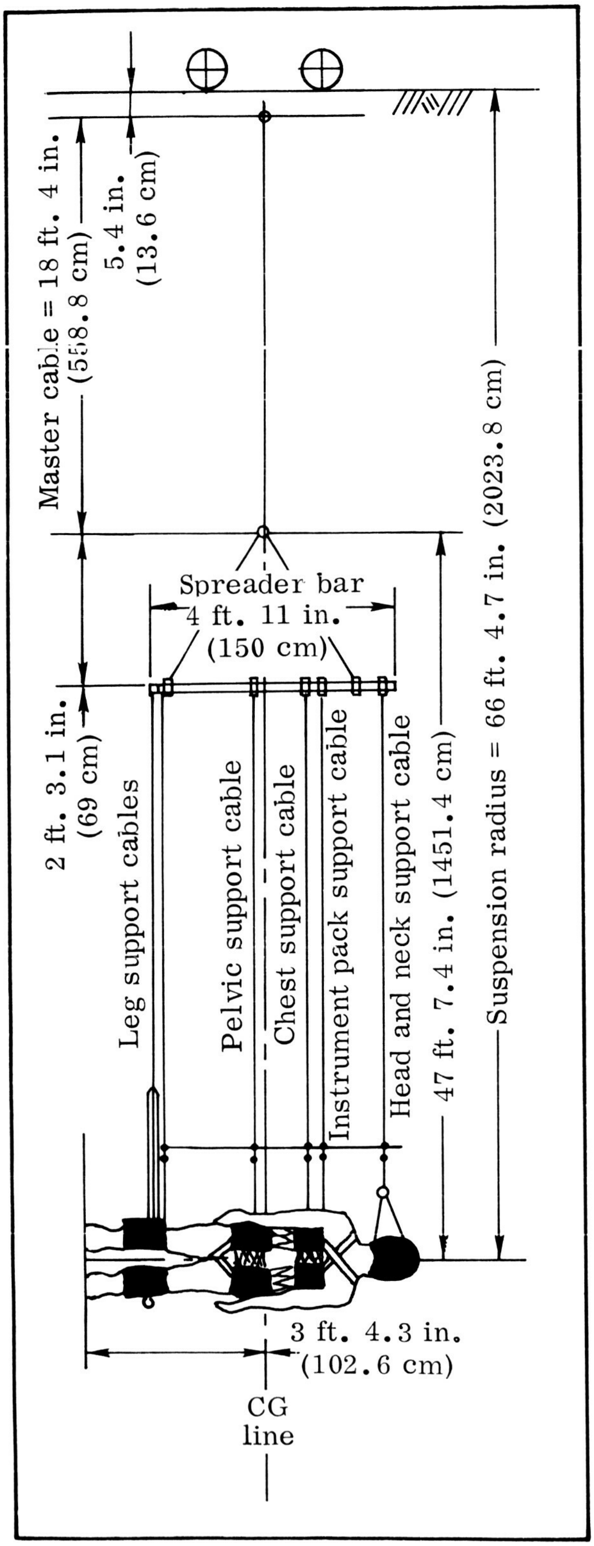

Figure 7. - Suspension cables and spreader bar dimensions

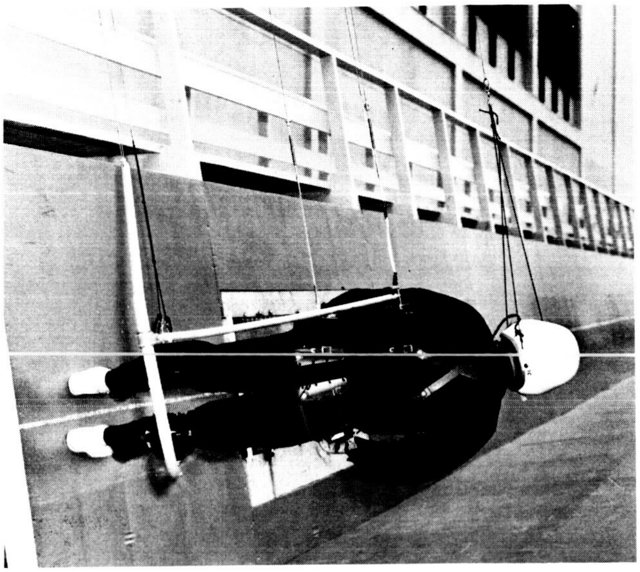

Figure 8. - Subject suspension cables misaligned

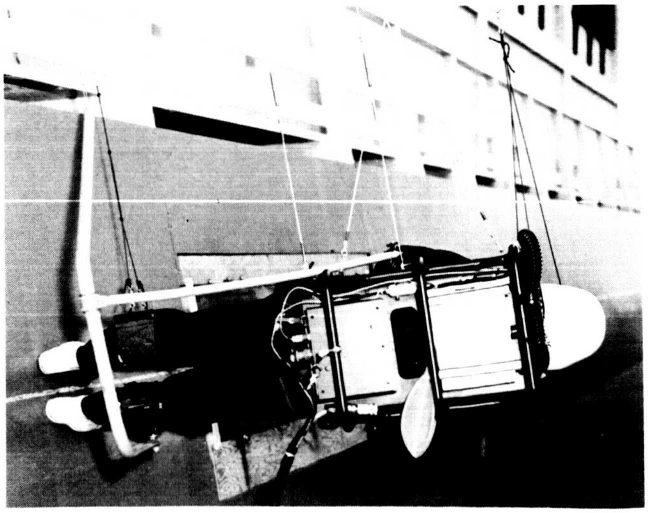

Figure 9. - Subject suspension cables corrected for alignment

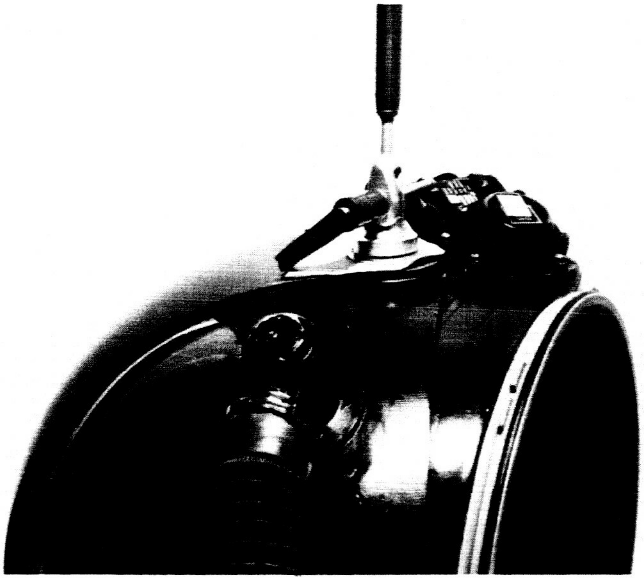

Figure 10. - Pressure suit helmet and neck suspension

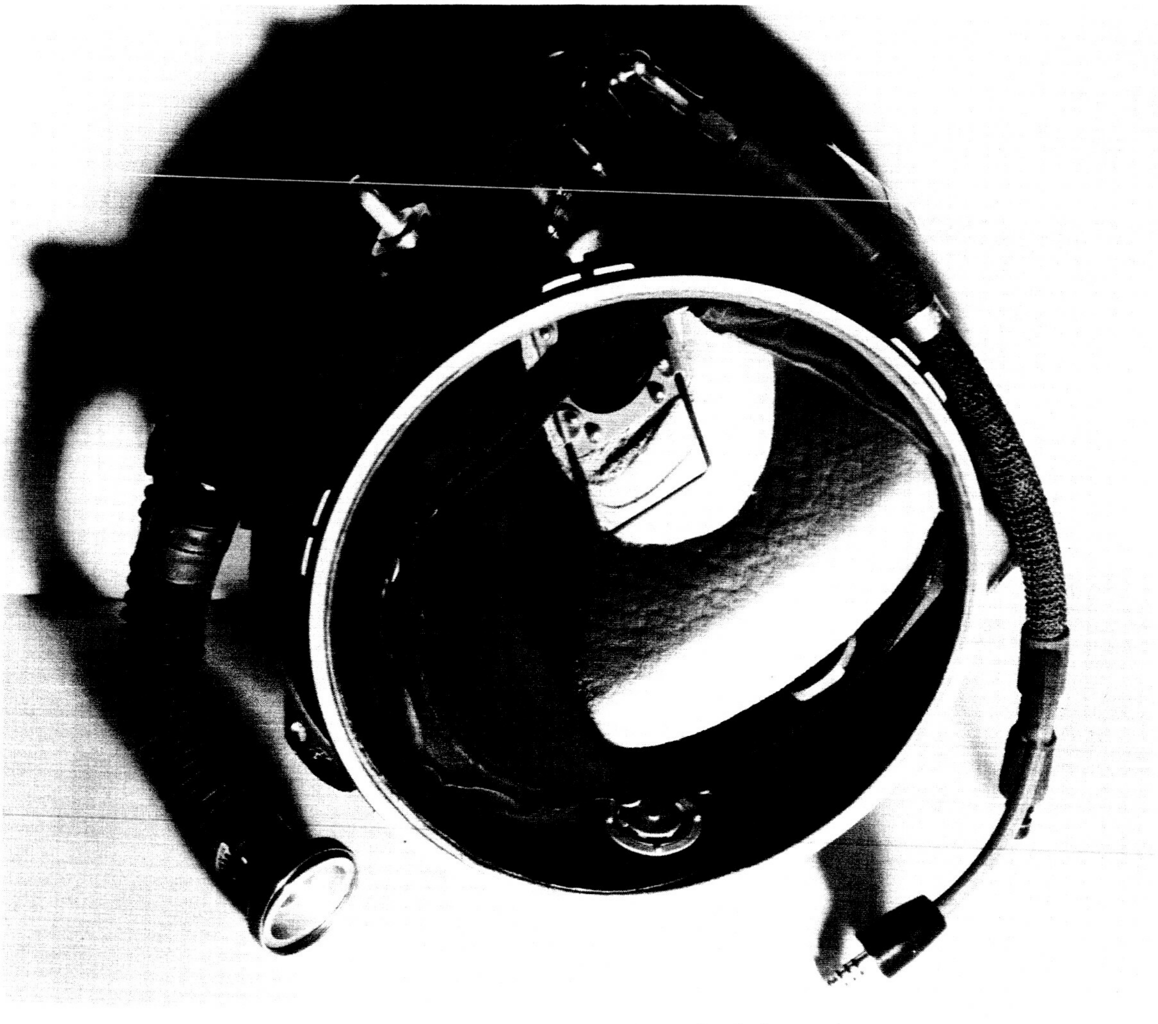

Figure 11. - Installation and detail of foam insert

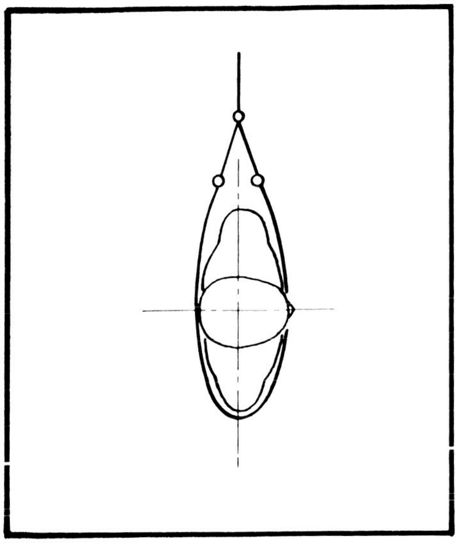

Figure 12. - Sling suspension

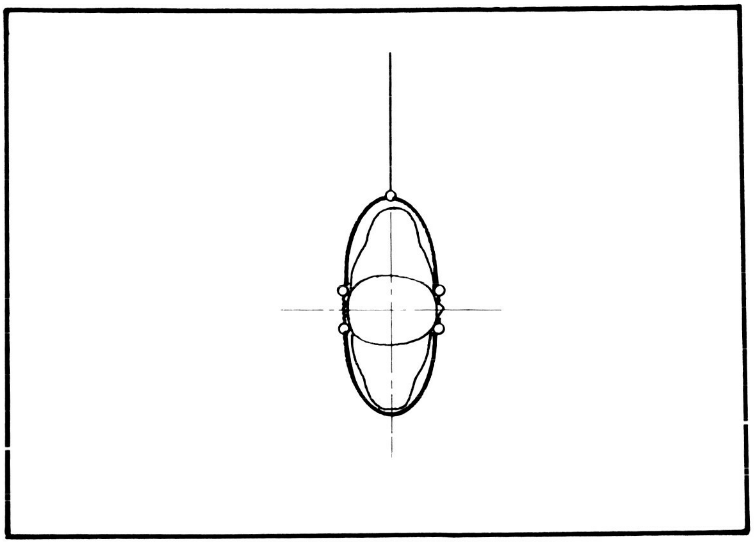

Figure 13. - Hard suspension

Figure 14. - Hard suspension assembly

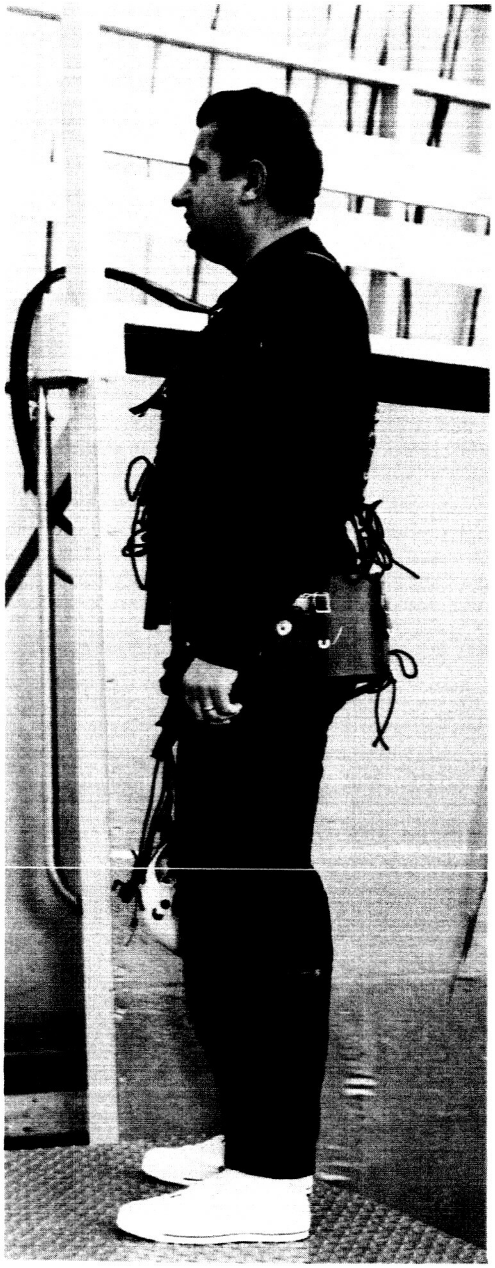

Figure 15. - Hard suspension, side view

Figure 16. - Hard suspension, rear view

Body suspension gear; trunk and pelvic support. - During the experiments conducted on the original Northrop small scale LGS it was found that abnormal respiration and headaches resulted from using the conventional sling suspension shown in Figure 12. Since neither of those two symptoms can be tolerated under work physiological testing, it was necessary to design a suspension system which would not produce such undesirable side-effects.

This problem was solved by a so-called "hard" suspension against which the subject could rest as in Figure 13. The upper half of this hard suspension was made identical to the lower half, permitting the subject to be suspended either on the left or on the right side. The hard suspension was further separated enough in the abdominal region to permit a more normal respiration. Foam padding, which can be seen on Figure 14, was used to make the support area more comfortable.

The rigid support plates were shaped to the subject's contour and were made from one-quarter inch magnesium. Bosses were welded onto those plates in the support area. Helicoil inserts installed in the bosses permitted the installation of fine threaded eyebolts. The subject was then connected by pip pins to the suspension cables.

The hard suspension was also designed in such a way as to allow adjustment in all directions for the anthropometric variations of different test subjects. Nylon lacing was used first but later replaced by ordinary heavy duty black shoe laces which were found more suitable. Figures 15 and 16 show the adjustment possibilities for the trunk and pelvic supports.

The weight for the trunk support was 4.75 lbs (2.155 kg) while that for the pelvic support was 5.75 lbs (2.608 kg). The total weight of the hard suspension assembly was 10.50 lbs (4.763 kg) which includes the upper and lower adjustable retention straps and buckles.

Body suspension gear; leg supports. - The upper leg support used is a sling type made from canvas and two wooden dowels to keep the sling stretched. Two eyebolts were installed in these dowels which in turn were attached to the suspension cable by snaps. Three strips of Velcro were sewn longitudinally into the subject's shirtsleeve suit. Three matching strips of Velcro were sewn horizontally onto the inside of the sling support preventing slippage during experiments. The Velcro strips on the shirtsleeve suit can be seen just barely in Figure 16, while the sling support is evident on Figures 9 and 17.

During pressure suited operation a shoe lace was used to retain the sling support in position by tying it longitudinally to the suit lacing along the lower portion of the upper leg. The weight of the upper leg support was .09 pounds (.041 kg).

The lower leg support consisted of three parts: the leg support bar, the tie bar, and the leg support. The design of the leg support bar and tie bar was based on the Hewes and Spady (1) method and can be seen in Figure 17. The tie bar was first attached to the subject's trunk support cable at one end and to the leg support bar at the other end. Then the tie bar attachment was changed from the trunk support cable to the side of the upper pelvic support plate about which it was able to rotate. The attachment to the leg support bar remained the same. Two collars on the leg support bar permit the rotation of the tie bar at this point. Thus the leg support bar followed the action of the lower leg and prevented it from hitting the walkway floor which otherwise would have occurred during extreme lower leg extensions. Later, the tie bar was further modified in shape to clear instrument pack II without changing the attachment points. The upper end of the leg support bar terminated in an ogive shaped plug with the cable attachment through an eyebolt. This shape of this plug prevented any possible interference between the leg support cables because of their proximity.

The leg support bar was made from 1.25 in. O. D. x .058 in. wall, 6061-T6 aluminum tube, while the tie bar was made from .875 in. O. D. x .059 SAE 4130 normalized steel tube. The weight of both bars was 4.2 pounds (1.905 kg).

Figure 17. - Suspension details

This support proper was contoured to the subject's leg. A section of the welded assembly and foam padding is shown in the following Figure 18. The foam padding supporting the leg was encased in an elastic stretch cover and attached to the contoured support by lacing. The welded leg support assembly was made from magnesium plate and is illustrated in Figure 19. A bushing was inserted to provide a bearing surface with the matching pin located at the end of the leg support bar. This allowed rotation of the leg support in relation to the leg support bar. Two safety straps were installed in addition to the Velcro attachment similar to the upper leg support sling. The weight of the leg support was 1.8 pounds (.816 kg) including the foam pad and safety straps.

The total weight of the complete suspension gear was 16.59 pounds (7.525 kg).

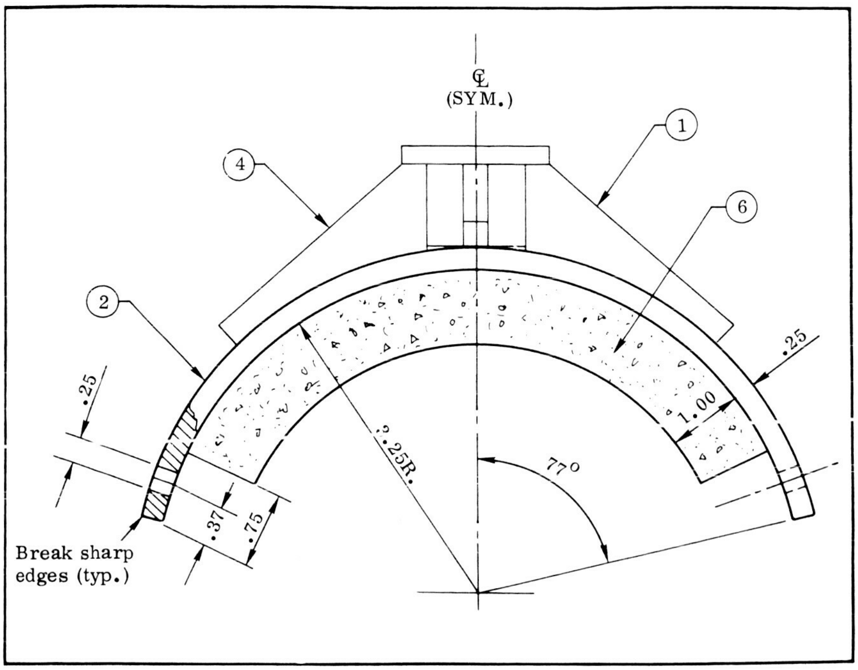

Figure 18. - Leg support assembly

Figure 19. - Leg support assembly

Suspension system checkout. - Several tests were conducted in the checkout of the suspension system. Details of the system can be seen in Figures 20 and 21. During the series of checkout tests the subject performed various maneuvers. Some were representative of the experiments planned although violent maneuvers such as backflips were performed for checkout only.

Figure 20. - Subject suspension system, three-quarter front view

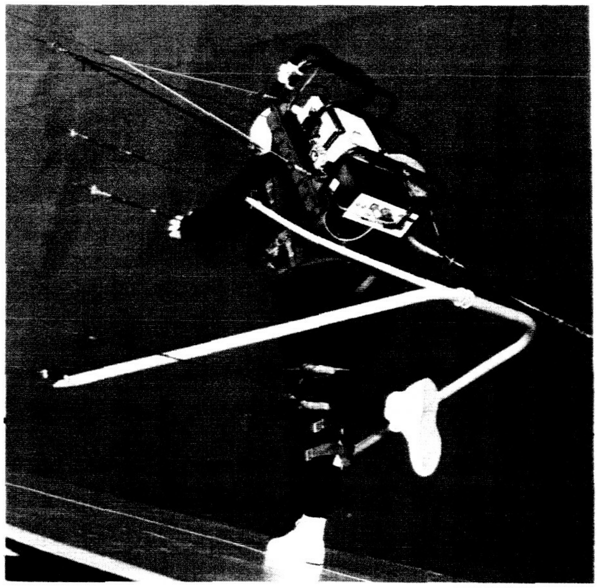

Figure 21. - Subject suspension system, three-quarter rear view

Walkway

The walkway extends 100 feet (3048 cm) and makes up the working section of the facility. It was constructed of board lumber (2 x 4, 2 x 6, and 2 x 10 sections). The subject's walking surface itself was made up of staggered one-inch exterior plywood sections. The sections were designed in such a way as to include a catwalk for the escort and test observer. Individual frame sections were prefabricated and erected on site. They were then aligned and joined together by 2 x 4's along with the plywood walking surface and the 2 x 10's for the catwalk floor. A 2 x 4 railing on either side of the catwalk was also installed. The dimensions for the design of the walkway are shown in Figure 22 while Figure 23 is an actual end view. A plywood and 4 x 4 framed endstop was installed for the safety of the subject as well as to reduce visual distractions to a minimum.

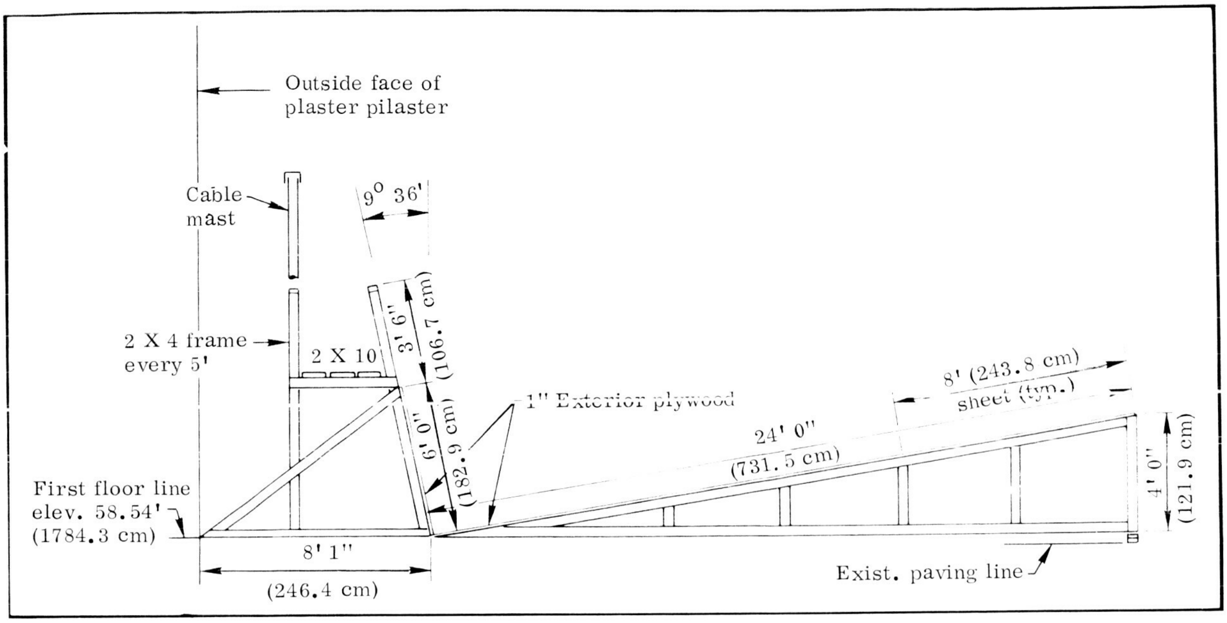

Figure 22. - Walkway and backdrop dimensions

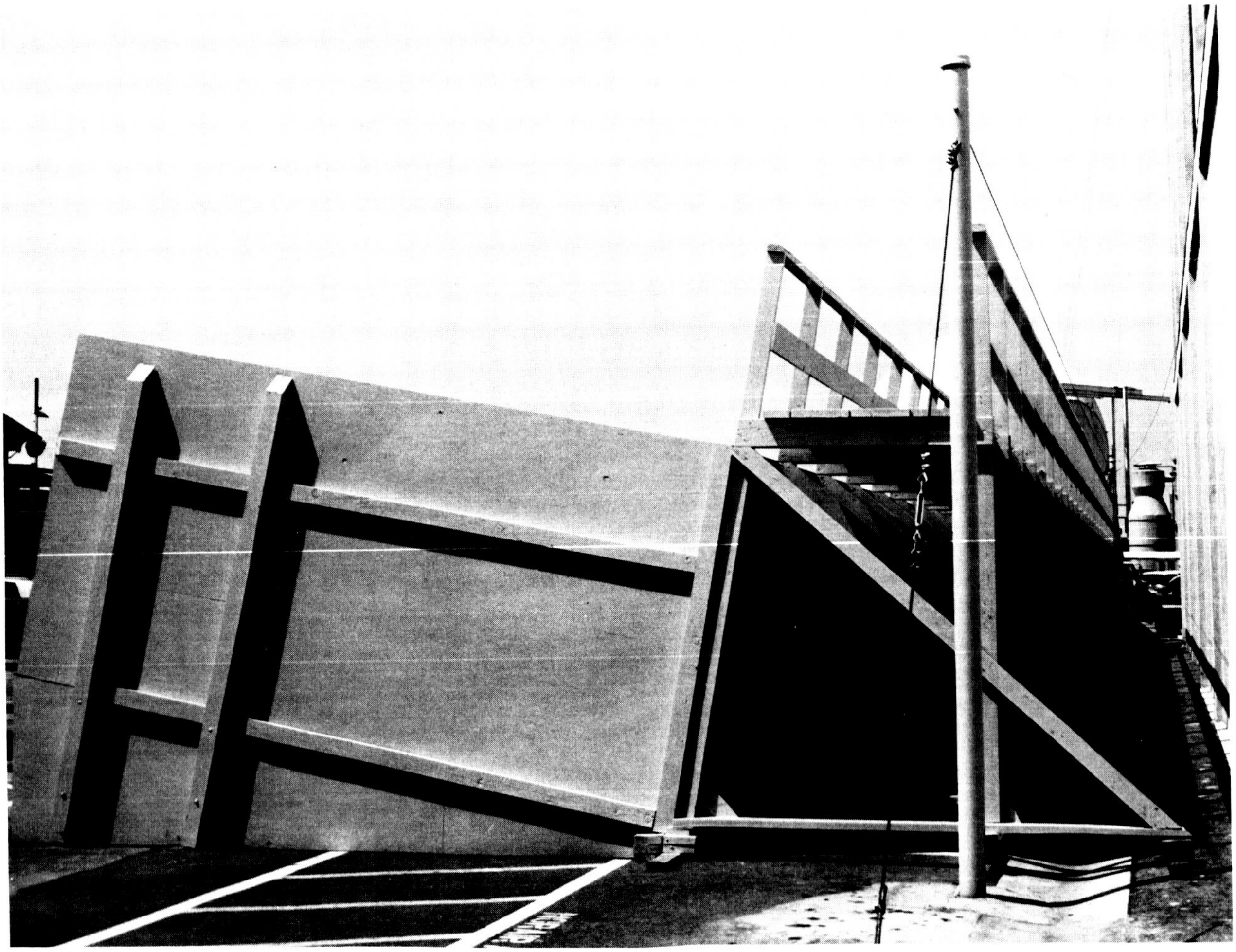

Figure 23. - End view of walkway structure

Inclined Treadmill

It was necessary to design and fabricate an inclined treadmill to meet the conditions required for work physiological testing. These conditions demanded extended periods of work performance (such as walking) under simulated lunar gravity for the establishment of the subject's steady-state conditions as well as for the actual test duration to validate his metabolic data. Without the treadmill, the subject would require an impractically long walkway to reach steady state levels. An overall view with dimensions of the assembled treadmill is shown on Figure 24. The design of the treadmill also included the capability for adjustment to provide a range of inclines or declines up to ± 30 degrees (at 5 degree increments) for ascending and descending. The adjustment of treadmill inclination or declination is performed manually by hand crank as demonstrated in Figure 25. The treadmill was installed flush into the walkway structure (Figure 26) and bolted into position by angles.

Some difficulties were encountered in the design and fabrication of the treadmill because of the required angle of $9^{\circ}\ 36'$ from the vertical. In this position the belt rides on two additional rollers which deflect the bottom edge of the belt considerably, especially at lower speeds. The original hydraulic drive unit produced a top speed of only six mph and eventually failed. This was replaced by a 1.5 horsepower, 1750 rpm, adjustable speed drive with the speed control located inside the test control center within easy reach of the test director. An emergency button on the speed controller stops the treadmill instantly. The position and operation of the speed controller is seen in Figure 27. A speedometer is also installed at the lower forward end of the treadmill and indicates the belt velocity from 0-10 miles per hour.

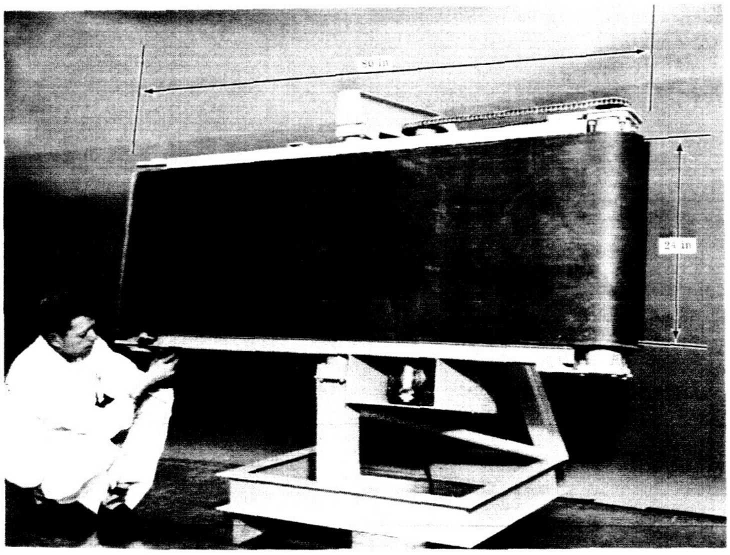

Figure 24. - Inclined treadmill assembly

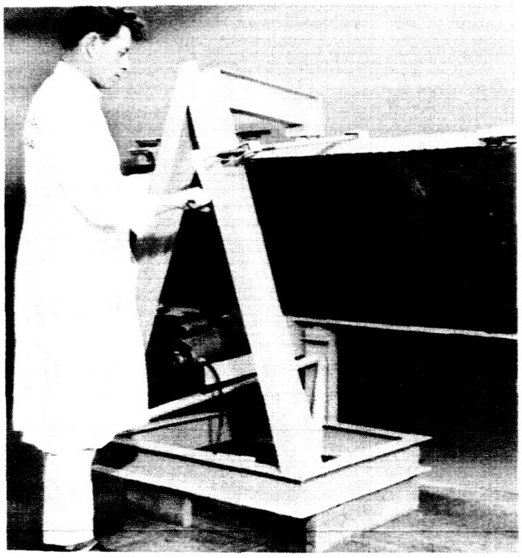

Figure 25. - Treadmill angle adjustment

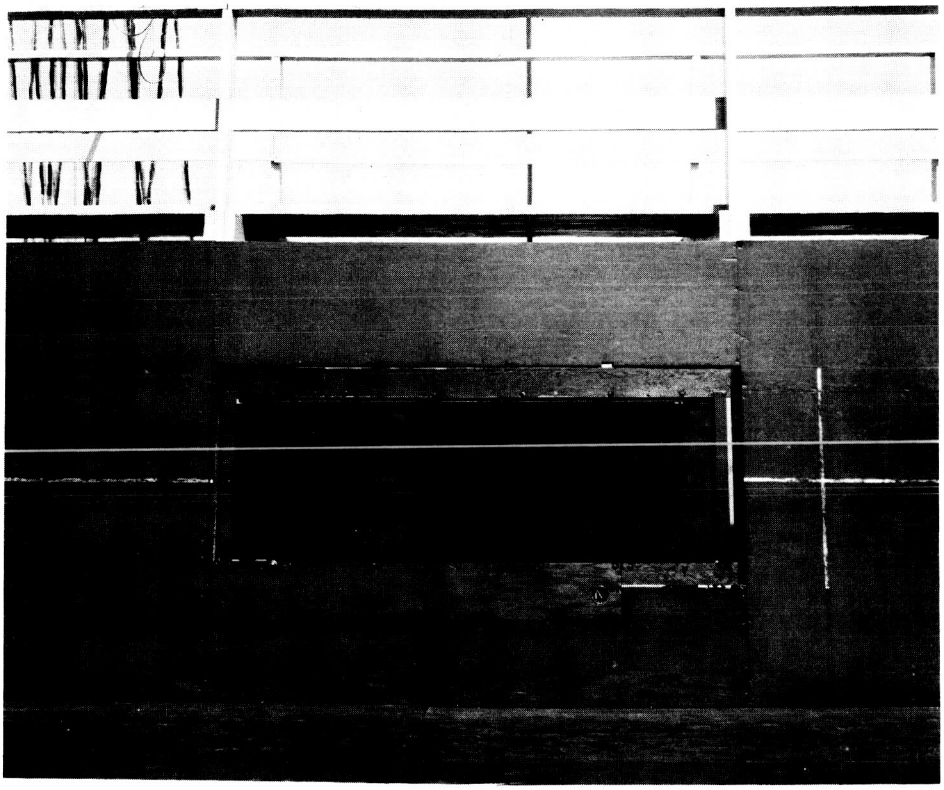

Figure 26. - Treadmill installation, front view

Figure 27. - Treadmill speed control

Platforms of 3/4 in. plywood, sliding out of channels from behind the walkway, extended as far as the belt in front and behind the treadmill to cover the gaps produced otherwise in the ascending or descending positions. Safety requirements dictated this measure to prevent the subject's feet from jamming in the structural gaps. The operational limits of the treadmill are listed in Table 1.

TABLE 1.- OPERATIONAL LIMITS OF TREADMILL

POSITION		SPEED RANGE
Horizontal		0-10 mph
Ascending	0 - 30°	0-10 mph
Descending	10°	0- 6 mph
	20°	0- 4 mph
	30°	0- 2 mph

In ascending, the subject actually helped to move the treadmill belt while in descending he worked against the direction of the belt and thus reduced the effective treadmill speeds to the values shown in the previous table.

The treadmill speeds with different subjects up to 4 mph varied as much as ±10% according to the tachometer. This variation reached as much as ±20% in the higher speed range from 4-10 mph. These variations made it necessary to calibrate the treadmill for each operational condition.

The method of treadmill calibration to correct speed settings for various subjects' weights and gait characteristics was achieved by the belt revolution counter attached to the side of the belt from behind the rear roller. A calibration table indicated the number of counts necessary for 30 seconds to produce the various belt speeds. Although the treadmill was warmed up for 10 minutes prior to each test run, each time a test subject stepped on to the belt, his desired belt speed was calibrated. Upon reaching the corrected speed, the test began. Depending upon the test duration at every 3 to 5 minutes during the test, the belt speed calibration was verified and, when necessary, adjusted.

This method of treadmill calibration was adopted as a standard practice for all NSL work physiological experiments including those conducted on the earth gravity treadmill.

Backdrop

The purpose of the backdrop was to provide a rigid area below the subject for the installation of a visible grid system used in the biomechanics motion analysis. In addition, this backdrop provided a visual reference plan for the subject on the walkway and thus contributed to his orientation on the simulator.

The backdrop was made in 20 foot (609.6 cm) sections. Four sections were identical and extended 12 feet (365.8 cm) from the walkway, while one section, the so-called center test section, reached 24 feet (731.5 cm) from the walkway. A cross section of this center test section is shown in Figure 22. Figure 28 shows the arrangement of the sections in plan view.

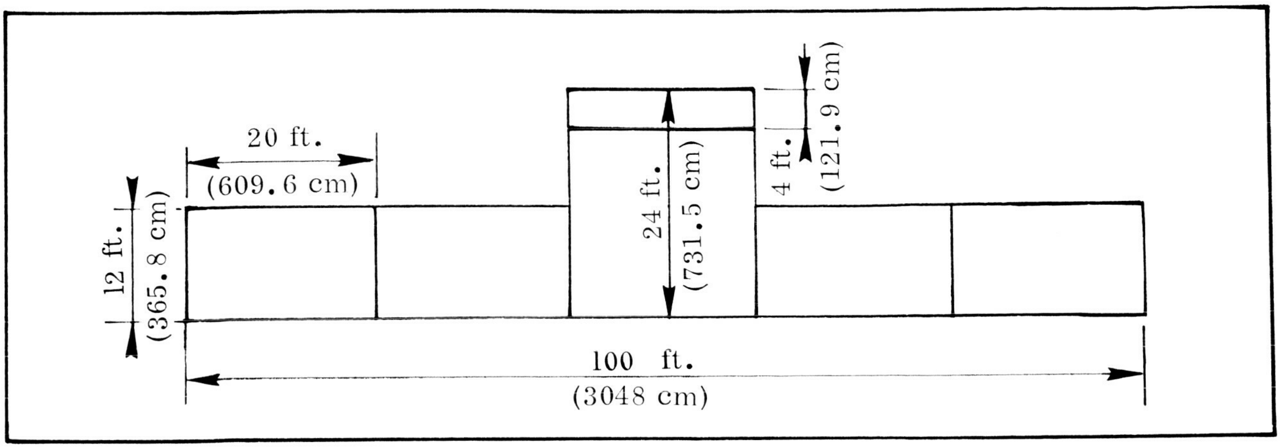

Figure 28. - Backdrop, plan view

The four 12-foot (365.8 cm) backdrop sections were made with 2 x 4's and covered by 3/8 inch (.953 cm) thick exterior plywood while the center test section, though also made with 2 x 4's, was covered with 1-inch exterior plywood for the attachment of test devices. This center test section consisted also of a removable four-foot make-up section which extended out into the adjacent roadway. This four-foot make-up section was stored near the simulator when not in use to avoid obstructing traffic. A plan view of this center test section area is shown in Figure 29. Construction of the grid system for the biomechanics motion analysis can be seen in Figure 29.

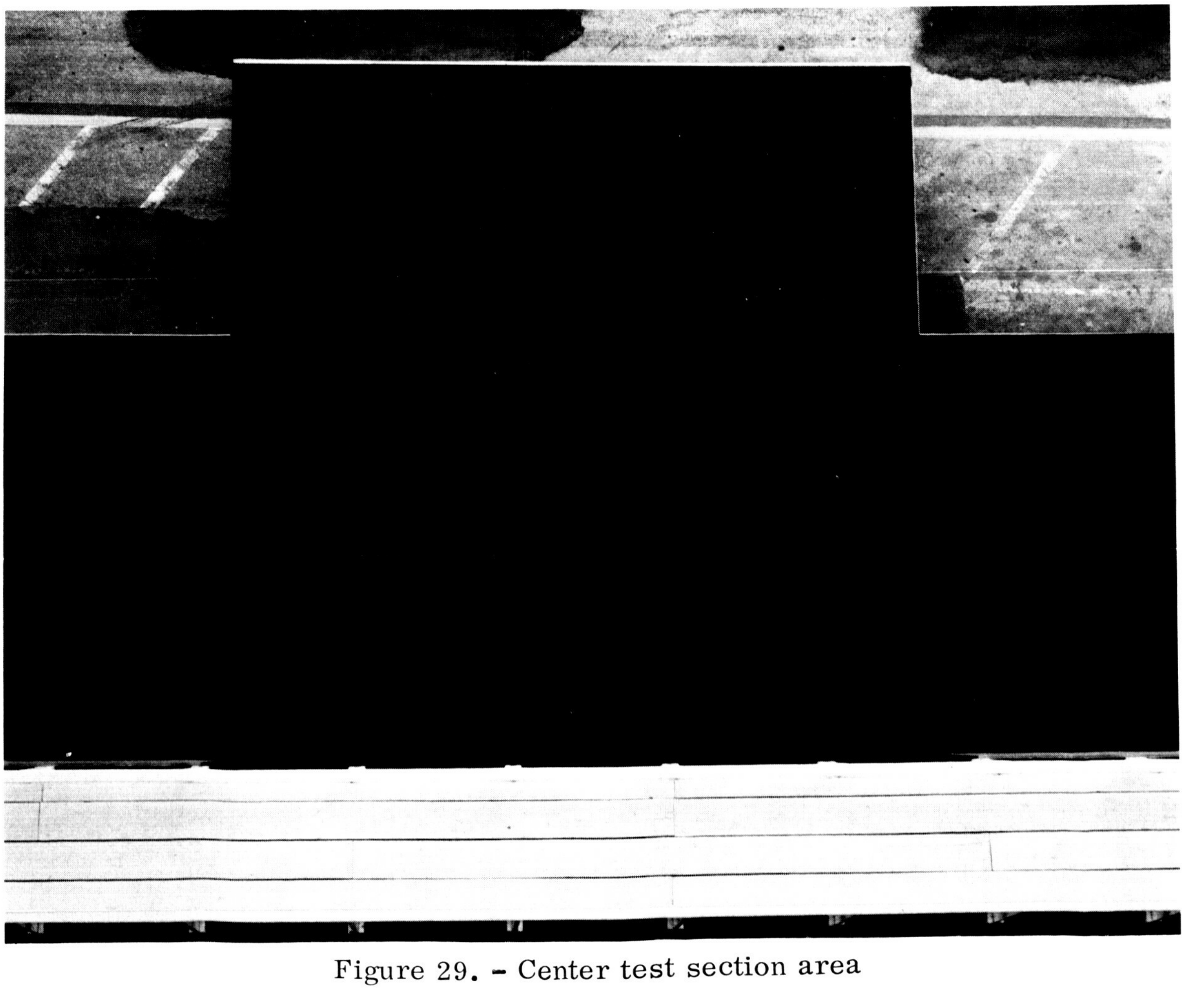

Figure 29. - Center test section area

Test Devices

Test devices were designed and fabricated to implement the various experiments conducted during the study program. The more important of these equipments are described in the paragraphs that follow.

Adjustable walkway. - Although the treadmill provided up to 30 degrees ascending and descending slopes in the physiological tests, it was necessary to install an adjustable inclined walkway section for the biomechanics motion analysis. An illustration of this test device is shown in Figure 30. The adjustable walkway was also designed to provide an ascending and descending slope range from 0 to 30 degrees. Figure 30 shows the walkway in the ascending position. For descending, the walkway was installed in a reverse position on the center test section.

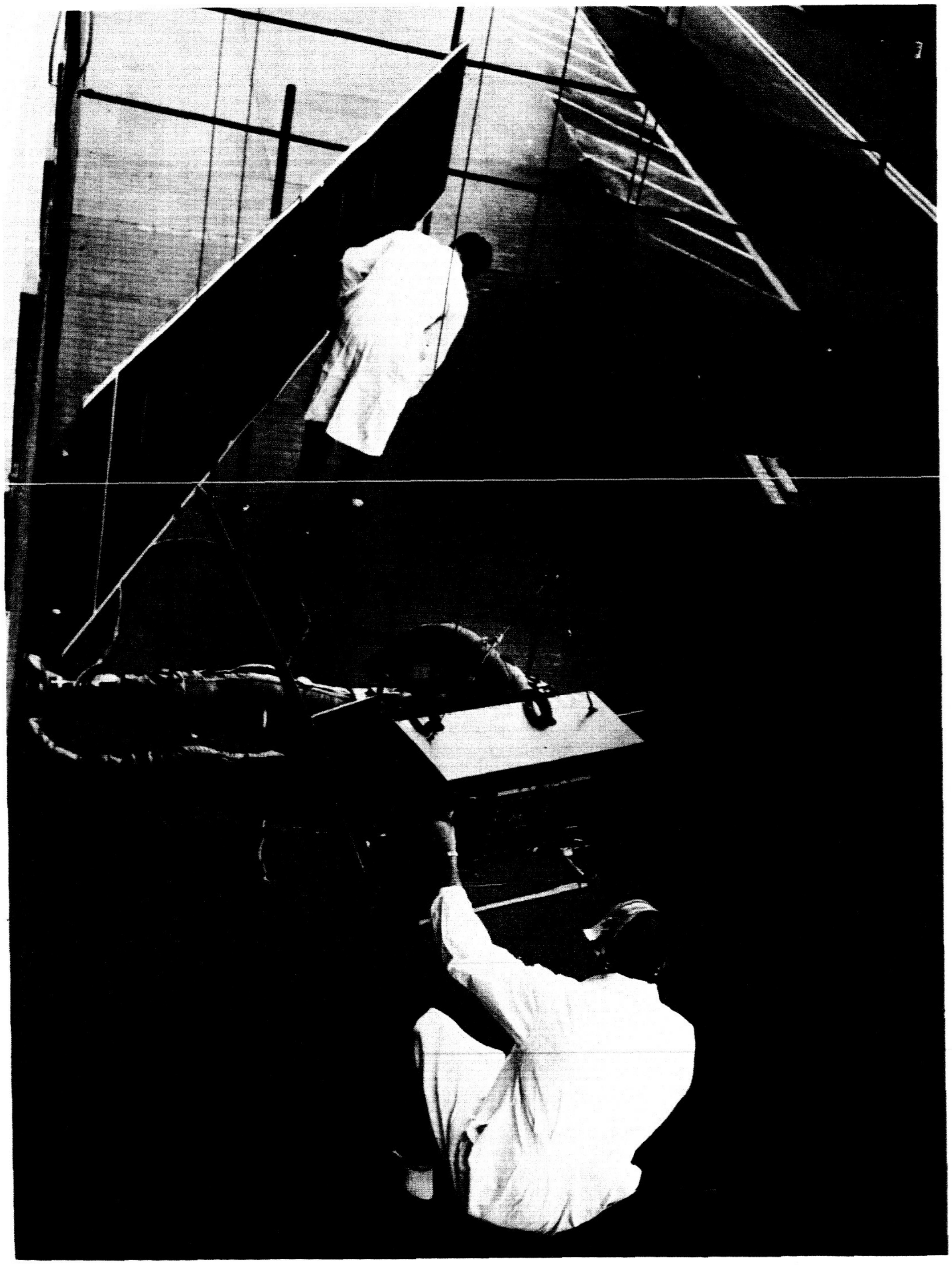

Figure 30. - Adjustable walkway

Stairway. - A test device for ascending or descending steps was also designed and fabricated. The stairway dimensions are shown in Figure 31. These were taken from the recommendations in Reference 2. A total of 18 individual steps produced an overall rise of 10 feet 6 inches (320 cm). The structure of this step test section is evident in Figure 32.

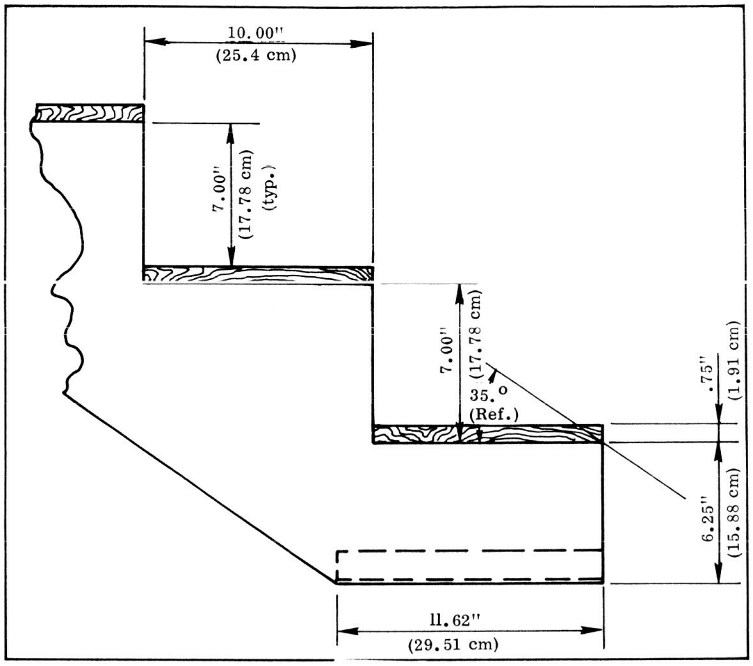

Figure 31. - Step detail

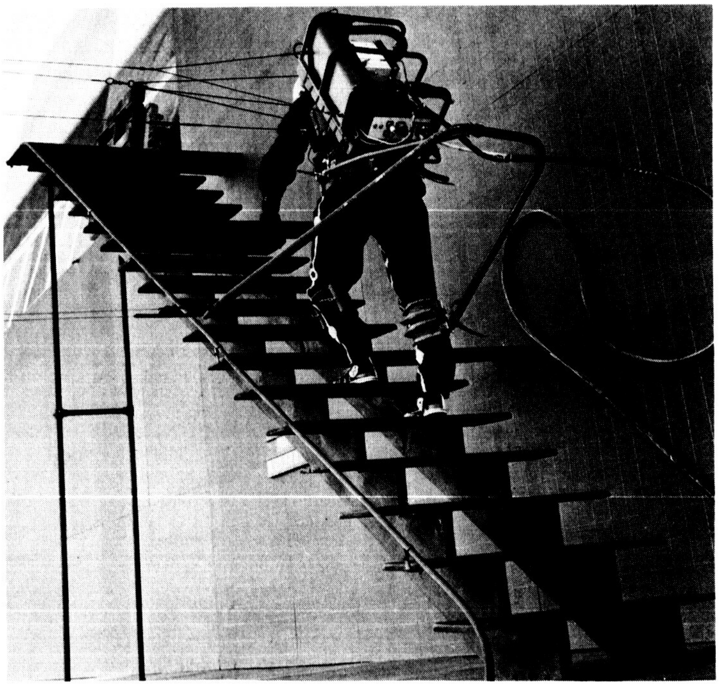

Figure 32. - Step test section

Platform. - To conduct experiments for jumping to and from elevated surfaces an adjustable platform was designed and fabricated. Its structure and method of installation can be seen clearly by Figure 33.

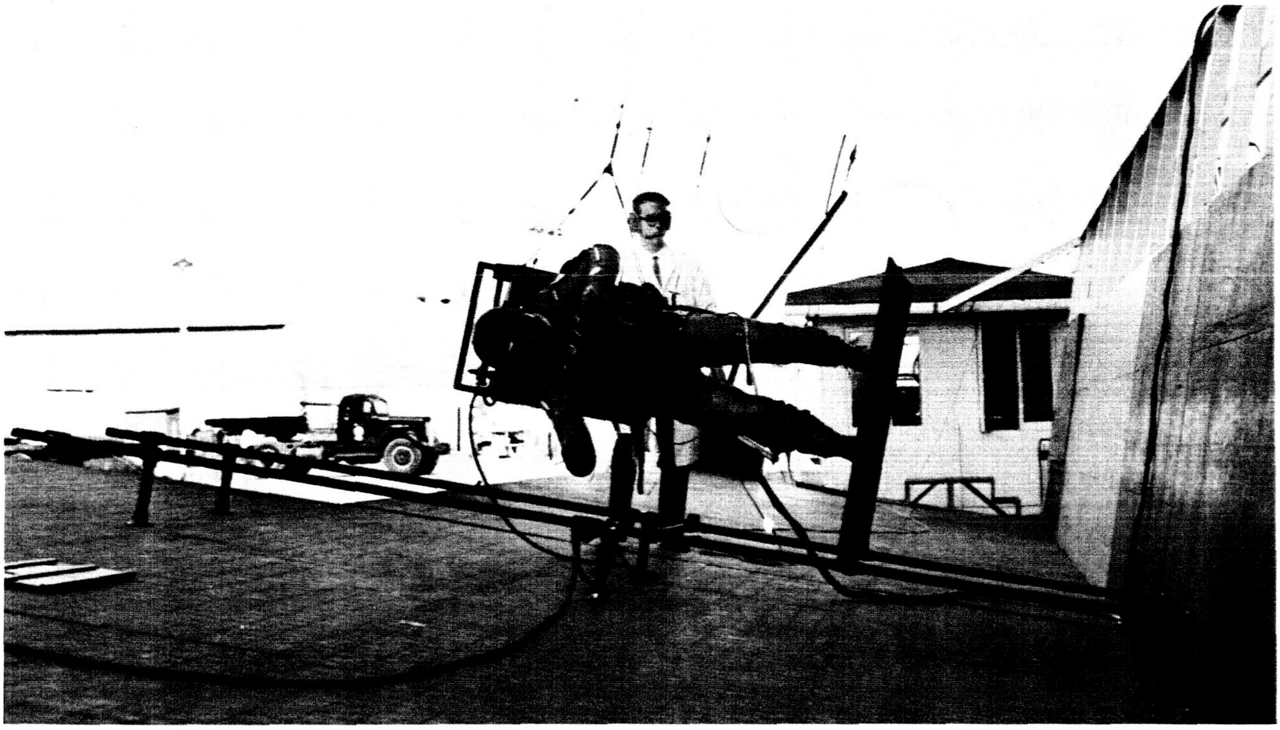

Figure 33. - Platform

Miscellaneous devices. - A single pole, a ladder, and a universal test section were also designed and fabricated. Their construction and installation method was very similar to that of the platform. They are not discussed in this report because they were not used for any experimental analysis.

Test Control Center

The Test Control Center building was installed at the north end of the simulator proximate to the start of the walkway. Two windows in the building face the simulator to enable the test director to observe the subject while monitoring and recording experimental data.

The size of the building is ten by twelve feet (304.8 by 365.8 cm). Its exterior appearance is shown in Figure 34.

The following equipment was located inside the test control center.

- Work physiological monitoring and recording equipment
- Communications
- Environmental master controls
- Treadmill speed control and OFF/ON switch

- A heater and an air conditioning unit for the removal of the heat loads from the ECS (Environmental Control System)

- Miscellaneous test hardware and supplies including test identification numbers

The power for the test control center was supplied by the adjacent NSL building. A conduit line was installed above ground. A telephone was also installed and placed within easy reach of the test director when stationed at the consoles.

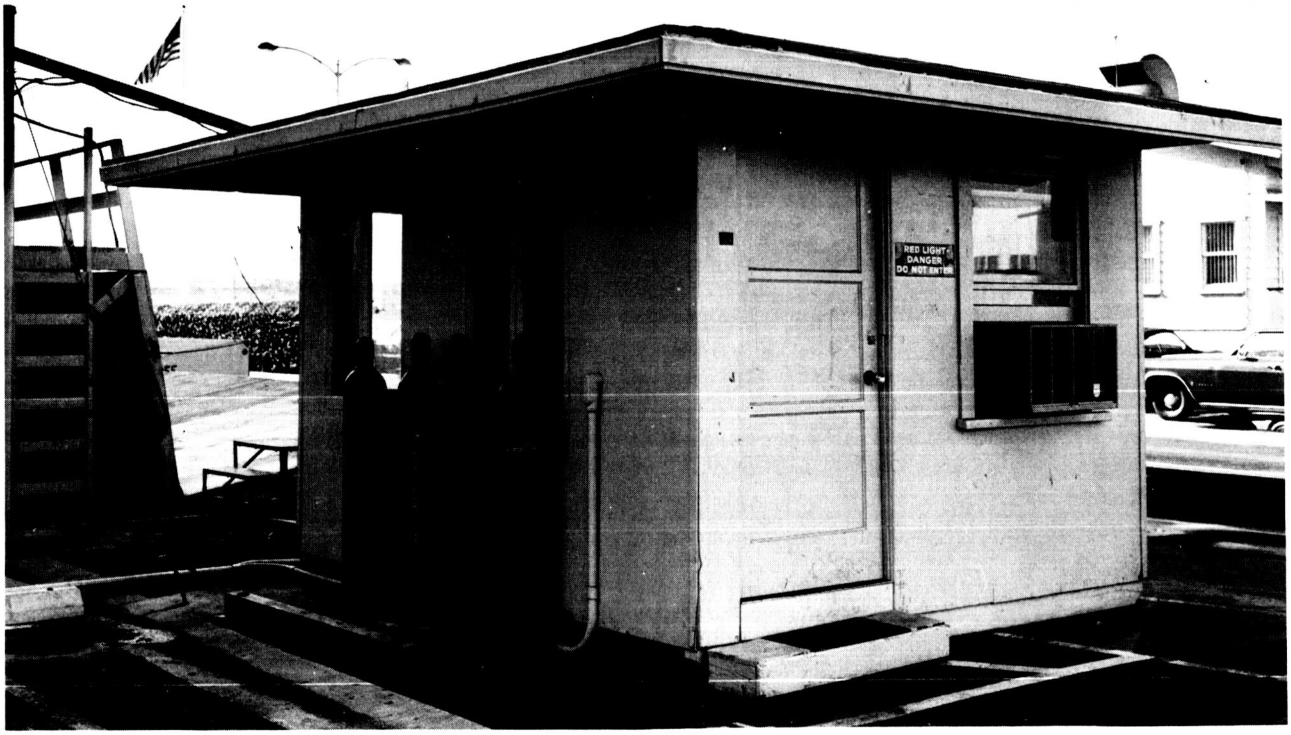

Figure 34. - Test Control Center building

Environmental Control System

To conduct experiments in the pressure suited, vent flow, and pressurized condition, it was necessary to design and fabricate an environmental control system (ECS). Table 2 lists the parametric requirements of the system applicable to use on the LGS versus the solutions necessary for the operation of the Navy MK IV two gas system full pressure suit.

TABLE 2. ENVIRONMENTAL CONTROL SYSTEM PARAMETERS

REQUIREMENT	SOLUTION
Pressurization and cooling of subject	Plant air, filtered and regulated, supplied to subject by umbilical
Pressurization of respirometer and sample	Pressure tank supplied by the outlet of subject's suit pressurization
Breathing atmosphere	Regulated 100% oxygen supply through ● secondary umbilical from 250 cu ft bottle located on the east side of the test control center ● 10 cu ft bottle located on instrument pack

Pressurization and cooling of subject. - Pressurization and cooling of the test subject included consideration of the environmental control console, umbilical, and instrument pack equipments. Further discussion of these elements follows.

Environmental control console: The plant air supply ranging from 100 to 120 psi was brought from the adjacent building to the test control center by installing a line above ground along the side of the power supply. The flow of the air supply is illustrated in Figure 35.

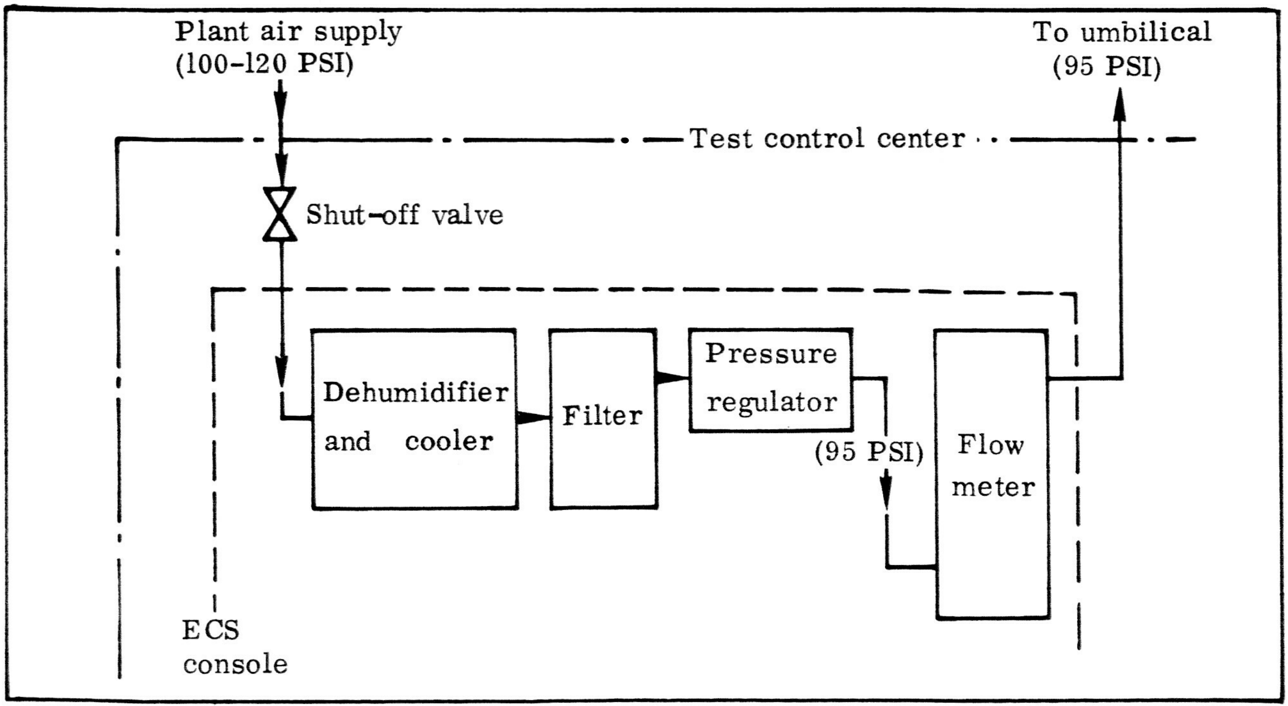

Figure 35. - Schematic, ECS console

The plant air supply enters the test control center at a pressure ranging from 100 to 120 psi. A shut-off valve is installed in the line just before it enters the ECS console. This valve is within reach of the test director when he is stationed at the consoles. The air supply passes through a dehumidifier and cooler and then through a filter where most of the remaining water particles are removed. The line pressure is reduced to 95 psi by a regulator just before the air passes through the flowmeter. This flowmeter is calibrated at 3.5 psig (18.2 psia) for pressure suit operation and indicates the pressurization flow in cfm. This flow then leaves the ECS console and the test control center via the umbilical to the subject. The actual location of the environmental control components on the console are shown in Figure 36.

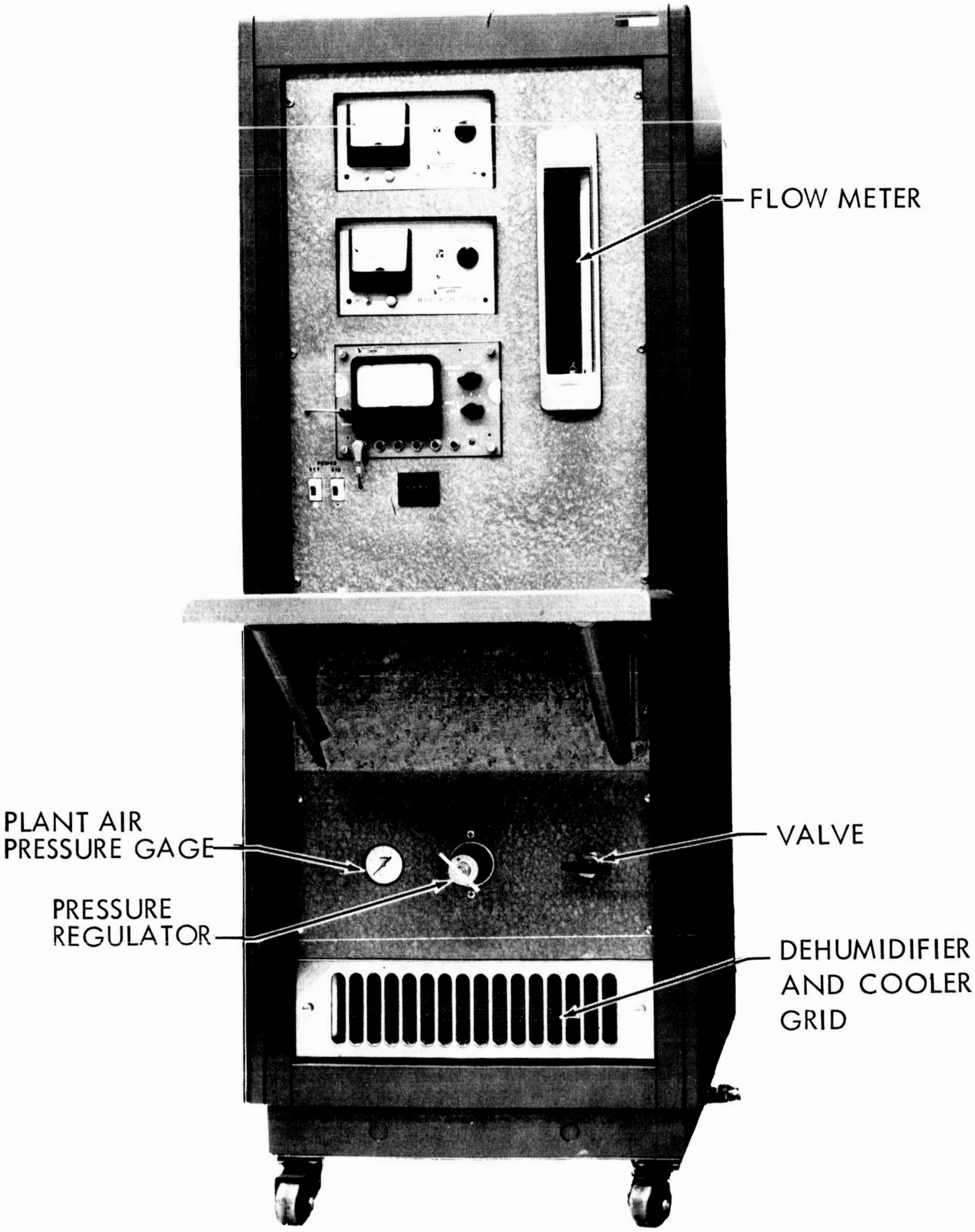

Figure 36. - Environmental controls

Umbilical: The umbilical originates 200 ft. (6096 cm) away in the test control center and terminates at the subject's instrument pack. It is suspended in loops between two poles behind the catwalk of the simulator as shown in Figure 37.

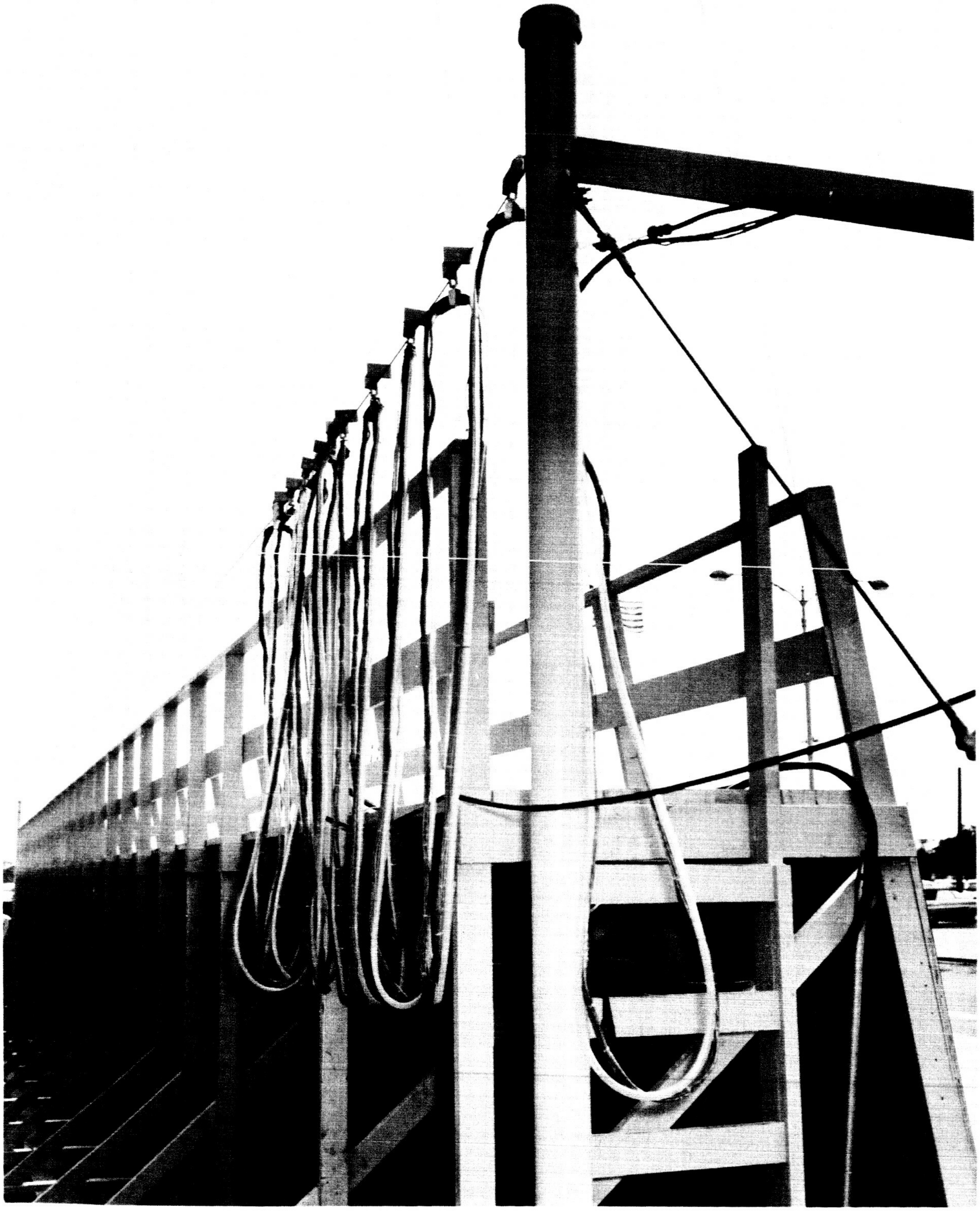

Figure 37. - Umbilical suspension

The umbilical loops are suspended from aluminum brackets that ride on an aircraft control type pulley. The brackets also contain a bumper on either end to push the adjacent bracket during the extension and contraction of the umbilical line. At the far end the umbilical crosses over the walkway. It is held and positioned by the escort according to the subject's motion along the walkway. This operation is illustrated in Figure 38. The termination of the umbilical on the subject's instrument pack can be seen quite clearly in Figure 21.

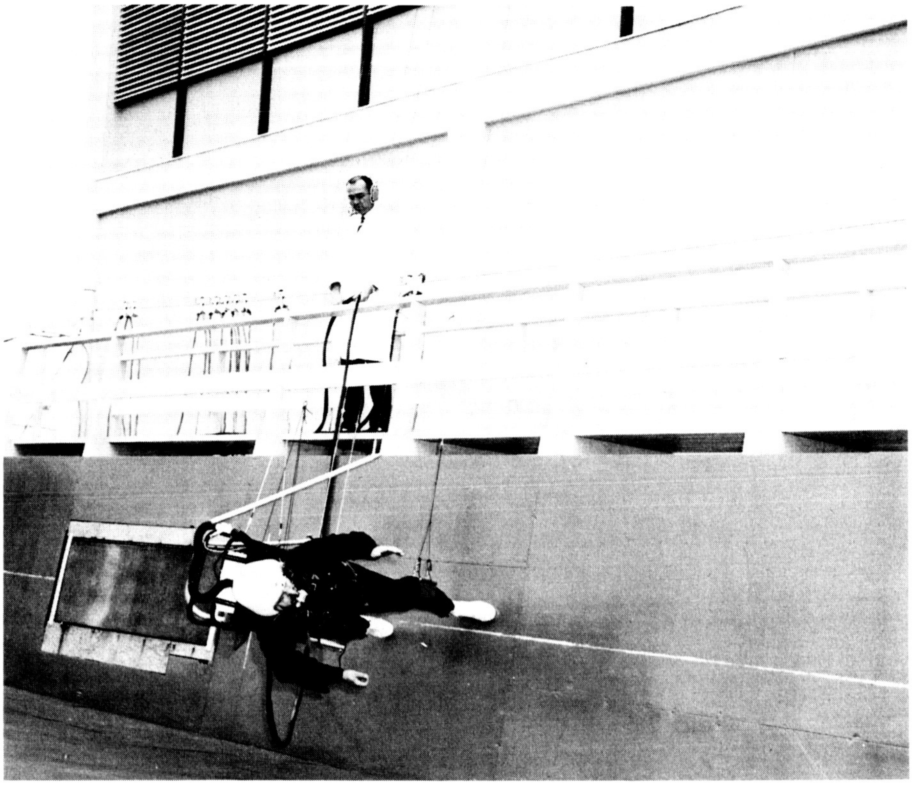

Figure 38. - Umbilical operation

An umbilical line pressure of 95 psi was selected to keep the pressurization flow diameter down. Had the pressure been reduced to 0 to 5 psi in the ECS console, a a very large diameter umbilical would have been necessary. Such an umbilical line would have been highly impractical considering the flow rates required.

Instrument pack: Pressurization, cooling of subject, pressurization of respirometer and sample, as well as the breathing atmosphere, are now shown together as a system in the following schematic diagram, Figure 39.

The 95 psi pressurization flow passing through a pressure regulator on the instrument pack was reduced to 3.5 psi. From here the pressurization flow entered the subject's suit through a quick disconnect. The return line from the suit, through a quick disconnect, passed into the pressure tank. From there the flow was discharged to ambient air, the outflow being controlled by a control valve located on the pressure tank (shown in Figure 40). Two pressure gauges with a range of from 0 to 15 psi were installed to indicate the suit inlet and outlet pressure.

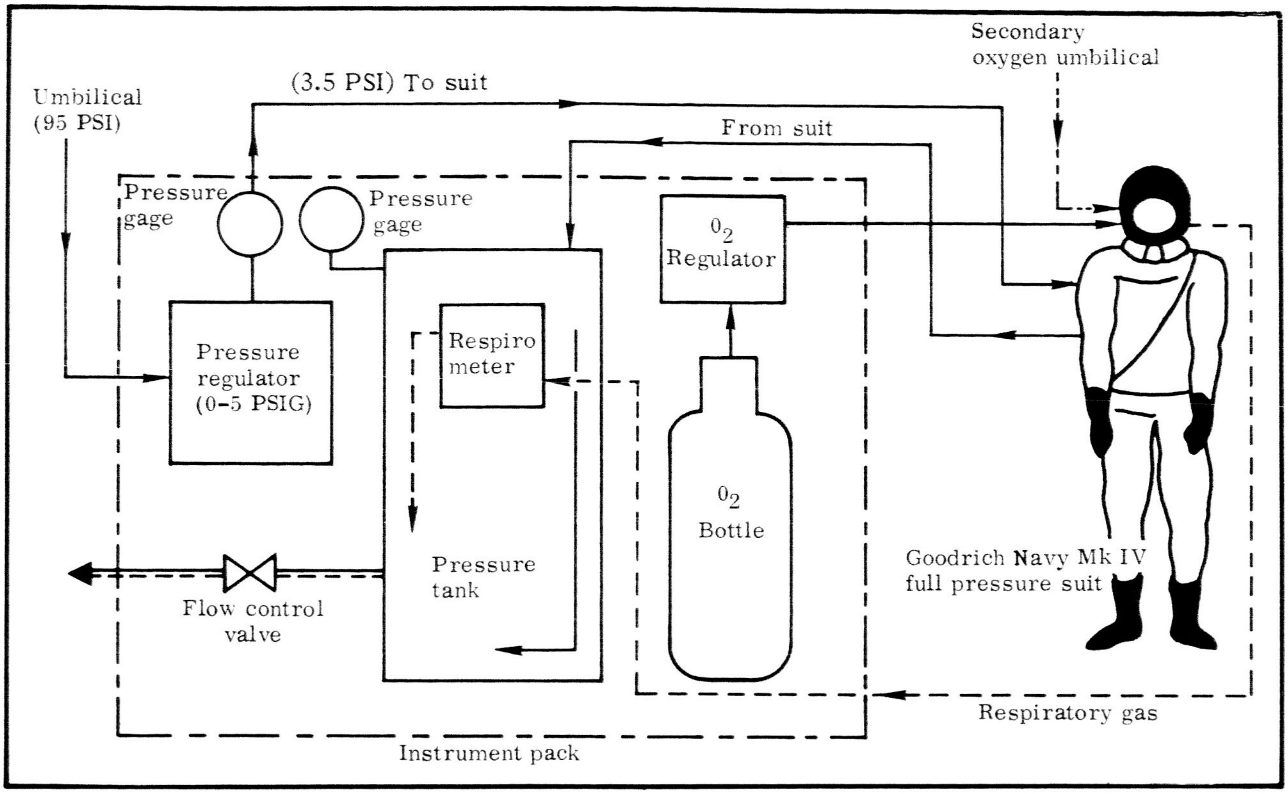

Figure 39. - Instrument pack flow diagram

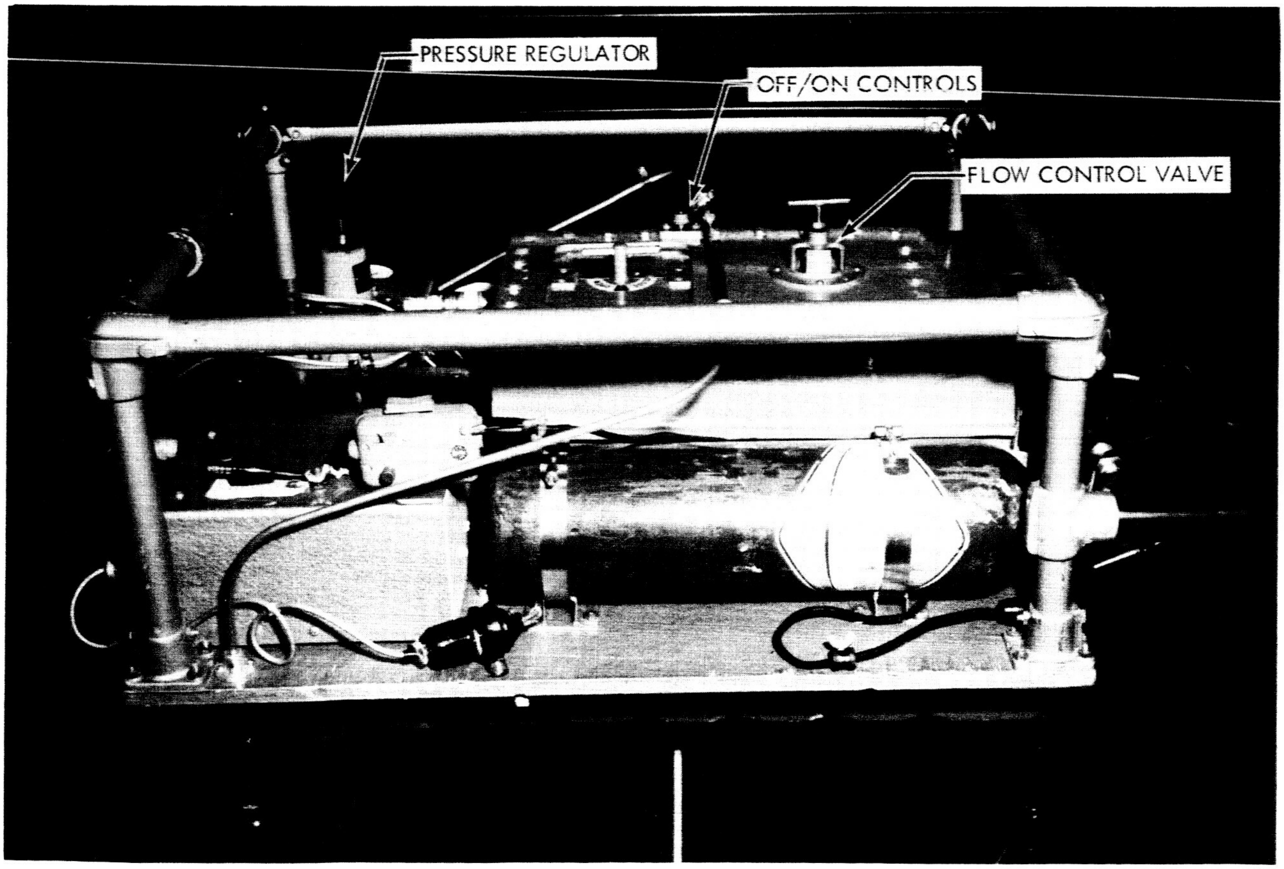

Figure 40. - Instrument pack

Pressurization of respirometer and sample. - To obtain the correct measurement of the respiratory volume flow of the subject, it was necessary to pressurize the respirometer and the respiratory sample taken under work physiological testing.

This was achieved by installing the respirometer in a pressure tank which contained practically the same pressure as that in the subject's pressure breathing circuit when installed in the position indicated in Figure 39.

After each test the sample collected in an aliquot had to be removed for subsequent gas analysis. Thus the subject had to be depressurized first by the manual control of the pressure regulator. Then it was possible to open the access door and to remove the sample as indicated by Figure 41.

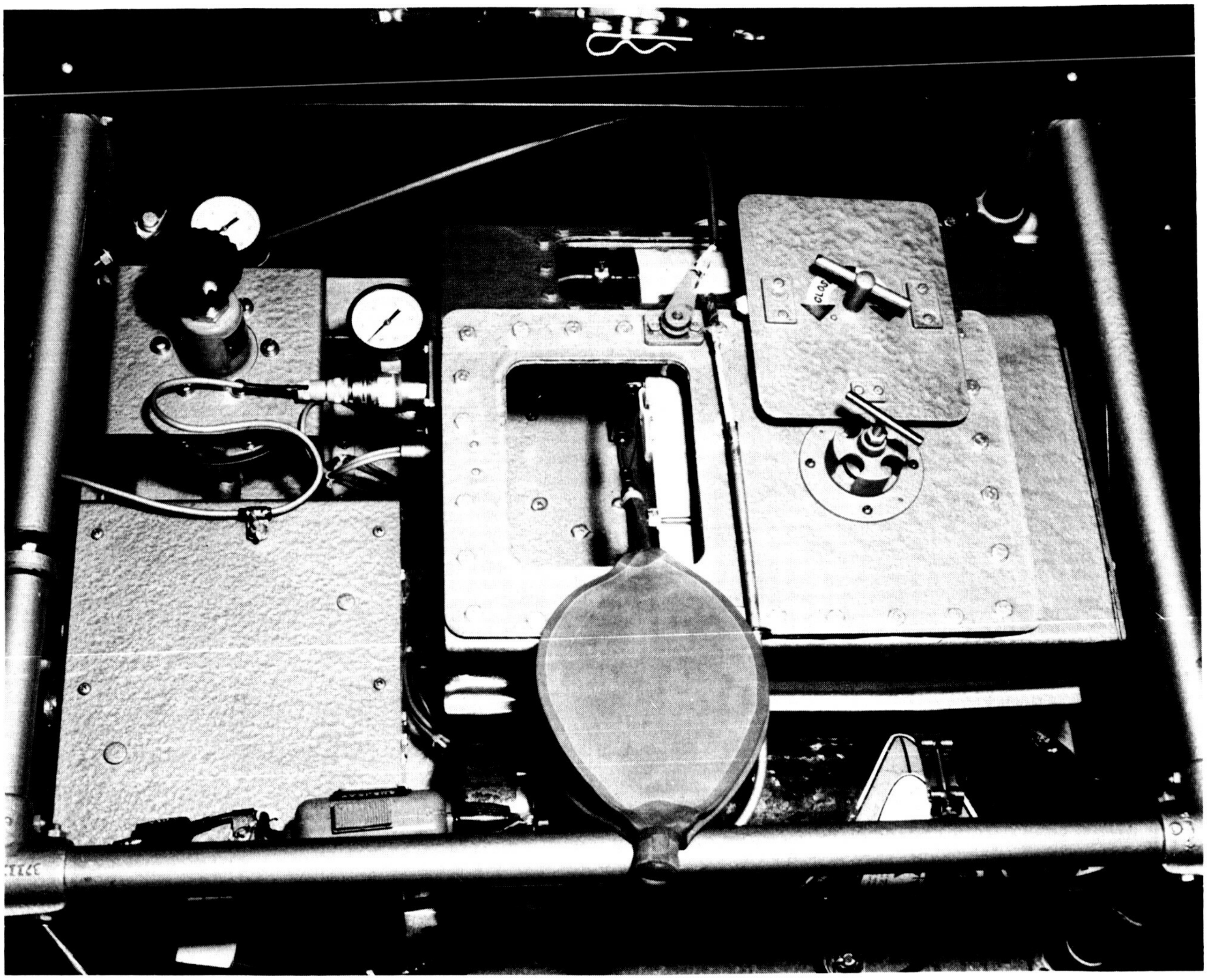

Figure 41. - Instrument pack, details

Figure 40 also shows the respirometer reading through a plexiglass window which had to be recorded for the test duration. The OFF/ON control lever for the respirometer is also visible in Figure 40.

Breathing atmosphere. - The breathing atmosphere in the Navy MK IV full pressure suit had to be supplied separately. This was performed for two different test conditions.

The first test condition involved prolonged experiments conducted in a local area of the LGS. Under these conditions it was possible to use a large oxygen bottle of 250 cu ft by placing it in the vicinity of the local test area and running a secondary oxygen umbilical to the subject's helmet. This method is illustrated in Figure 42. In conducting experiments for baseline data (see Figure 42), it was also necessary to supply the subject with pressurization without the use of the instrument pack. This was done by using a respirator unit for pressurization in conjunction with a suit test kit. The subject then expired through the original suit valve in the face seal to the torso. For work physiological tests, however the instrument pack was located nearby and the subject's expiration was conducted through the instrument pack as under normal testing.

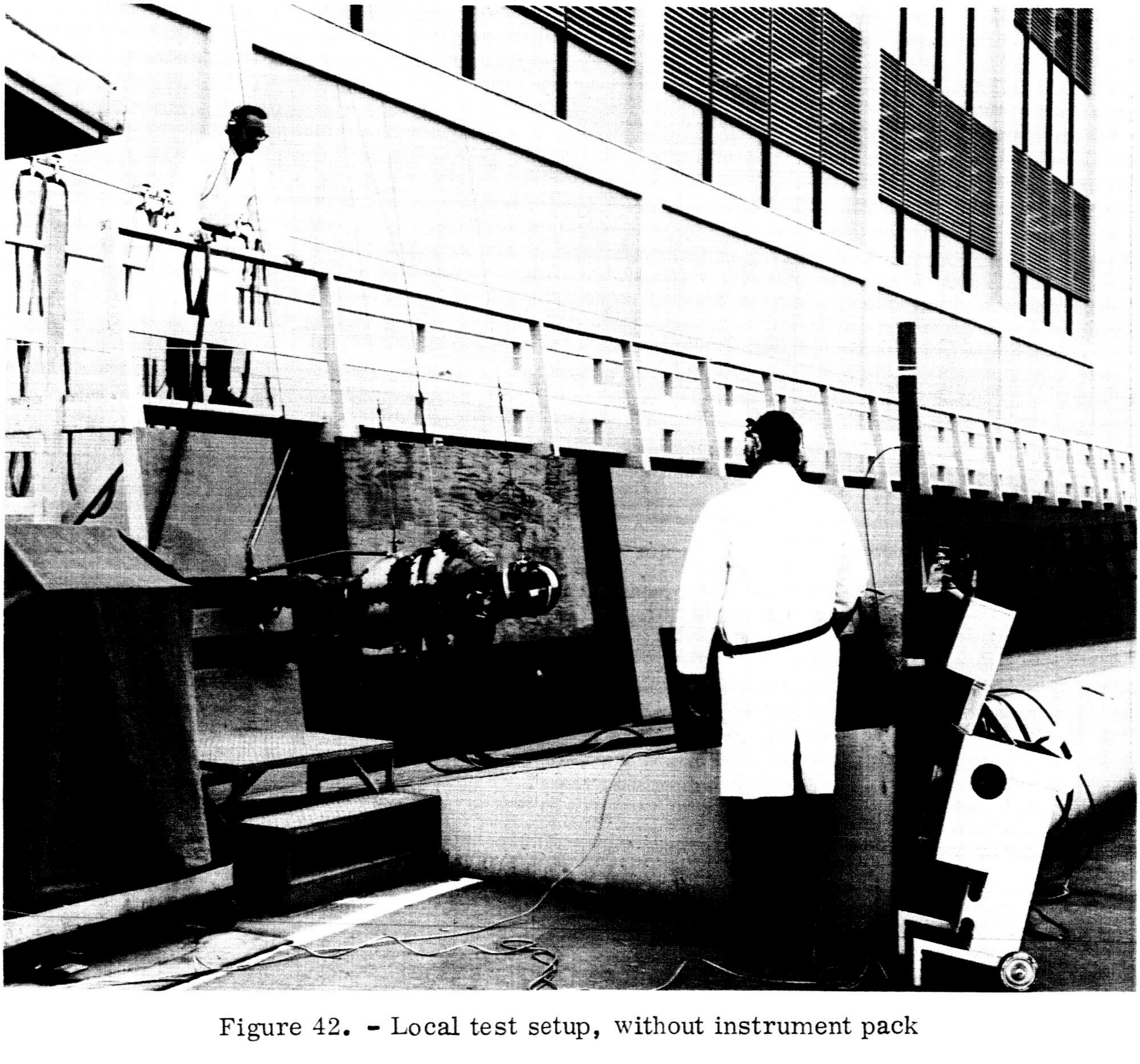

Figure 42. - Local test setup, without instrument pack

The second test condition involved experiments conducted along the walkway. Since no oxygen line was included in the umbilical, a 10 cu ft bottle was installed on the instrument pack. It was clamped in place as shown in Figure 40. Figure 43, in turn, shows the oxygen bottle contents indicator, oxygen regulator, and OFF/ON valve. The oxygen pressure was reduced by the regulator and flowed to the pressure suit helmet. Quick disconnects were used at either end of the line. Another oxygen pressure regulator which was part of the helmet admitted the oxygen to the face compartment in the subject's helmet.

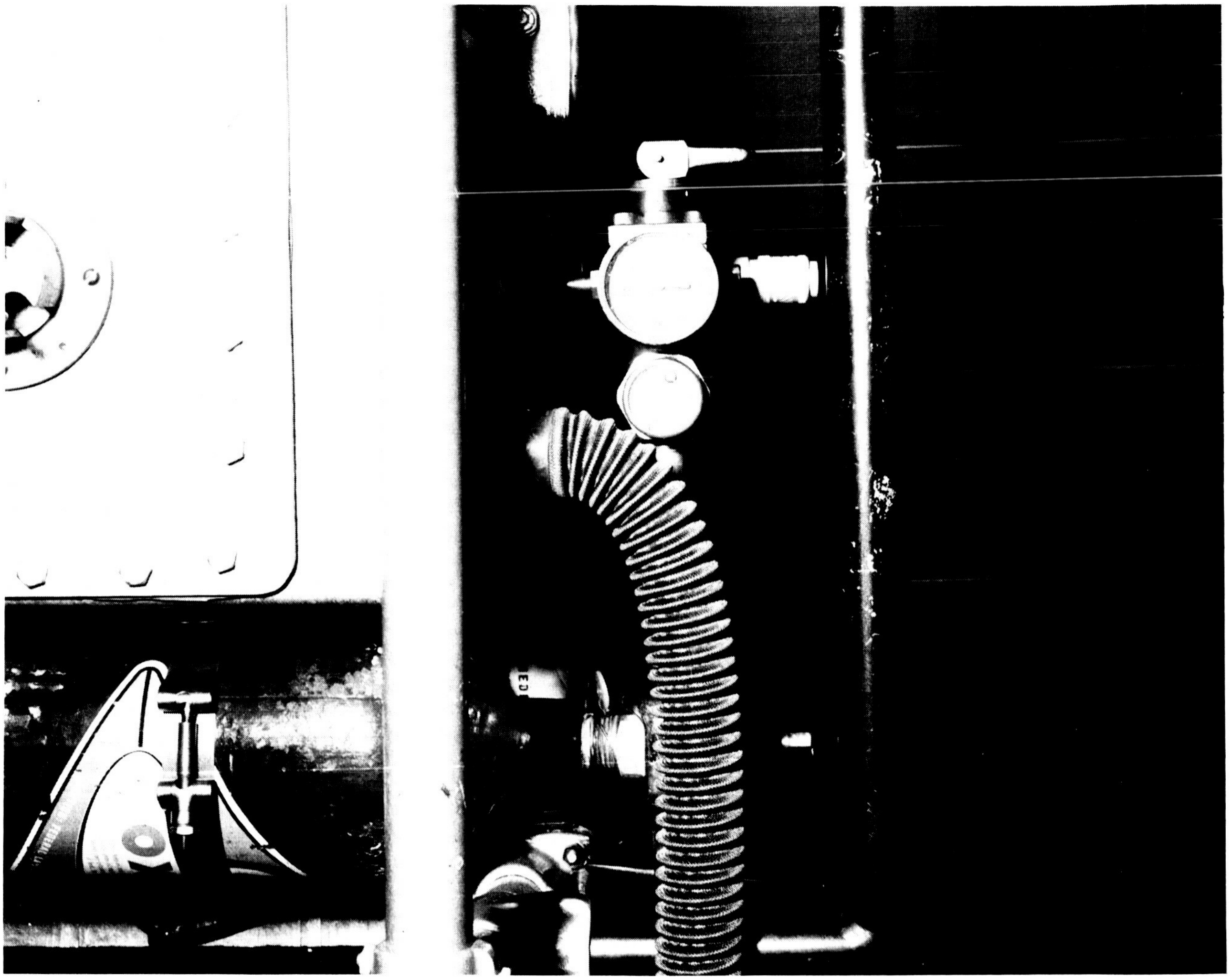

Figure 43. - Oxygen regulator and indicator

The pressure suit helmet had to be modified for the type of respiration required in work physiological testing. The original visor was reinforced by fiberglass lay-up internally as well as externally. A fitting containing an outlet elbow was installed permanently in the side of the helmet. A large hole was drilled in the center plate in front of the subject's mouth. The body of the respiratory valve was modified and a close fitting insert with a stop flange was welded to it. A bushing containing an O-ring was installed permanently in the center hole of the visor. The respiratory valve was inserted in the bushing and locked in position by a pip pin. The rubber mouthpiece for the subject was flexible enough that it could be slipped over the respiratory valve prior to its insertion. A view of the components involved is shown in Figure 44. With these components in place and the subject equipped with a noseclip, he withdrew oxygen from the face compartment to the respiratory valve through the side elbow on inspiration. On expiration the expired gas was discharged through the respiratory valve to the respirometer. This flow is illustrated in Figure 39. The volume flow of air passing through the respirometer was recorded then mixed with the pressurization flow to be discharged to ambient through the previously mentioned flow control valve.

Figure 44. - Pressure helmet modification

Instrument Packs

Several instrument pack configurations were designed and fabricated in support of work physiological and loadbearing tests. The type of equipment contained within each instrument pack was dictated by the function it had to perform. Table 3 indicates the cross section of equipment included in the three instrument pack versions.

TABLE 3. - INSTRUMENT PACKS

Instrument Pack Components	Operational Modes		
	1000	2000	3000
	Shirt Sleeve	Pressure Suit Vented	Pressure Suit Pressurized
Respirometer	Instrument Pack I	Instrument Pack II	Instrument Pack II
Bioinstrumentation Junction Box			
Communication Junction Box			
Pressure Tank		Not Used	
Oxygen Bottle		Not Used	
Total Weight, lbs	26.5	76.0	76.0

Instrument Pack I. - Instrument Pack I consisted of a military style pack frame upon which the various components were mounted. This pack was used only for shirt sleeve experiments and consequently carried only the respirometer, respiration rate detector, the bioinstrumentation junction box, and the communications box. Their respective locations are evident in Figure 45. The respirometer was held in position by two aluminum channel sections which in turn were bolted to the plywood pack frame. The bioinstrumentation junction box was bolted directly to the pack frame. A welded roll bar structure made from magnesium was attached to the side of the pack frame by clips. This bar proved very effective in preventing damage to the equipment located on the instrument pack in the event the subject fell on the simulator. An OFF/On pull arrangement for manual activation of the respirometer by the subject was installed. This consisted of green and red "apples" (ball handles) and corresponding cables guided by flared aluminum tubing to the respirometer lever. A sheet of aluminum was formed, sprayed flat black, and installed on the side of the pack facing the biomechanics data camera (overhead) to eliminate any equipment images in the photographic recordings.

The pack itself was suspended at two points along its center of gravity line and was attached to the subject by two conventional shoulder straps which terminated on the chest support plates (see Figure 20) while the lower straps terminated on the pelvic support plates (see Figure 21).

Instrument Pack II. - This instrument pack was designed for the pressure-suited mode of operation. Table 3 indicates that a pressure tank and oxygen bottle had to be installed in addition to the components used in Instrument Pack I. It was necessary to house the respirometer and respiration rate detector in a pressure tank for the reason described previously. Figure 46 provides a plan view of Instrument Pack II which reveals most of the components used.

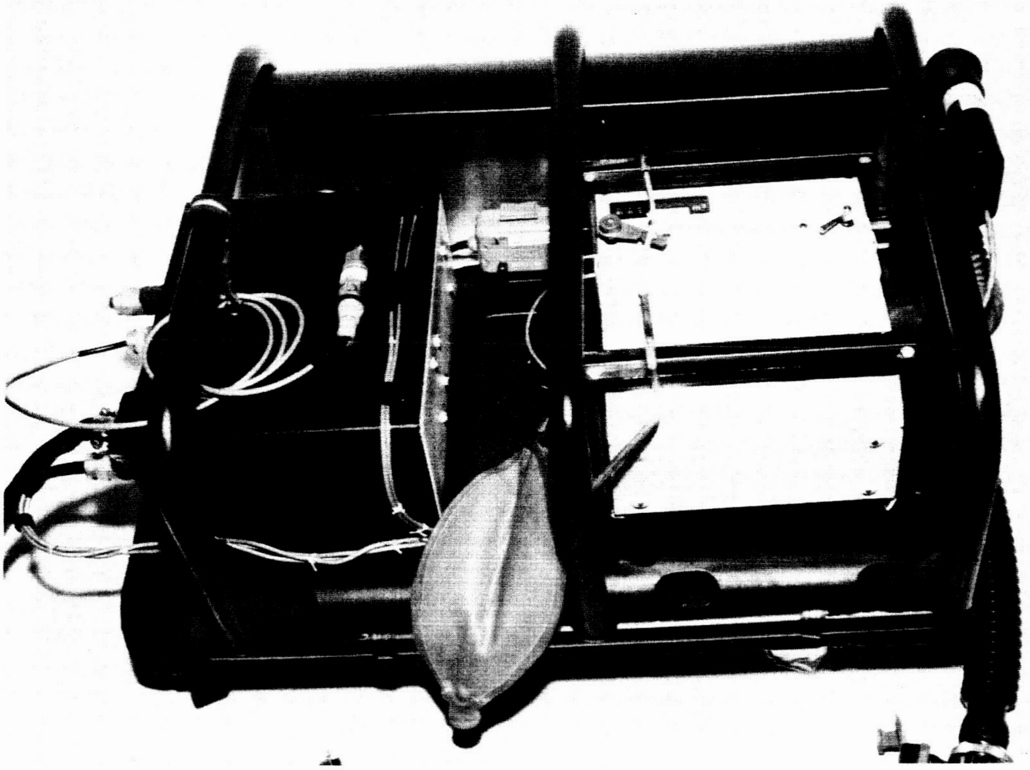

Figure 45. - Instrument pack I

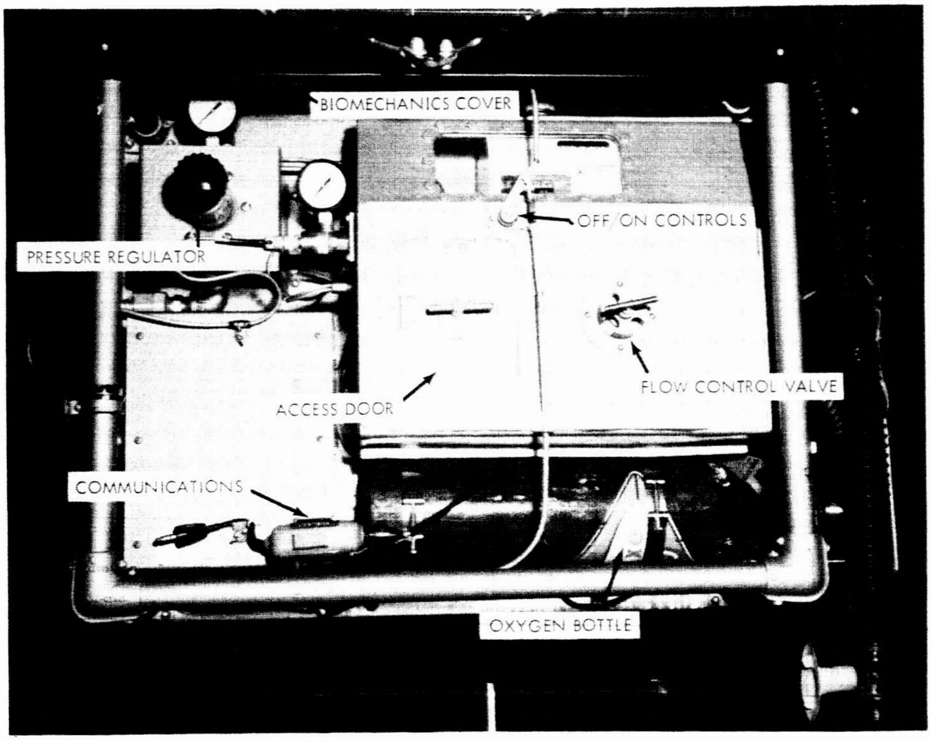

Figure 46. - Instrument pack II, plan view

The pressure tank for Instrument Pack II was made from aluminum plate with the sides as well as the front and back halves welded together. A plexiglass window was installed to permit reading of the volume flow indicator and thermometer on the respirometer. The quick access door mentioned earlier provided access to the respiratory sample for its removal. A large plate with a seal was installed on the front half of the pressure tank by 1/4-inch bolts with plate nuts on the inside. This plate was removed only for access and removal of the respirometer itself. The OFF/ON lever and its controls were very similar to that of Instrument Pack I and can be seen clearly in Figure 46. The respiration rate detector (see Figure 47) was directly attached to the access plate at the top end of the instrument pack.

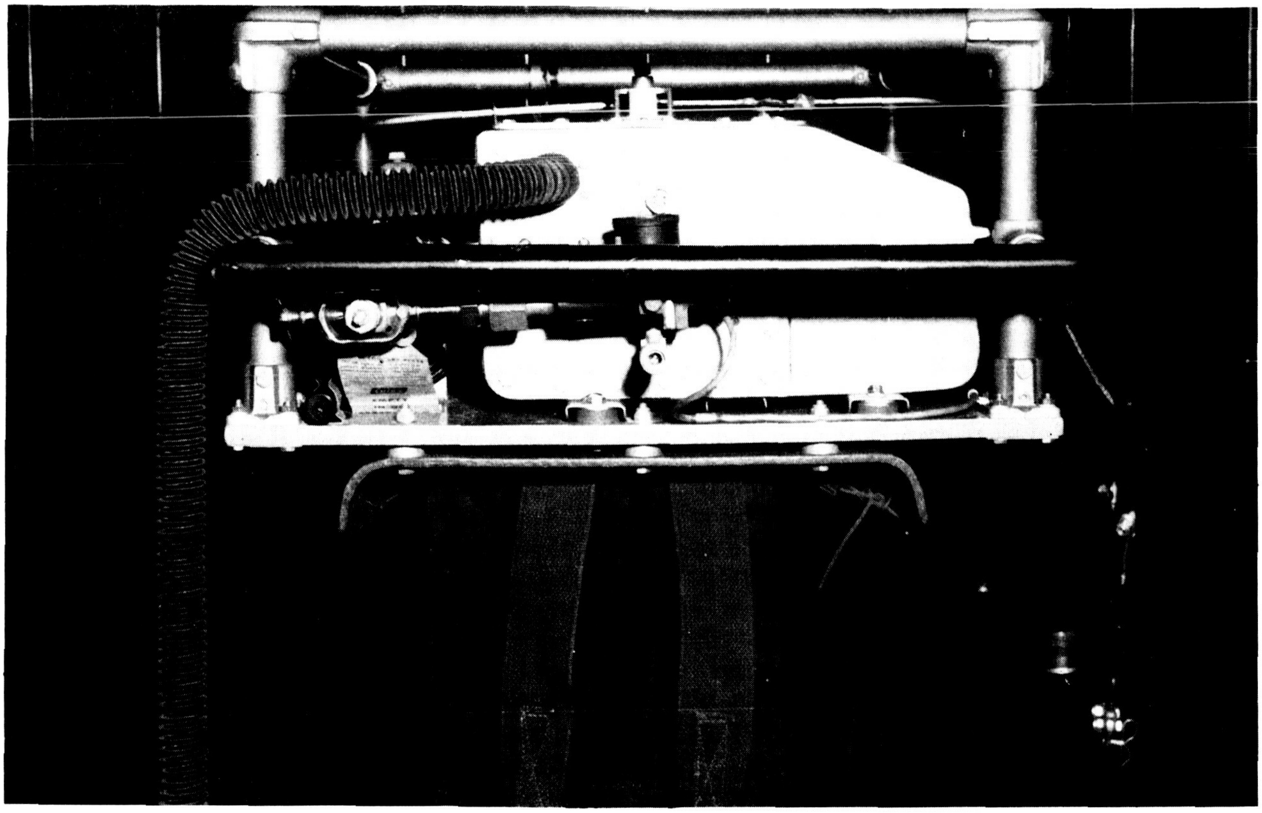

Figure 47. - Instrument pack II, end view

All components were bolted to a 1/2-inch plywood board which in turn was bolted to a pack frame identical to that used in Instrument Pack I. Figure 47 indicates this attachment method. Roll bars for the prevention of damage to the components were installed using the tube fittings shown in Figures 46 and 47. A two-point suspension through the end members of the roll bar structure was used. Two short cables were connected to these suspension points from a common single suspension point. However, a turnbuckle for adjustment was installed in each of the short cables to align the mass center with the center of suspension.

A sheet of aluminum painted flat black was installed on the biomechanics data camera side of the instrument pack, similarly to that on Instrument Pack I. This, including the two-point suspension, is shown in Figure 48.

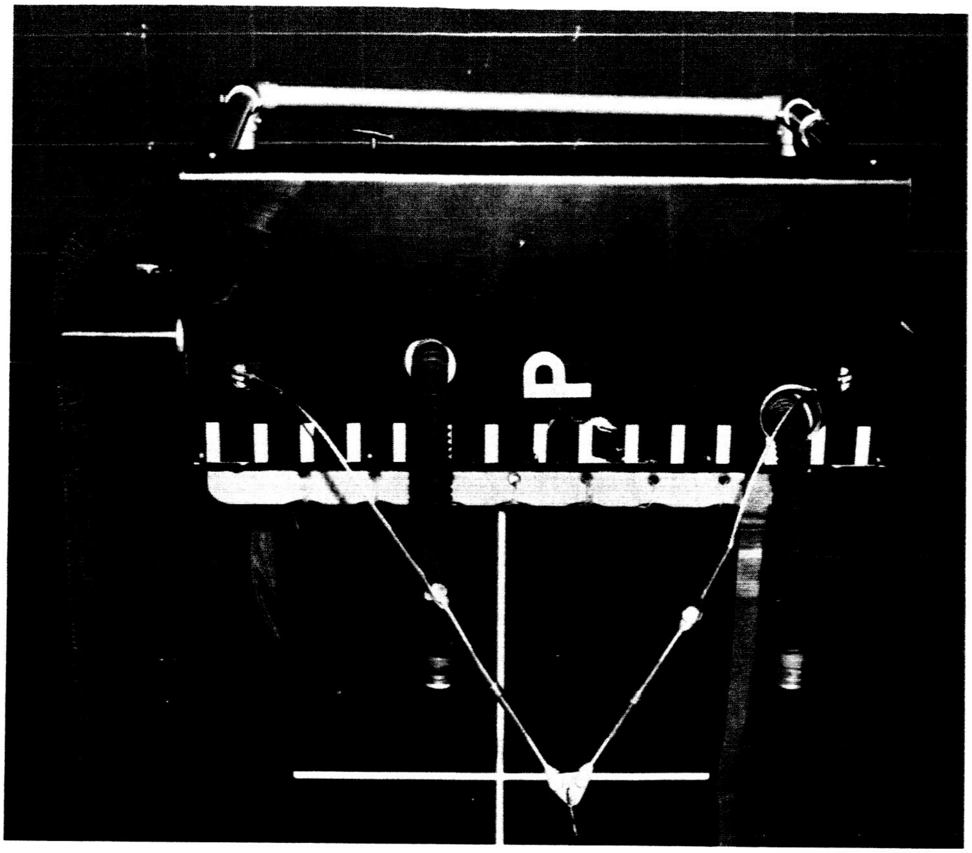

Figure 48. - Instrument pack II, suspension

DISCUSSION

Suspension System

Rail installation. - The rail itself functioned successfully throughout the testing phase. No problems were experienced with the liner or the attachment. Wind blowing over the top of the building, however, did deposit gravel in the track. This made a trial run along the simulator necessary each day before actual testing commenced. When gravel was detected in the track, it was necessary to sweep it out even though safety regulations did not permit anyone on the roof top of the building. It is evident that a cover for the complete rail section will be necessary to facilitate future testing. An alternate solution would be the installation of a safety rail along the top edge of the roof from which cleaning of the rail could be accomplished without violating building safety regulations.

Dolly. - The safety tabs in the side members of the dolly (see Figures 4 and 5) had to be made removable to permit removal of the dolly from the track. The tab shape had to be further modified to clear the rail support brackets which did not meet the original design dimensions. This problem was discovered and corrected during the checkout phase of the simulation facility.

Spreader bar with suspension cable. - The dimensional relationship between the master cable and body segment support cables as shown earlier in Figure 7 proved to be very successful. It did not exhibit the oscillatory patterns produced by rapid body segment motions observed on the NSL small scale simulator which utilized a considerably shorter suspension cable length.

Head and neck support. - The supports for the shirt sleeve and pressure suited operation were found suitable throughout the program.

Trunk and pelvic support. - The hard suspension developed performed well without problems. The shoelaces used in this gear had to be replaced only once during seven months of testing.

Leg supports - upper leg support/lower leg support. - The upper support interfered occasionally with that of the lower leg at subject's velocities above five to six miles per hour. This occurred without any disturbing effects on the subject in the shirt sleeve mode. In pressure-suited operation, however, they were quite distracting and affected the subject's stability somewhat. Improvement of this design is indicated for future pressure suit testing.

Walkway

The present walkway is sufficient in width. To conduct future experiments, however, it is recommended that the length of the walkway should be increased to 200 feet (6096cm) for the determination of maximum physical values. This comment is based on experience with subjects having to come to a sudden halt at the endstop before reaching terminal velocity.

Inclined Treadmill

The treadmill motor, although providing a top speed of ten miles per hour horizontally, rapidly decreases in speed when operated for descent of the subject according to Table 1. Consequently the subject never could reach his maximum physical performance during these experiments. The treadmill in general served well throughout the experiments. Should further testing be undertaken for descending, it would be necessary to completely redesign the drive system and install a considerably stronger motor.

Backdrop

The present and original grid system installed on the backdrop barely lasted through the testing period. The grid wires were displaced repeatedly during the installation and removal of test devices. The Monel wire also corroded considerably under exposure to the local atmosphere and weather. A temporary cover used during the night was tried but did not reduce deterioration of the grid wires. An improved grid system should be considered for conducting experiments on a continued basis.

Test Devices

The devices themselves served reasonably well. Their installation and removal, however, required considerable effort and manpower. A lifting device that could swing the various test devices into place would be of considerable help in the future.

Test Control Center

The test control center was adequate in floor space, size, and layout for the purpose it was installed. Future testing can be conducted from this building with very little modification.

Environmental Control System

The dehumidifier and cooler was not sufficient to keep the subject comfortable when ambient temperatures reached 90°F. To provide a continuous testing operation the dehumidifier and cooler would require replacement by a larger unit. The pressurization system worked well. For future testing it would be advisable to include an oxygen line in the umbilical to the subject because of the limited (twelve minutes) test duration available through the oxygen bottle carried on Instrument Pack II.

REFERENCES

1. Hewes, D. E., and Spady, A. A., Evaluation of a Gravity Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment, NASA Technical Note, TN D-2176, 1964.

2. McCormick, E. J., Human Engineering, McGraw-Hill Book Company, 1957.

APPENDIX A

DETERMINATION OF SIMULATION CORRECTION

The cable suspension system confines the motion of the test subject to the path described by the radius of the cable length R. This produces some error in the simulation of the constant lunar gravity state. Of greatest importance is the increasing gravity vector produced by the suspension cable with the increase in $\Delta\theta$, the angle traversed, shown in Figure A1.

Jumping is one of the activities investigated on the lunar gravity simulator. This activity produces some of the greatest variations from the nominal 1/6 g desired from the simulator. Thus an analysis is performed to determine the correction factors to be applied for various jump heights. This correction then holds true for all excursions along the projected z plane of the simulator.

The vertical jump height h', as in Figure A2, represents the projection of the simulated jump height h, as well as the projection of the corrected height H which would have been achieved along the tangent at point O under the constant gravity gradient vector produced by the angle θ.

This assumption is made for the ideal simulation under a constant value of the subject's energy expenditure without any constraints.

where

O = base point for jump simulation (center of gravity of subject standing on walkway)

O' = base point for vertical jump

h = theoretical path of subject c.g. along simulated jump ($\overline{OP_z}$)

h' = vertical projection of jump height h ($\overline{O'P_z'}$)

z = arc length of jump height h (arc from O to P_z)

H = corrected path of subject c.g.

R = length of suspension cable

θ = angle to base point O

$\Delta\theta$ = angle traversed in simulated jump

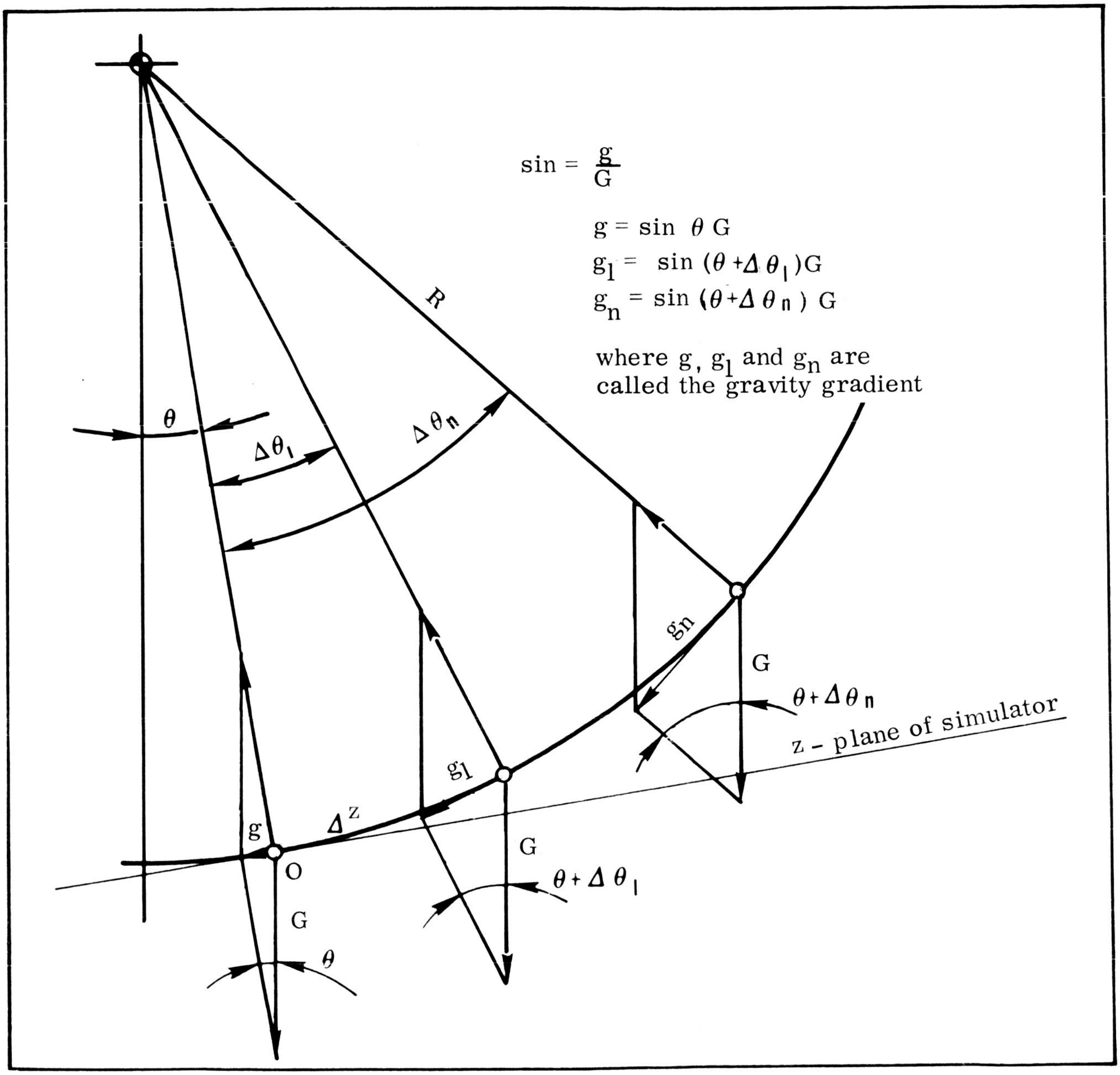

Figure A1. - Suspension gravity vectors

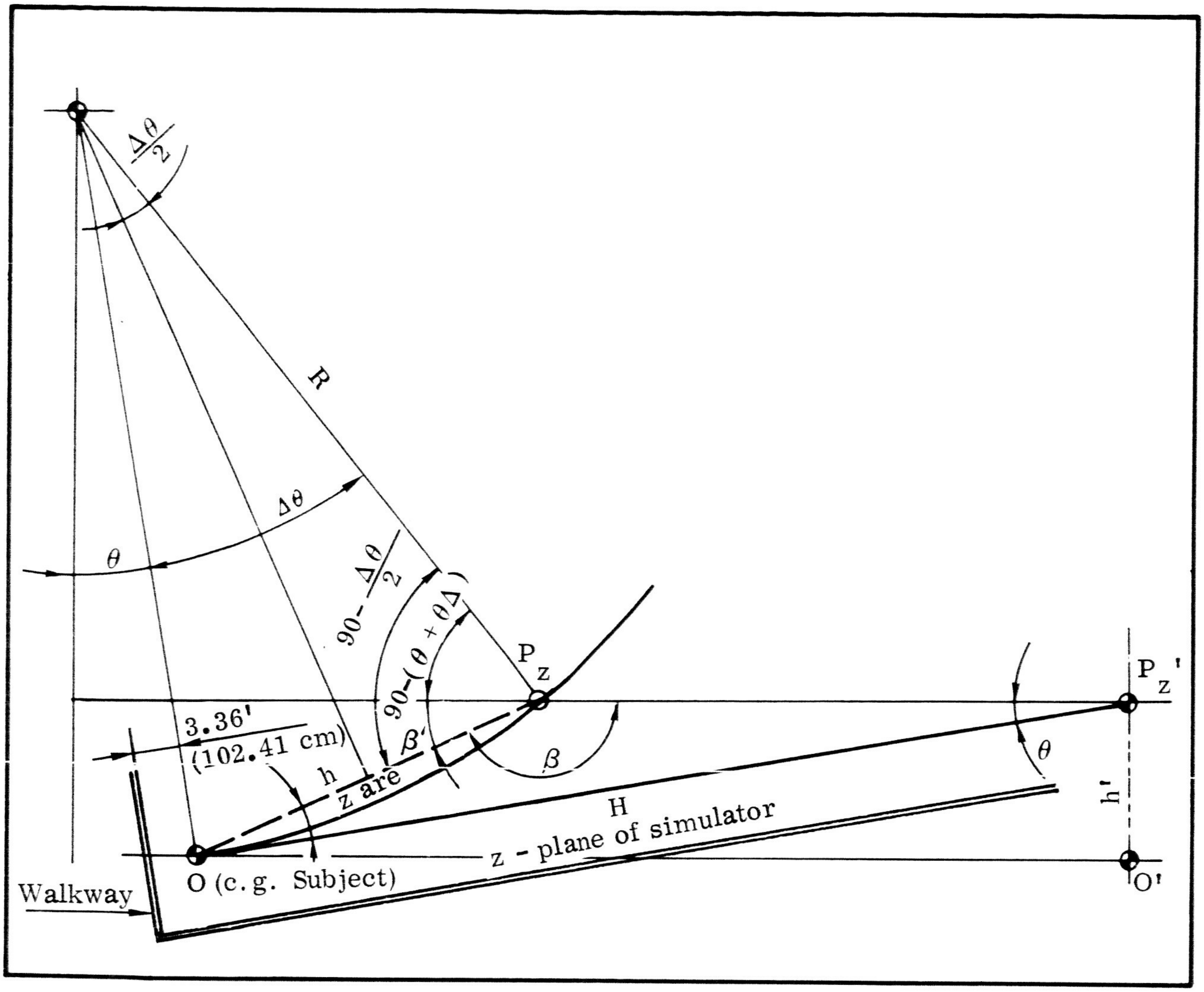

Figure A2. - Jump height geometry

From the relation given in Figure A2 the angle

$$\beta' = \left[90 - \frac{\Delta\theta}{2}\right] - \left[90 - (\theta + \Delta\theta)\right] = 90 - \frac{\Delta\theta}{2} - \left[90 - \theta - \Delta\theta\right]$$

$$= 90 - \frac{\Delta\theta}{2} - 90 + \theta + \Delta\theta = \theta + \Delta\theta - \frac{\Delta\theta}{2} = \theta + \frac{\Delta\theta}{2}$$

and

$$\beta = 180 - \beta' = 180 - (\theta + \frac{\Delta\theta}{2}) = 180 - \theta - \frac{\Delta\theta}{2} \qquad (1)$$

According to the law of sines $\frac{H}{\sin\beta} = \frac{h}{\sin\theta}$ from which

$$H = h\,\frac{\sin\beta}{\sin\theta} = h\,\frac{\sin(180 - \theta - \frac{\Delta\theta}{2}}{\sin\theta} \qquad (2)$$

and

$$\sin\left(\frac{\Delta\theta}{2}\right) = \frac{h}{2R} \qquad (3)$$

reworked to yield

$$h = 2R \sin\left(\frac{\Delta\theta}{2}\right) \qquad (4)$$

Verification of this correction method is made by using the values of NASA TN D-2176, pg. 17 (Ref. 1)

where R = 60 ft.
and h = 8.5 ft as the measured height

using Equation (3)

for $\sin\left(\frac{\Delta\theta}{2}\right) = \frac{h}{2R} = \frac{8.5}{2 \times 60} = .07085$

and $\frac{\Delta\theta}{2} = 4°4'$

$\theta = 9°36'$
and $\sin\theta = .1667$

from Equation (2)

$$H = 8.5\left[\frac{\sin(180-9°36'-4°4')}{\sin\theta}\right] = 8.5\left[\frac{\sin 166°20'}{\sin\theta}\right] =$$

$$= 8.5\ \frac{.2363}{.1667} = 8.5 \times 1.42 = 12.1 \text{ ft.} \qquad (368.8 \text{ cm})$$

which agrees very closely with the value of 12.2 determined previously in the above report.

The correction referred to earlier in the discussion is then derived by the following analysis

Returning to Equation (3) where

$\sin\left(\frac{\Delta\theta}{2}\right) = \frac{h}{2R}$ for which 11.8 in. (30 cm) increments of h were calculated.

The constant R = 796.80 in. (2023.87 cm) for this simulator.

The correction factor $f_c = \frac{H}{h}$

From the previous relation of the sine law

$$\frac{H}{h} = \frac{\sin\beta}{\sin\theta}$$

Having found $\left(\frac{\Delta\theta}{2}\right)$ for the various increments, angle β was determined by using Equation (1) where

$$\beta = 180 - \left(\theta + \frac{\Delta\theta}{2}\right)$$

Since $\theta = 9^\circ 36'$ and $\sin \theta = .16677$ are known values it was possible to determine the correction factor f_c as a function of the projected height h. These values are found plotted by the dotted line in Figure A3 while the solid line represents already the corrected height computed by $h \times f_c$.

The following example is found illustrated in Figure A3 where the uncorrected height h of the c.g. travel of the subject = 135.8 in. (345.0 cm) $f_c = 1.5$ and the corrected height = 203.7 in. (517.5 cm).

The following locomotion activities were observed and their maximum displacement in the z plane were recorded. These are listed in Table A1 and used to calculate their corresponding correction factor.

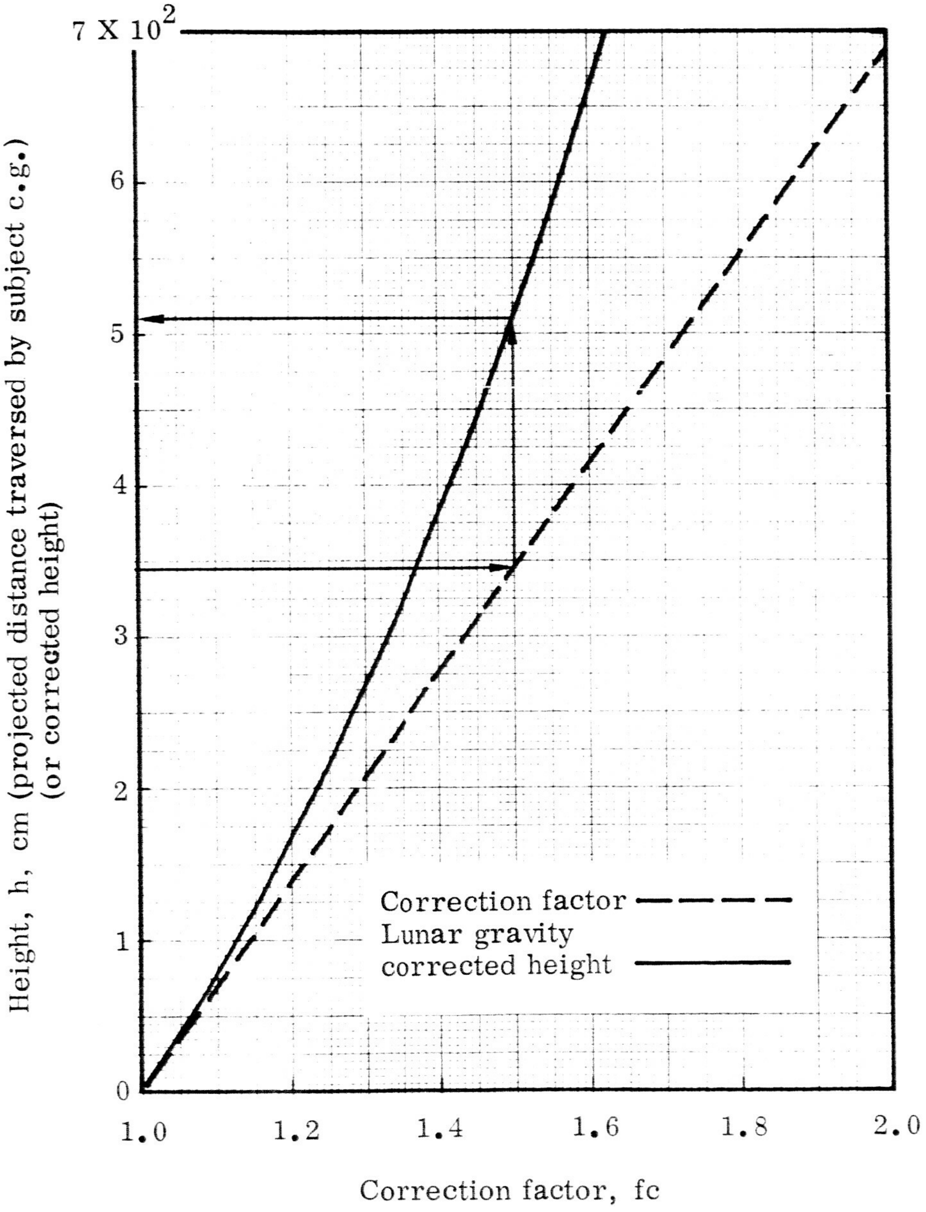

Figure A3. - Height versus correction factor

TABLE A1. CORRECTION FACTOR IN Z PLANE

Locomotion Activity	Maximum z Displacement, cm	Correction Factor, f_c
Walking	5	1.008
Running	6	1.016
Loping	12	1.020
Jumping	35	1.053

There is, however, one more component in the z plane which must be mentioned. The subject has to carry the suspension gear in addition to his own weight when displacing himself. This brings about a weight ratio which should be considered in the performance prediction for the unencumbered subject. Since three different subjects were used in the experiments, their individual ratios were computed and are shown in Table A2.

TABLE A2. - SUBJECT/SUSPENSION GEAR WEIGHT RATIO

Subject	Subject Weight, kg	Weight Ratio $= \frac{\text{Subject with gear}}{\text{Subject}}$
A	84.48	1.089
B	83.92	1.090
C	70.31	1.107

The above ratios were based on the constant total weight of the suspension gear of 7.52 kg.

APPENDIX B

ANALYSIS OF CENTRIFUGAL FORCE INFLUENCE

The dynamics of motion in the z displacement was investigated theoretically to provide an insight into the effects of the centrifugal force.

The velocity along the path Δz arc can be found by using the projection of the velocity vector in the z displacement under 1g from O'Pz' as shown in Figure B1.

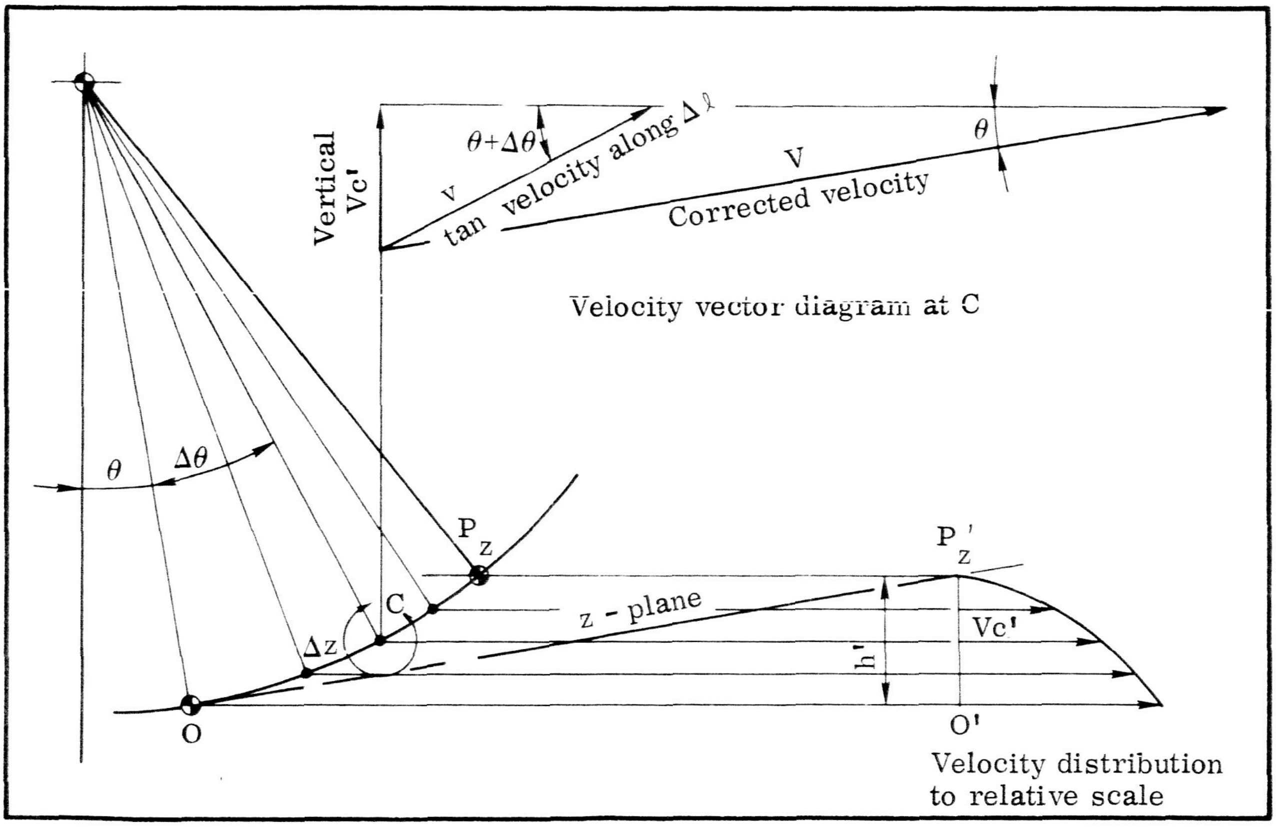

Figure B 1. - Velocity diagram

The vertical jump velocity in the y-projection is determined by

$$V = \sqrt{2gh'} = \sqrt{1961.34} \times \sqrt{h'} = 44.287 \sqrt{h'}, \ \mathrm{cm/sec}$$

For the purpose of illustrating the velocity distribution, the height h has been broken down in 1/4 increments.

The fractional velocity values can be seen plotted in their distribution to a relative scale in Figure B1.

TABLE B1.- VELOCITY DETERMINATION

at h'	1.00-h'	v velocity of a point on the periphery cm/sec
0	1.00	$v = 44.287\sqrt{h'} = 44.287\sqrt{h'}$
.25	.75	$v = 44.287\sqrt{.75} \times \sqrt{h'} = 44.287 \times .866\sqrt{h'} = 38.35\sqrt{h'}$
.50	.50	$v = 44.287\sqrt{.50} \times \sqrt{h'} = 44.287 \times .7071\sqrt{h'} = 31.32\sqrt{h'}$
.75	.25	$v = 44.287\sqrt{.25} \times \sqrt{h'} = 44.287 \times .500\sqrt{h'} = 22.14\sqrt{h'}$
1.00	0	$v = 44.287\sqrt{0} \times \sqrt{h'} = 0 = 0$

Each of these vectors can be broken down as shown typically by the vector diagram at C to yield the tangential velocity along $\Delta\ell$ as well as the corrected velocity V.

The tangential velocity vector v in turn will produce a centrifugal force which when vectorially added to the gravitational force will give a resultant force as shown in Figure B2.

The centrifugal force $F = \frac{W}{g}\,\frac{v^2}{R}$ which indicates that the larger the suspension radius (R), the less effect will be produced by the centrifugal force.

The previous figure illustrates the vectorial addition of $\overline{F + G}$ to yield the resultant P. Under this condition, the subject will experience the changing side forces during his motion dynamics.

The fractional centrifugal forces were computed for each of the fractional velocities for a unit height h' and their distribution is shown to scale in Figure B3.

In summarizing, it can be said that the resultant force P, according to the force parallelogram in Figure B2, will not produce any additional gravity vector along the path of Δz since it acts normally (90°) to it.

Subjective observations made by the test subjects indicate that the centrifugal forces during jumping and other experiments along the z plane were not even noticeable.

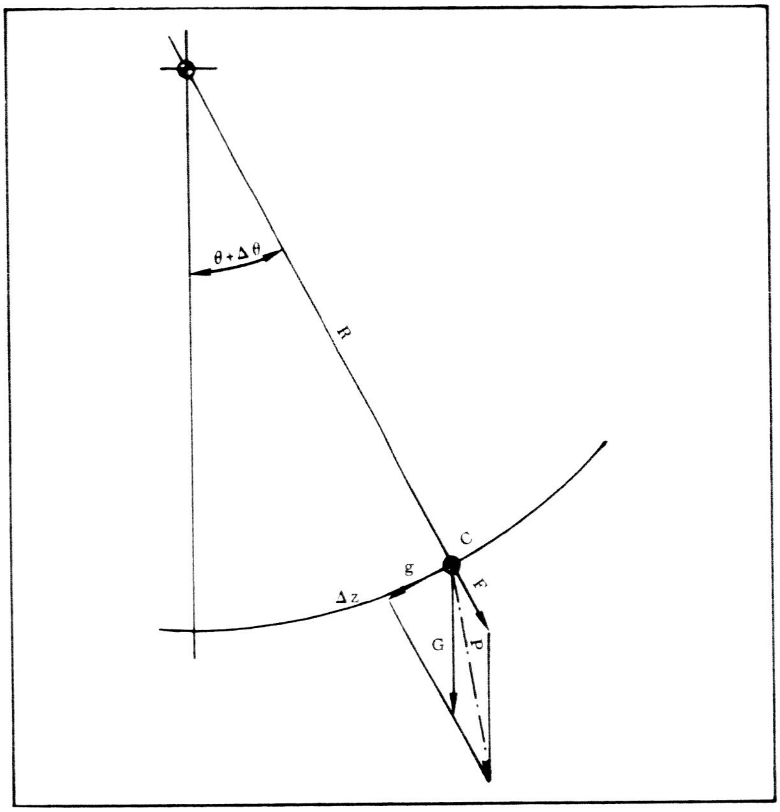

Figure B2. - Force vector diagram

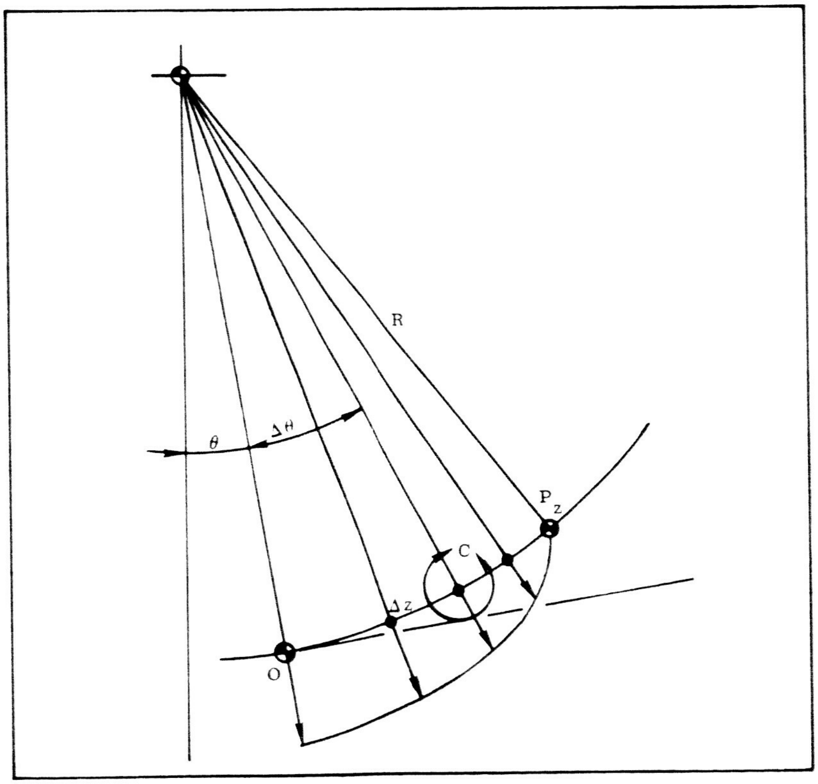

Figure B3. - Centrifugal force distribution