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EVALUATION OF THE METABOLIC COST OF LOCOMOTION IN AN APOLLO SPACE SUIT

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FOREWORD

This report was prepared by the department of Life Sciences, AiResearch Manufacturing Company, a division of The Garrett Corporation, Los Angeles, California. The technical assistance of M. J. Belton, W. Sanborn, W. Price, A. K. Walther, A. Camacho, and L. J. Miller are gratefully acknowledged. The effort and cooperation of the six test subjects is also gratefully acknowledged.

ABSTRACT

In a series of tests conducted with the A7L space suit, six subjects performed locomotion exercises under conditions that simulated lunar gravity. Independent variables were treadmill velocity, walking surface, and lunar gravity simulation technique. The primary dependent variable was the level of energy expenditure of the subjects. In this report, conclusions are drawn about the average metabolic rates for each task, the effects of surface conditions, the effects of simulation technique employed, and the differences between different types of space suits.

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EVALUATION OF THE METABOLIC COST OF LOCOMOTION IN AN APOLLO SPACE SUIT

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INTRODUCTION

Recent developments in pressure suit technology have provided joint designs that reduce the torque forces opposing body movements. The improved designs allow the wearer better mobility at lower energy costs, thereby permitting performance of a wider range of activities. The research program reported herein was designed to determine the metabolic cost of self-locomotion under simulated lunar-gravity conditions for a man wearing one of these improved pressure suit designs--the A7L Apollo suit presently used for lunar exploration. Performed for the NASA Manned Spacecraft Center (MSC) under Contract NAS9-9459, the program included determination of energy costs for subjects traversing at 2-, 4-, and 6-kph velocities in two types of simulators, one of which provided soft as well as hard soil surfaces.

EXPERIMENTAL DESIGN

The experimental design for this program is shown in fig. 1. Each block in the matrix represents a different test condition, each of which was performed by all six subjects. Thus, a total of 54 test modes were completed. The independent variables were (1) treadmill velocity, (2) simulation technique, and (3) surface material.

The primary dependent variable, determined by open-circuit spirometry, was metabolic rate. Other dependent variables measured during the tests included heart rate, respiration rate, minute volume, and carbon dioxide production.

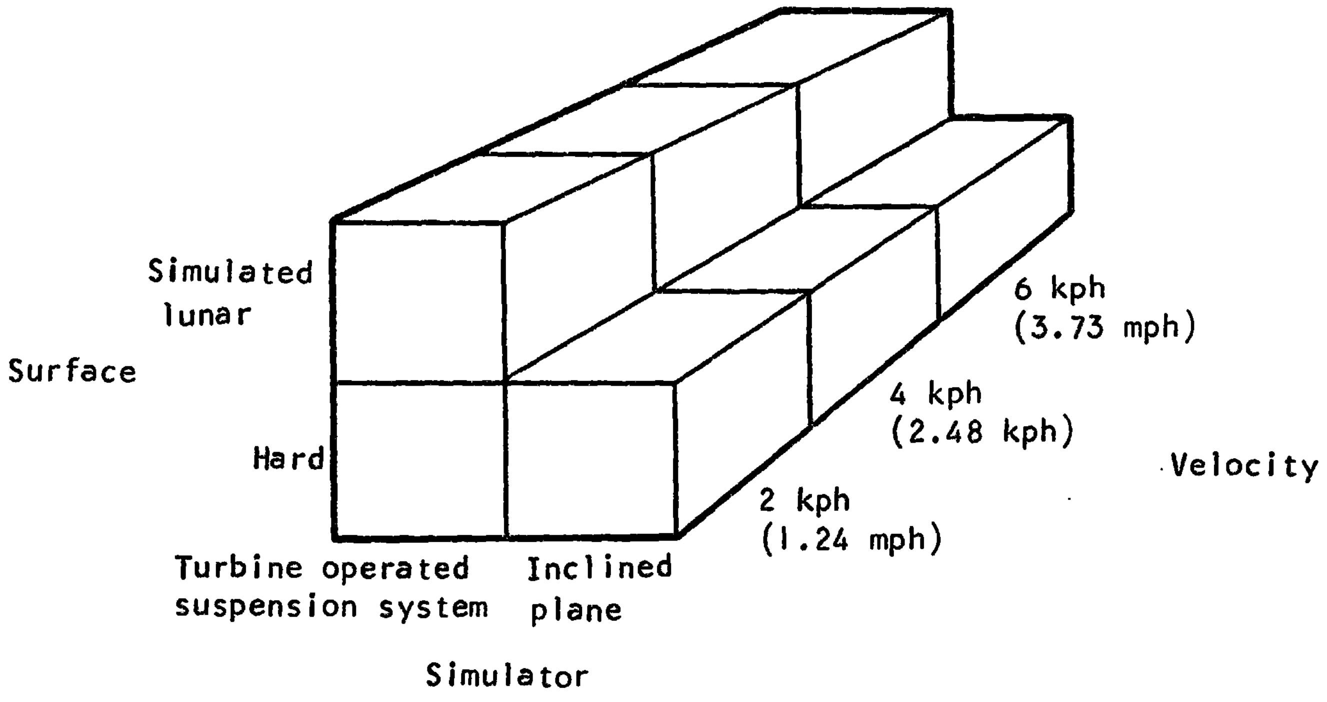

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Figure 1. Experimental Design

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METHODS

Test Subject Selection and Training

Six male subjects were selected from the AiResearch test subject panel. Selection was based on suit fit, psychological and physiological response to stress-inducing situations, ability to pass a special physical examination, and physical conditioning. Each potential test subject was fitted in the suit, pressurized, and exercised to ensure compatibility. Tentative subject selection was made by human engineering and physiological observers. Those who fit the suit, demonstrated the best coordination, and did not become excited or confused under stressful conditions were given a thorough physical examination. The six men who best met the criteria were selected as test subjects for this program.

Each subject was given practice in walking on a treadmill at I g in mufti. This activity was followed by unsuited and pressure-suited training in both the inclined-plane and turbine-operated suspension system (TOSS) lunar gravity simulators. During this period, the subjects were familiarized with the bioinstrumentation and various measurement techniques. Training was continued until the metabolic rates become stable for each subject when measured during exercise in mufti on a treadmill at I g. Metabolic rate measurements were repeated at the end of pressure-suited testing to demonstrate that significant changes in the test subjects' physical conditions had not occurred. The experimental design, testing techniques, and test crew roles were discussed with the test subjects until each had an understanding of what was expected of him during each test.

The height, weight, and body surface area of the subjects that participated in this program are given in table I. All six subjects completed all phases of the program.

Metabolic Rates Before and After Pressure-Suited Tests

The oxygen consumption for each of the six test subjects was measured at rest, 2 kph (1.24 mph), and 4 kph (2.49 mph) at I g in mufti immediately prior to and immediately following the pressure suited tests. Oxygen consumptions were measured by closed-circuit spirometry using a Goddard Pulmonet. A respiratory quotient (R.Q.) of .83 was assumed in converting oxygen consumption to kcal/min.

Pressure Suit Description

The basic pressure suit garment was an International Latex Corp. A6L that had been upgraded to an A7L configuration. The pressure suit used had as an integrated part of the garment a thermal meteorite garment. Testing was performed without the normal communications cap to permit modification of the helmet to include a set of AiResearch one-way valves. This modification included two I-in. penetrations at the side of the helmet for attachment of (I) respiratory gas lines leading from the mouthpiece and one-way valves to a respirometer mounted in an airtight container and (2) a gas line returning the respirated gas to the

TABLE I

ANTHROPOMORPHIC CHARACTERISTICS
OF TEST SUBJECTS

Subject	Height		Weight		Age, years	Body surface area, m^2
	in.	cm	lb	kg		
R.B.	70	177.8	162.0	73.5	31	1.90
D.C.	68	172.7	159.0	72.1	43	1.84
S.D.	69.5	176.5	162.0	73.5	29	1.89
M.G.	71	180.3	157.0	71.2	26	1.89
K.S.	71.75	182.2	169.0	76.7	27	1.97
R.W.	70.5	179.1	168.0	76.2	33	1.94

helmet on the opposite side. This return line was fitted with a deflector adjusted to direct the expired gas down into the suit to minimize carbon dioxide rebreathing. Communications were obtained by mounting a microphone near the one-way mouthpiece and a small speaker inside the helmet by the right ear. The helmet configuration is shown in figs. 2 and 3.

Lunar Gravity Simulation

The tests conducted during this program were performed at the AiResearch outdoor facility especially designed for collecting physiological data from men working in reduced-gravity environments. A general layout of the area is shown in fig. 4.

Inclined-plane simulator.--The inclined-plane simulator provides the subject with three degrees of freedom at 1/6 g (ref. 1 and 2). It consists of a treadmill, a suspension system, and a tower for the suspension system.

The treadmill is a 60-in.-wide inclined flat conveyor that measures 16 ft between the centers of the head and tail pulleys. The surface is of uniformly tufted rubber that provides dependable traction. The treadmill is mounted on a frame that holds it at an angle of 9-1/2 deg from vertical. The frame is positioned at that distance from the base of the tower which provides optimum traction and acceleration for the suspended subject. The subject is suspended perpendicular to the treadmill surface, which results in an effective gravitational force to his feet almost equivalent to that on the lunar surface. The suspension system consists of cabling that is attached to foam-rubber-filled slings holding the subject at one end and to a trolley at the other end. The trolley runs along a 40-ft-long horizontal beam attached to the tower 136 ft

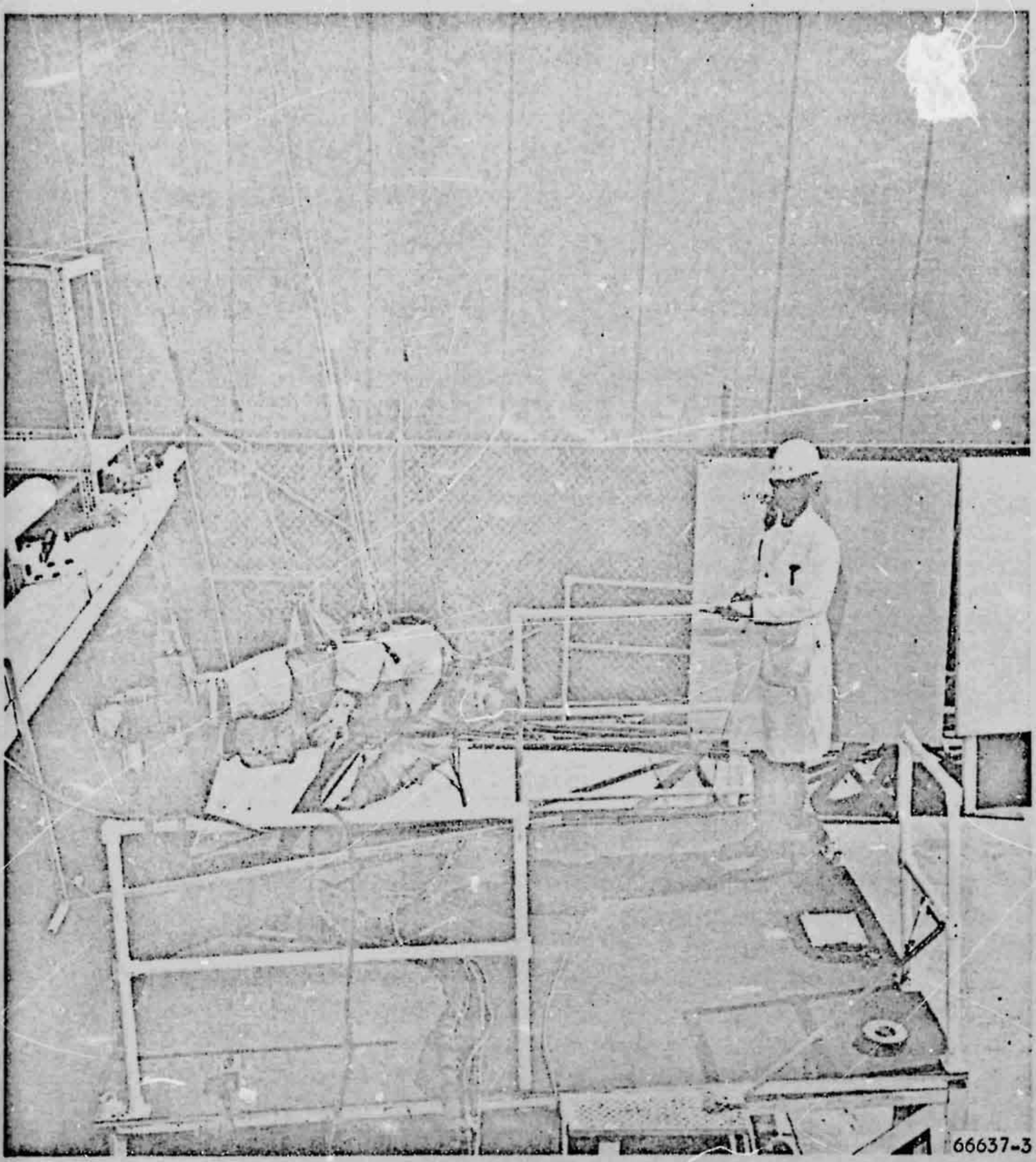

Figure 2. Subject Holding Helmet with Internal Apparatus Exposed

Figure 3. External Hose Connections to Helmet

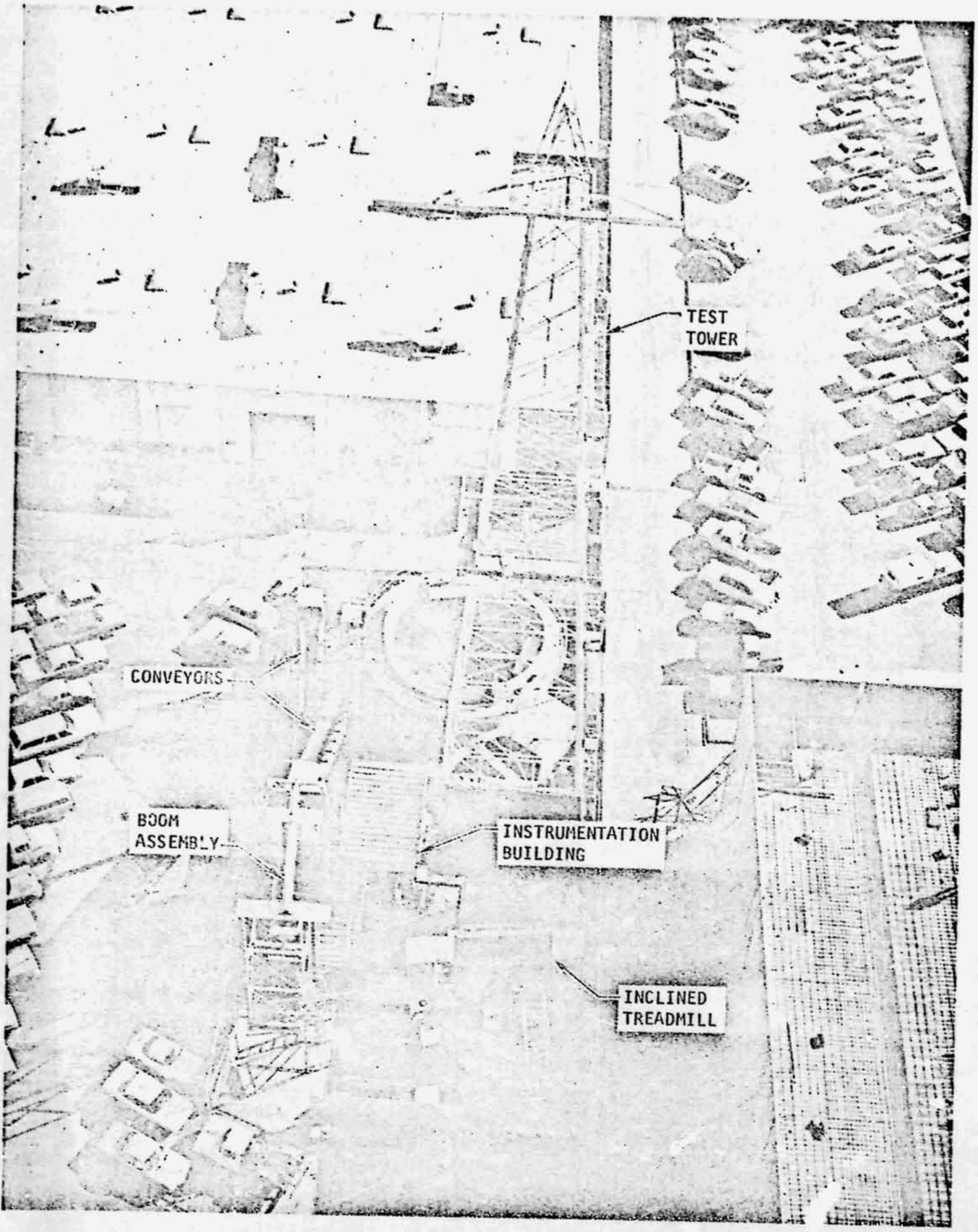

Figure 4. General Test Area

above the ground. Two sets of high-quality rollers on the trolley minimize friction drag forces during movement along the beam. A swiveled eyehook is provided between these rollers for the attachment of the main supporting cable, which is made of 1/4-in. stainless steel wire. This cable extends from the trolley to a height of 75 ft where it attaches to the load distribution bar. The cables used for suspending the subjects and backpacks are attached to this bar. A safety cable made of 5/16-in. Dacron braided rope proof tested to 1500 lb will support the suspension system in the event of main support cable failure. A suited subject is shown in the inclined-plane simulator in fig. 5.

Vertical suspension simulation.--Lunar gravity simulation with vertical suspension was provided by a turbine-operated suspension system (TOSS) designed and developed by AiResearch to improve the dynamic response over other systems used for the simulation of reduced gravity in manned testing. The basic system, illustrated schematically in fig. 6, consists of a C-brace gimbal, a swivel, a yoke with air pad bearing, a cable that passes over and under a system of pulleys, a lightweight beam, and a turbine take-up pulley. The air turbine acts as a constant-tension device which winds up the vertical cable during upward movements of the subject and provides a braking force during downward movements. The system provides the six-degrees-of-freedom desired for reduced-gravity simulation. The sources of the degrees-of-freedom, with reference to the center of gravity of the subject, are listed in table II.

The variable-surface treadmill system used in conjunction with TOSS contains four conveyor belts, a flat-belt conveyor (the treadmill), a storage hopper, the drive for each belt, the platform structure, and other equipment required to operate the system. Soil is deposited on the treadmill belt to simulate lunar surface conditions. The depth of the soil surface deposited on the belt for any given treadmill speed is determined by the position of a combined spreader and hopper gate. The gate is hydraulically operated by a manual control valve. Fig. 7 shows a suited subject walking in the TOSS on simulated lunar soil.

A fiberglass shell contoured to the shape of the pressure suit is used for mounting the subjects in the TOSS simulator. The shell encloses the torso of the pressure suit, distributes the suspension loads over large areas, and provides a stable and uniform structure for suspension and attachment of equipment. In the hip and shoulder areas, the shell was cut to prevent interferance with leg or arm movements. The fiberglass shell is lined with a plastic foam to eliminate irregularities in matching the suit configuration. Holes are cut out of the front piece for the ventilation and instrumentation connections and for the pressure suit helmet adjusting strap. The backpack is fastened to the back piece the shell to ensure uniformity of position from test to test.

Figure 5. Suited Subject in Inclined - Plane Simulator

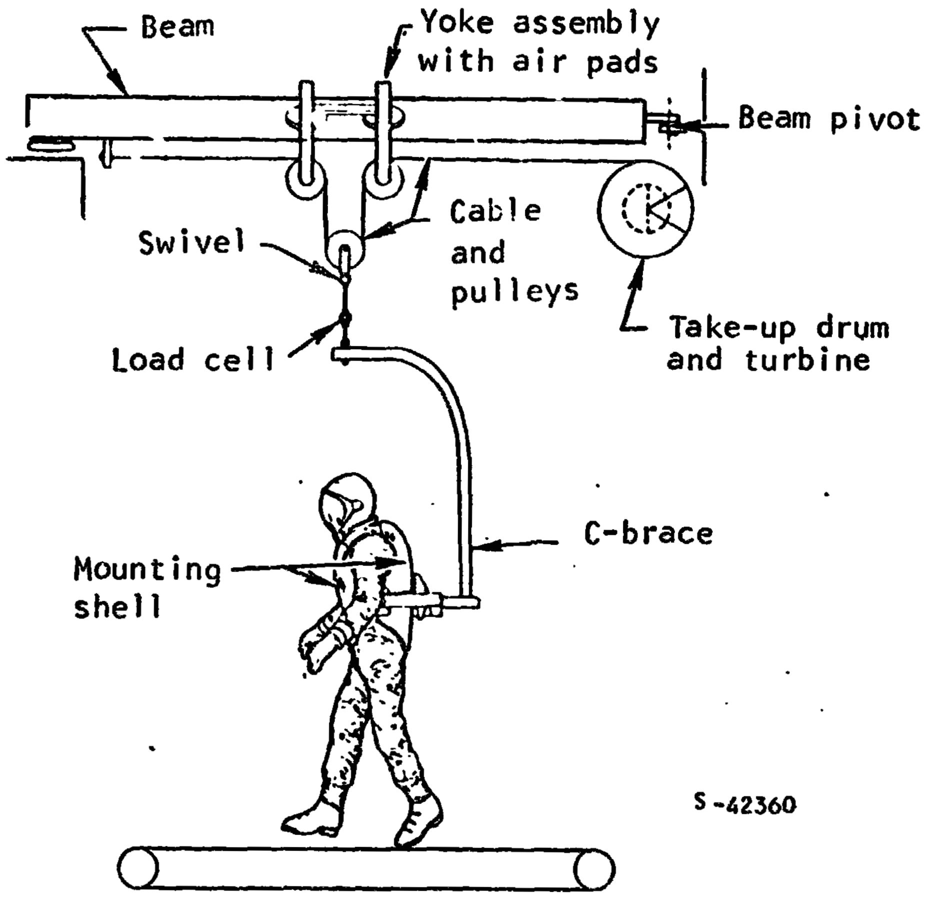

Figure 6. Turbine-Operated Suspension System

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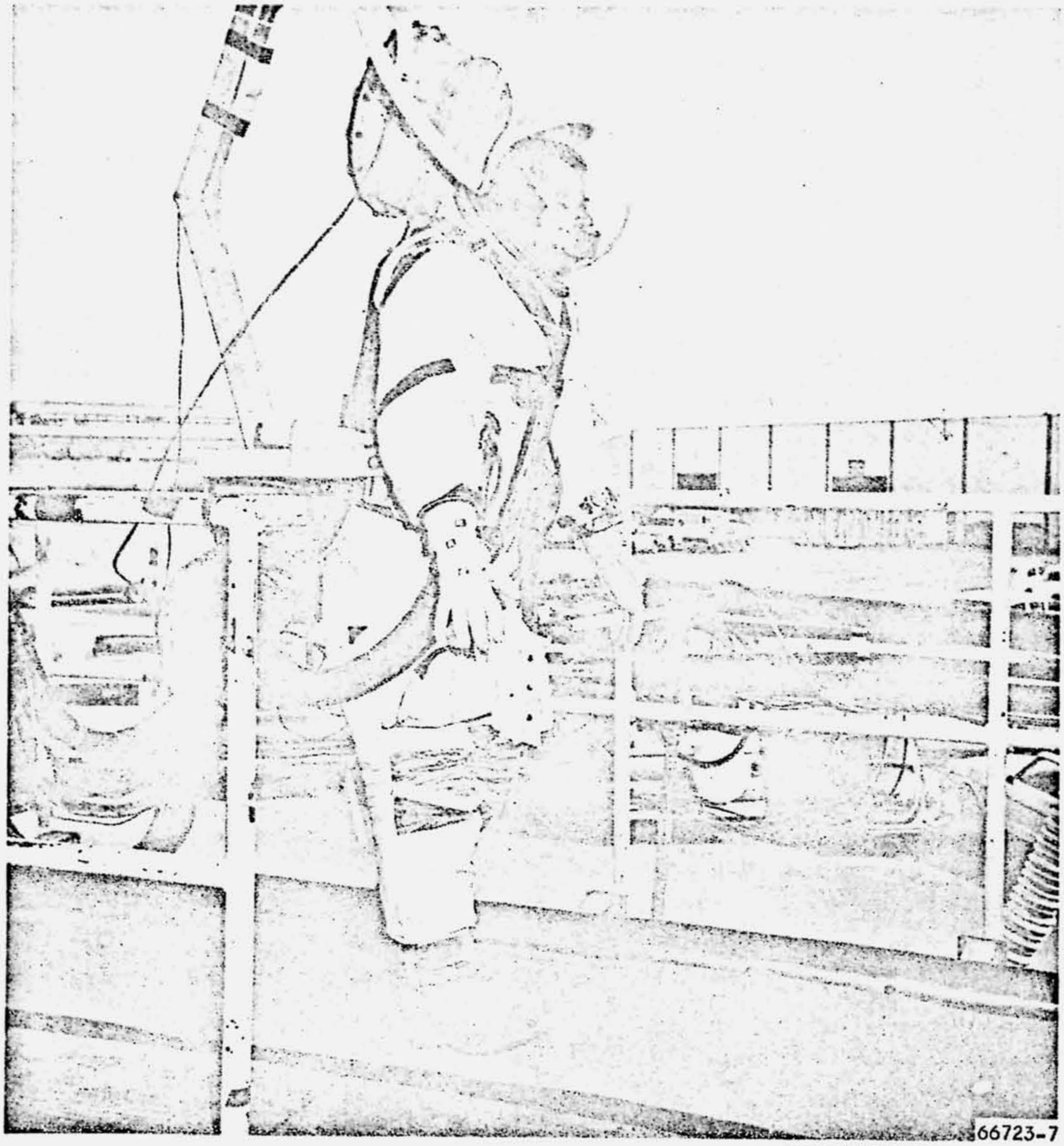

Figure 7. Subject Traversing in the TOSS on Simulated Lunar Soil

TABLE II

TOSS DEGREES-OF-FREEDOM

Component	Degrees-of-freedom
C-brace gimbal - pitch and roll	2
Swivel - yaw	1
Turbine take-up - vertical	1
Yoke (with air pads) - fore and aft	1
Beam (pivot and air pads) - lateral	1
Total degrees-of-freedom	6

Lunar Surface Simulation

The materials for simulating the lunar surface were selected based on data from the Surveyor program (refs. 3 and 4) and personal communications with personnel of the Jet Propulsion Laboratories.* The principle factors affecting the trafficability of a soil surface related to a man moving over that surface are not well defined. Whether the most predominant consideration is density or shear strength is not known. However, it is agreed that soil can fail either in bearing or shear by the subject push-off. A sandblasting type of sand with concrete aggregate and crushed granite was chosen as one of the most likely candidate soils to simulate the lunar surface. The rough or rubble-strewn surface areas around Surveyor spacecrafts I, III, and V show that a reasonably uniform surface particle size can be expected in the relatively smooth lunar maria. The size distribution was taken from the Surveyor V report, and although the area immediately adjacent to Surveyor V did not contain as many large particles as the areas around Surveyors I and III, there is good general agreement. The sizes of the concrete aggregate and crushed granite mixed with the sand range from 4.8 mm (0.187 in.) to 62 mm (2.5 in.). A distribution similar to that reported in the Surveyor program was obtained by adding the coarse aggregate volumetrically to the sand. In a comparison of the test data with the selection criteria, this material compared favorably with the reported lunar surface properties.

Environmental Control System

The environmental control system (ECS) used in this program was designed as an open-loop suit pressurization and ventilation system, which controlled the suit ventilation flow rate, suit inlet dry bulb temperature, and suit-to-ambient

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*Communications with R. F. Scott, Professor of Civil Engineering, California Institute of Technology (Surveyor team member), January and February 1968.

differential pressure. In addition, it was used to determine and record the suit outlet ventilation temperature, flow rate pressure, and dew point temperature. A schematic of the ECS is shown in fig. 8.

Physiologic and Metabolic Apparatus

Instrumentation.--The physiologic instrumentation used to determine the various parameters for these experiments is listed in table III and shown schematically in fig. 9. In addition to the analog data collection system, provisions were made for an analog-to-digital conversion system with automatic recording of all digital data on punched paper tape. The format of this tape was programmed to match the computer link located within the test facility. With the digital recording system, it is possible to calculate the data for each mode as it is accumulated or as often as desired. Thus, it is possible to evaluate the data as they are obtained. The digital data acquisition system comprises a 20-channel multiplexing unit, an amplifier, an analog-to-digital converter, a buffer unit, and a tape perforator.

All parameters require signal conditioning prior to data recording. Power sensitivity, balance, and range adjustments were included in the signal conditioning equipment. All information recorded on the digital system is conditioned for a dc output of 0 to 10.0 mv. Standard system accuracy is ±.1 percent. Standard system quantization using the successive approximation analog-to-digital converter is three digits (1 part in 1,000).

Metabolic rates were measured by indirect calorimetry. The basic respiratory system for the suited tests is shown in fig. 10. In this system, inspired air is drawn from the helmet through a set of AiResearch one-way valves mounted internally to the mouthpiece. The expired gases pass from the valves through an external hose leading to a Franz-Mueller-type respirometer encased in a pressure vessel that is attached to the C-brace. The expired volume is measured by the respirometer. Expired volume is conducted back to the left side of the helmet where it passes through a port in the rear of the helmet and is deflected downward into the airstream from the helmet to the trunk of the suit. The one-way valves used in the system are shown in the helmet configuration (figs. 2 and 3). These valve assemblies contain 2 wedge-shaped aluminum foil valves which direct the flow. The dead space of this valve is 14 cc; total dead space, which includes the mouthpiece, is 16cc.

Tests were performed on the valve assembly to determine the pressure drop in the valves during rest and exercise as well as the stability of this pressure drop after prolonged use. A penetration was made in the valve assembly vestibule between the inhalation and exhalation valve. A thick walled plastic tube was installed from the penetration to a .15 psid Statham pressure transducer. The pressure transducer was calibrated against a water manometer, and the output was recorded on an Offner R. dynagraph. For the longest test performed, a subject wore a noseclip and breathed on the system while at rest for 15 min. The subject then continued to breath on the system while running at 8 kph (4.8 mph) for 15 min, which was followed by a second 15-min rest period. During the initial rest period, the pressure drop in the assembly was .15 in. H_2O. This value

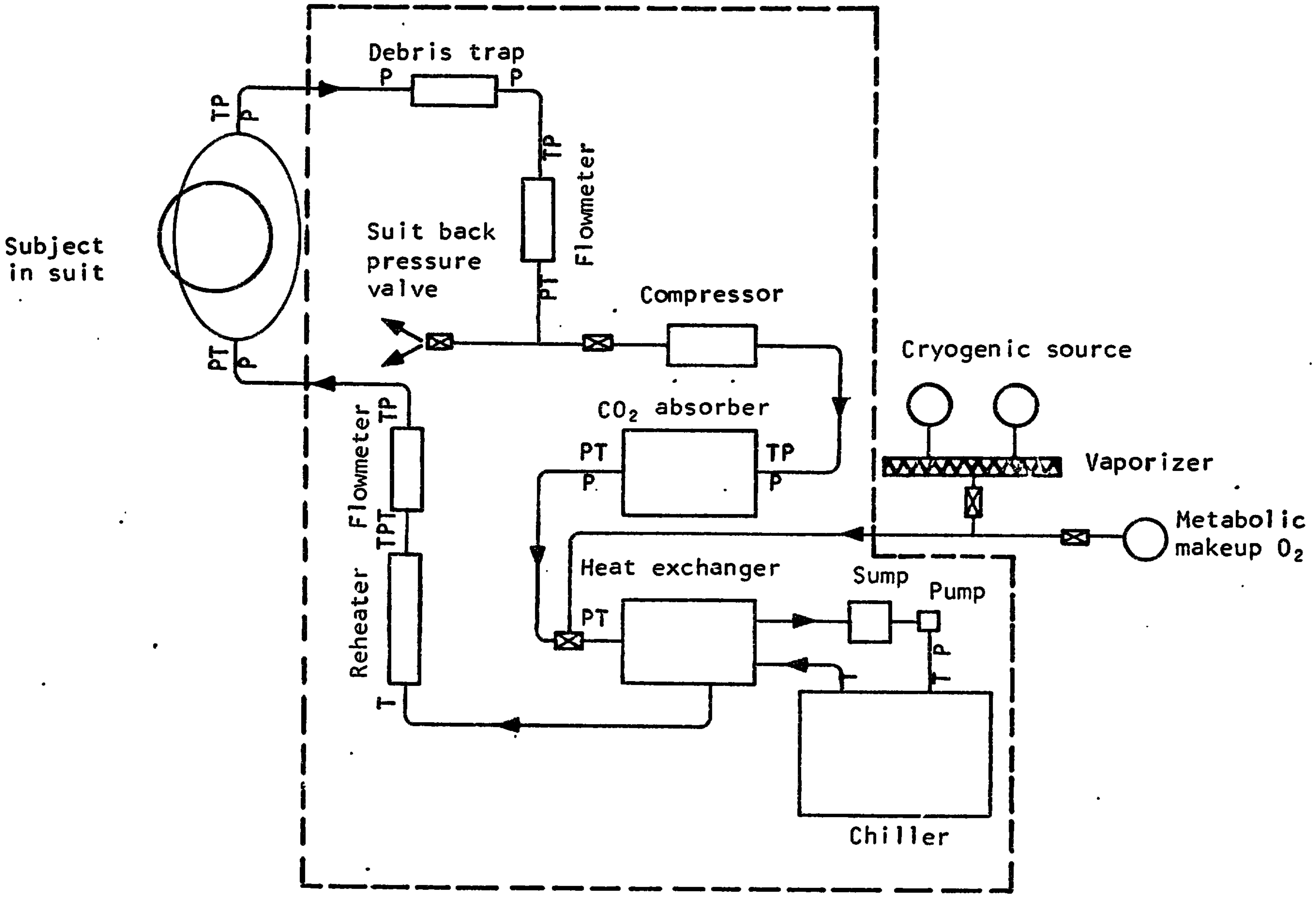


Figure 8. Mobile ECS Schematic

TABLE III

INSTRUMENTATION FOR DATA COLLECTION

Parameter	Sensor Accuracy	Recording Device Accuracy
Inspired/expired O_2 fraction	Beckman F-3 ±1%	Brown Recorder - 2 channel ±1%
Inspired/expired CO_2 fraction	Beckman IR-15A ±1%	Brown Recorder - 2 channel ±1%
Expired volume	Franz-Mueller Respirometer ±1%	Special modification for electrical output to offner Dynograph ±2 liters
Suit gas flow	Meriam Flowmeter ±1%	Manual recording
Suit temperature in	Cu-Co Thermocouple ±.75%	Brown Multipoint Recorder ±1%
Suit temperature out	Cu-Co Thermocouple ±.75%	Brown Multipoint Recorder ±1%
Suit pressure	Stathan Pressure Transducer ±1%	Offner Dynograph ±1%
ECG - heart rate	ECG/Cardio Tachometer ±1%	Offner Dynograph ±1%
Core temperature	Thermistor ±1%	Offner Dynograph ±1%
Respiration rate	Cu-Co Thermocouple ±.75%	Offner Dynograph ±1%
Suit dew point in	Cambridge Dewpointer ±1%	Brown Multipoint Recorder ±1%
Suit dew point out	Cambridge Dewpointer ±1%	Brown Multipoint Recorder ±1%
Franz-Mueller temperature	Cu-Co Thermocouple ±.75%	Brown Multipoint Recorder ±1%
Ambient pressure	Mercury barometer, Wallace and Tiernan Gauge ±.25%	Manual recording
Ambient temperature	Cu-Co Thermocouple ±.75%	Brown Multipoint ±1%
Treadmill velocity	Tachometer ±5%	Offner Dynograph ±1%
Subject weight	Buffalo Scale ±.25%	Manual recording
Subject height	Meter stick ±.1%	Manual recording
Surface area	Dubois Nomogram	Manual recording
Gravity gradient	Load cell ±5%	Manual recording

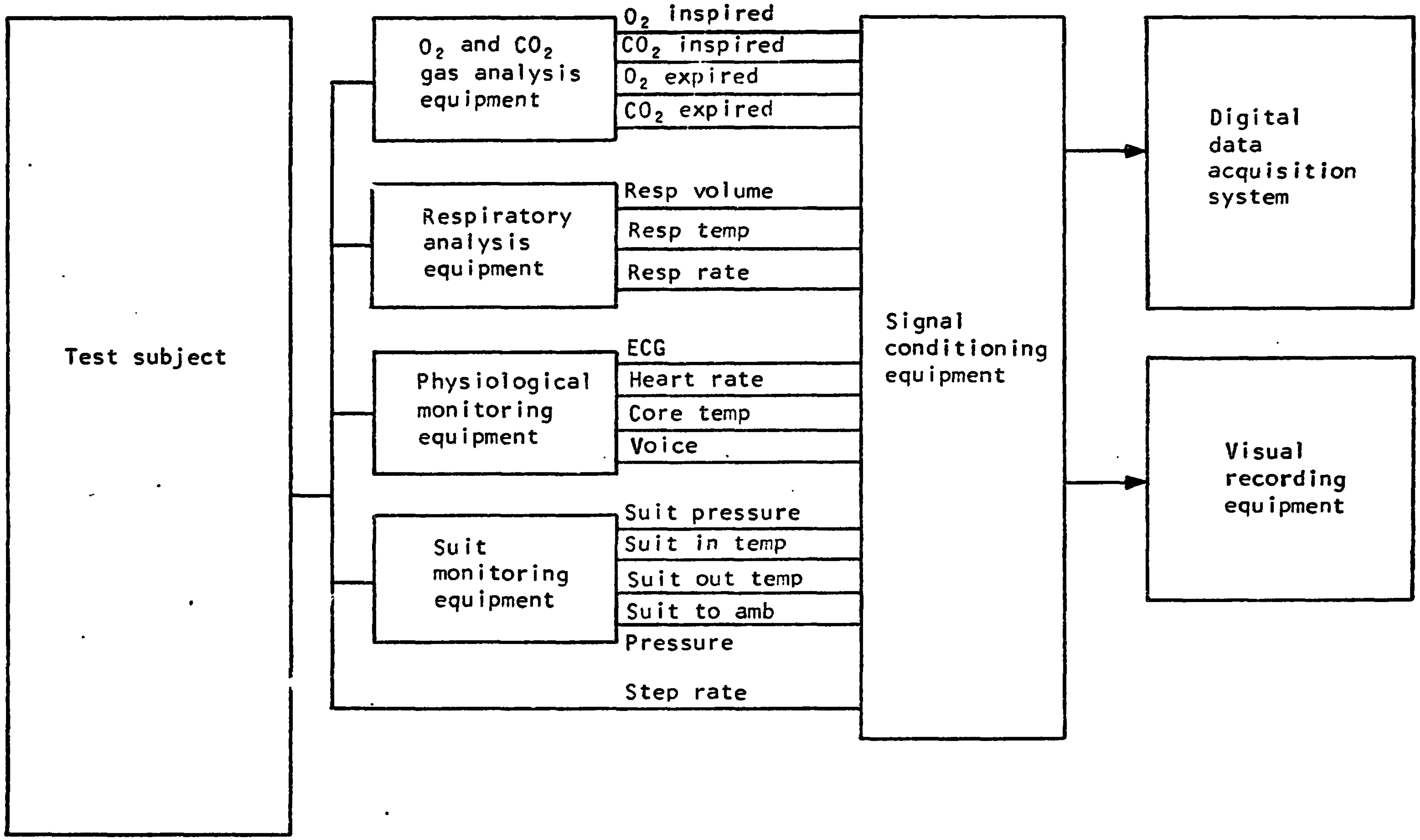


Figure 9. EVA Data Collection System Block Diagram

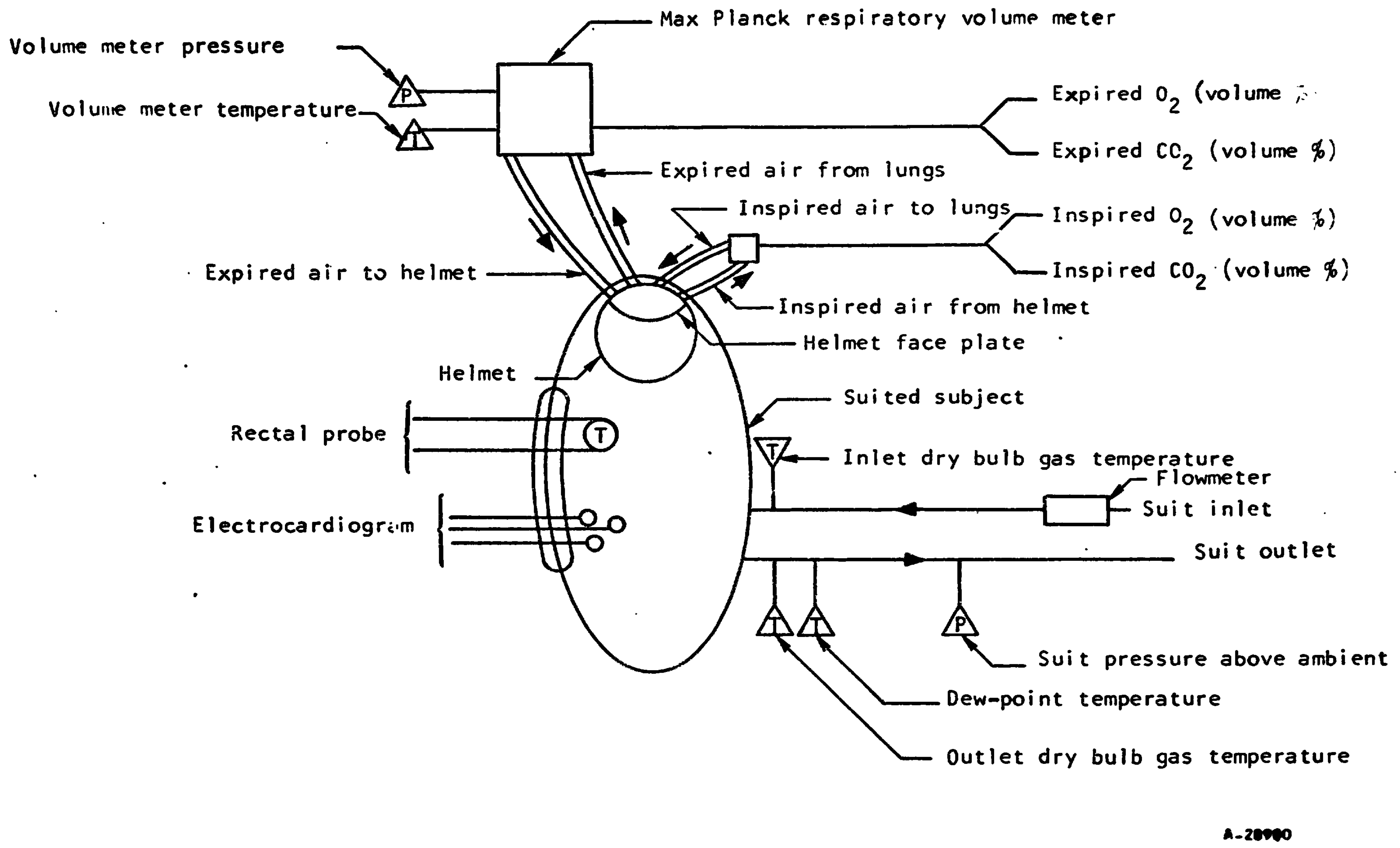


Figure 10. Schematic of the Basic Respiratory System

increased to .3 in. H_2O when the subject ran, during which the ventilatory volume averaged 22 liters/min. The .3-in. value remained constant over the entire exercise period. During the post exercise rest period, the pressure drop returned to the preexercise rest value of .15 in. H_2O, showing no change in the valve system over the 45-min test period. The values noted above were the same for both inspiration and expiration, demonstrating identical operations in both valves. DISA flow meters were attached to both the inspiration and expiration ports of the valve assembly to test for valve leakage. There was no measureable leakage in either valve during the tests. The pressure drop in the valve assembly as a function of flow rate is shown in fig. 11.

Minute volume measurement.--The respiratory minute volume was determined by passing the expired gas through a Franz-Mueller modification of the Kofranyl-Michaelis-type dry gas meter (Model 59, Max-Planck Institute for Work Physiology). This instrument, developed to determine the minute volume of humans performing various work loads, is ideally suited for these tests. The gas meter was encased in a pressure-tight cylindrical housing with a plexiglass window, thus permitting a constant visual readout. Total pressure and dry-bulb temperature of the gas at the meter were monitored and accounted for in all quantitative measurements. The respiration gas meter was calibrated to ensure an accurate and precise volumetric measurement.

For measuring minute volume rate, an electro-micrometer was mounted on the respirometer. The micrometer signal was fed into a ramping circuit that produced an accumulative breath volume signal. A switching signal was also fed into a Offner dynagraph recorder for visual monitoring. The electro-micrometer permitted descrimination of 20 cc. The pulse-train was used to derive respiratory rate.

The respirometer was calibrated electronically before and after each test period or at least four times per day. The respirometer also was calibrated against a fixed-volume pump before and after the test program.

Analysis of respiraton gases.--The CO_2 and O_2 concentrations in the expired and inspired gases were analyzed with a Beckman IR15-A infrared analyzer and a Beckman F-3 paramagnetic analyzer, respectively. Samples of the expiration gas were picked up at the respiration-gas meter housing and ducted through a 1/4-in.-o.d. Polyflow line to the expiration CO_2 analyzer, then to a variable-area purge meter located at the analyzer cell outlet port. From the purge meter, the gas was picked up by a diaphragm pump and pumped to ambient. Inspiratory gases were ducted from the inspiration side of the mouthpiece to the appropriate analyzers for analysis of the O_2 and CO_2 content.

The CO_2 and O_2 analyzers were calibrated with certified calibration gases prior to each test day and checked at the end of each test day. The inspiration and expiration CO_2 and O_2 analyzers were electrically connected to a Honeywell-Brown Electronik recorder for a precise readout.

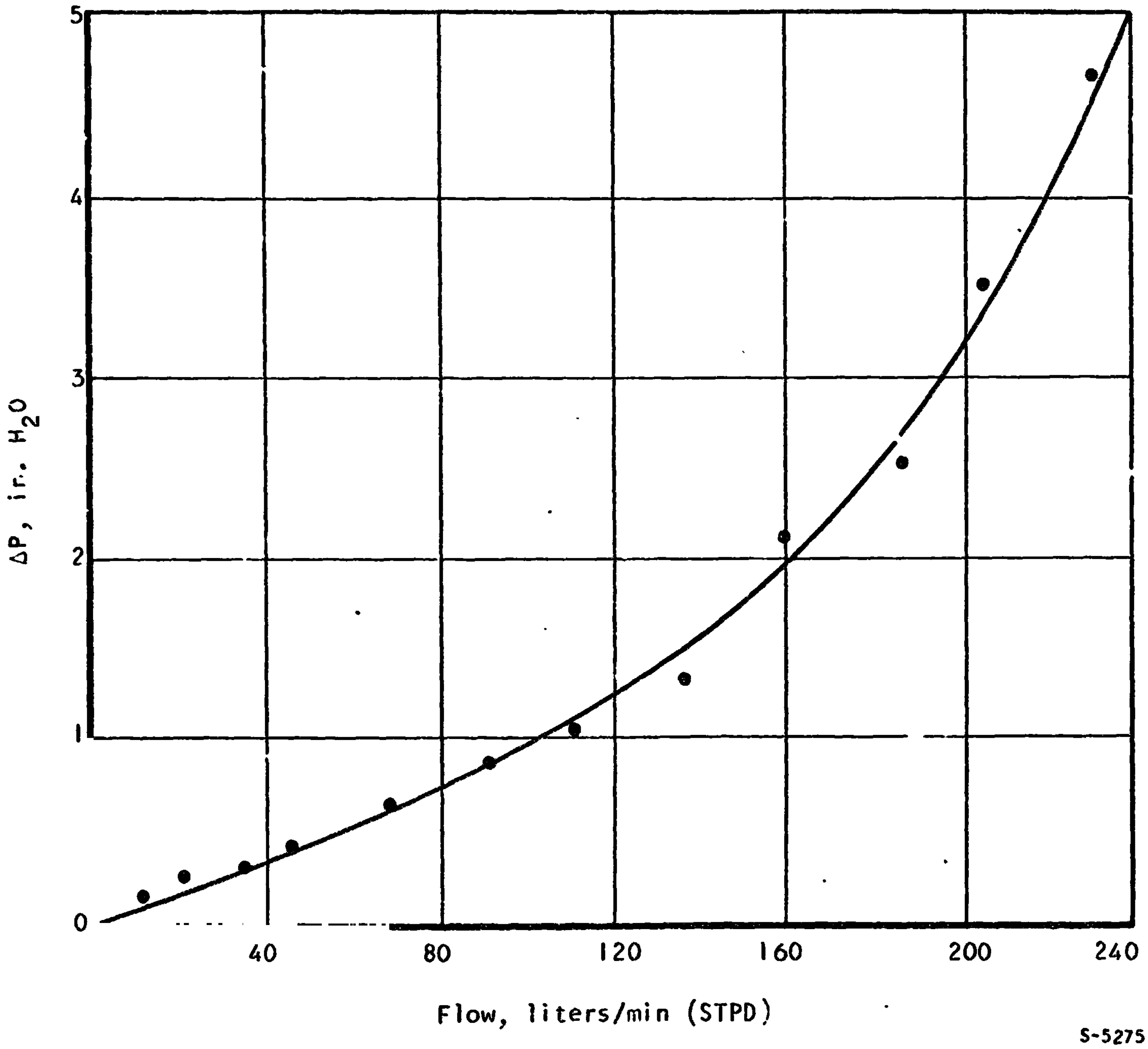


Figure 11. Pressure Drop as a Function of Gas Flow Through the AiResearch Respiratory Valve System

Biomedical recording.--Rectal temperature changes were measured with a thermistor probe (.46-cm dia by 3.9 cm long) and recorded on an Offner Type S dynagraph. All rectal temperature probes were inserted approximately 10 cm beyond the anal sphincter.

Continuous electrocardiograms were taken with a 3-electrode system that consisted of a bipolar modified V4 lead and a ground. Recording and monitoring was done on the dynagraph at 2-min intervals; the speed of the recording paper was maintained at 5 mm/sec.

Respiratory rate was measured with short-time-constant thermocouples located in the inspiratory and expiratory chambers of the mouthpiece. Monitoring and recording of respiratory rate was done on the dynagraph.

Pressure suit environment measurements.--The dry-bulb temperatures of the suit inlet and outlet ventilation gas were measured independently at the suit inlet and outlet quick-disconnect fittings. A copper-constantan thermocouple was situated at each of these fittings to measure the exact temperature of the gas entering and leaving the suit. The thermocouples were connected directly to a Honeywell-Brown strip-chart recorder. All other system and instrumentation temperatures were also measured with copper-constantan thermocouples connected to the Honeywell-Brown strip-chart recorder. Suit inlet and outlet dewpoints were measured using a Cambridge dewpointer. The output of the analyzer was recorded on a Brown multipoint recorder. Suit gas flow was measured by Meriam flowmeters and recorded manually. Suit pressure was controlled with reference to a Wallace and Tiernan pressure gage. A Statham pressure transducer also measured suit pressure, the output of which was recorded on an Offner dynagraph.

Weight equipment.--The scales used for weighing a subject are made by the Buffalo Company and are referred to as "Buffalo" scales. The weight of a subject can be determined to within ±2 gm of his total body weight. These scales were cleaned, reassembled, and calibrated before testing started.

The ring load cells used for checking the simulated gravity in each system are constructed of a high-quality machined ring with attaching lugs on either end. A full-bending bridge strain-gage arrangement is placed on the ring. This assembly is calibrated to read the tensile load applied in pounds.

Treadmill speedometer.--The treadmill speed was determined by a small generator assembly attached to the drive pulley of each treadmill system. Meters at the treadmill control box and in the instrumentation building allowed continual monitoring of belt speed. This system was calibrated by measuring actual belt length, timing the revolutions at various speeds with a stopwatch, and then adjusting the meter. The speed was checked again during each test and was held to ±1 percent.

Ambient pressure and temperature measurement.--Ambient pressure was recorded for each test using a high quality aneroid barometer. The ambient temperature was measured by a thermocouple located in the test area and was recorded on the Brown recorder.

Air supply.--The air supply for the TOSS simulator was supplied by an AiResearch GPS-90 air turbine compressor.

GENERAL TEST PROCEDURES

Preparation of Subjects

Test subjects reported to work 1 hr prior to the scheduled test for medical checkup, weigh-in, application of instrumentation, and donning of the pressure suit. Each test subject was required to complete a questionnaire (fig. 12) prior to instrumentation and donning of the pressure suit. In addition, each subject was interviewed for symptoms of ailments that might affect the data or his ability to perform the tests. If ailments were suspected, the subject was examined by a physician, who decided whether the subject would participate in the tests scheduled for that day.

The subject wore electrodes for continuous electrocardiogram recording and a thermistor probe for recording rectal temperature. The electrocardiogram was taken using a three-electrode system consisting of a bipolar modified V_4 lead and a ground. After the subject was cleared for test participation, the skin area at appropriate ECG electrode locations was shaved and thoroughly cleaned with a 70-percent solution of isopropyl alcohol. The electrodes were attached to the clean areas using a double-adhesive colostomy tape. The electrodes were then covered with adhesive tape to prevent moisture penetration and ensure adherence to the skin. The electrocardiogram tracings were checked to determine signal integrity.

Space suit donning was accomplished by the test subject with assistance from a suit technician. The subject then proceeded to the test area for hook-up with the applicable simulator.

Inclined-Plane Simulator Procedure

Upon arrival at the test site, the subject's bioinstrumentation was checked out by connecting the bioinstrumentation plug to the mating suit part. After completion of this check, the plug was disconnected to permit attachment of the molded fiberglass shell to the subject. The shell was attached and positioned by utilizing straps equipped with quick-adjust fittings.

The ventilating gas hoses were attached to provide suit ventilation, and the bioinstrumentation plug was again connected. The helmet was donned and all hoses to the bifurcated mouthpiece and respirometer were connected. As a precaution, all connections were rechecked prior to pressurizing the suit to 3.5 psig. The subject was then positioned on his left side with his feet on the inclined-plane treadmill and all support lines attached. The backpack was mounted on the subject's back and locked in place. Perpendicular alignment to the 9-1/2-deg treadmill was checked by adjusting the suspension lines until the subject was parallel with a special alignment bar.

The subject was then required to jump several times and walk a short distance to determine if the trolley was functioning properly, the left leg stabilizer bar had proper clearance, and the backpack was positioned correctly

SUBJECT QUESTIONNAIRE

DATE: ____________

1. Name: ______________________ Nude wt: ________ Height: ________
2. How did you sleep last night? Soundly: ______________

   Light: ______________

   Fitfully: ______________

   If fitfully how many times did you awaken? ______ times
3. How many hours did you sleep? ________ hours
4. Although directed not to imbibe alcohol, did you indulge?

   What kind? ______________ How many? ________
5. What were the basic components of last night's meal?

   ______________ ______________ ______________

   ______________ ______________ ______________
6. Did you have breakfast? ____ ________
7. If so, what did you eat? ______________ ______________

   ______________ ______________
8. Did you have lunch? __________
9. What did you eat? ______________ ______________ ______________
10. How do you feel generally? ________ Excellent ________ Good

    ________ Fair ________ Poor
11. Do you have any significant symptoms to report?
    (e.g., cold, aches, pains, etc.)
12. Do you think you will have any difficulty in completing today's test?

    ____

Figure 12. Subject Questionnaire

and anchored firmly. Leakage at all hose connections, the mouthpiece, and the respirometer were checked and instrumentation signals were observed prior to starting the actual test.

Upon completion of the test, the subject was assisted from the simulator. The space suit was doffed, and the bioinstrumentation sensors were removed. The subject was then asked to comment on the test with respect to task difficulty, comfort, and other factors that may have affected performance.

TOSS Simulator Procedure

Prior to subject arrival, the turbine air compressor was activated and system airflow established. The C-frame was neutrally balanced, and the air pads were pressurized and checked for correct operation. When the test subject arrived, a bioinstrumentation check identical to that performed on the inclined-plane simulator was made.

The test subject was then attached to the gimbal utilizing the fiberglass shell. Suit hoses and instrumentation plugs were connected and suit flow established. The subject's nose clip was applied and taped in place.

The helmet was donned and locked in place. The mouthpiece and respirometer connections were made and checked. The suit was then pressurized to 3.5 psig.

After pressurization of the suit, turbine pressure was increased until a lifting force equal to the weight of the C-frame assembly and subject was reached. The subject was then lifted from his feet and completely balanced in the pitch and roll axes by using lead weights where necessary. The pack system weight was brought to 75 lb, the subject's suit and system weight were determined, and the load cell was calibrated to zero. Turbine pressure was then reduced and the subject lowered to the treadmill to perform such tasks as jumping, walking, and standing to check out simulator performance. While these tasks were being performed, load-cell readings were taken to determine the turbine pressure setting required to simulate the desired 1/6-g condition.

Test Procedure

After checkout and calibration of all apparatus and instrumentation, the subject was placed in the simulator, the simulator checkout procedures were performed, and the tests were ready to commence. The first test point for every test condition was the resting metabolic rate measurement. This was measured at time zero and +2 min. After recording the +2-min data point, the treadmill was started and the subject performed the scheduled task for a period of 15 min. Recording of all physiological parameters was made during the last 5 min of the test at 1-min intervals. The subject rested until all physiological parameters returned to normal rest levels (e.g., heart rate, temperature). The second test could then commence. There was an absolute minimum period of 8 min (6 min at the end of one test, plus 2 min at the start of the next test) between periods of exercise on the treadmill. The average resting duration, however, was approximately 20 min. The sequence of test events was random among subjects to reduce the probability of other effects in the data.

Calibration of Gas Analyzers

All gas analyzer equipment was calibrated at least four times a day. Operating pressure for calibration was the same as that of the gas analyzer during testing, i.e., suit pressure.

Data Reduction

Raw data were collected during this experiment at intervals of 1 min, and sufficient personnel and recording equipment were employed to record all the data within the same 15-sec period. The data were recorded directly from the instruments on data sheets, punched tape, and strip-chart recorders. The data were subsequently entered, along with a preprogram, in an SDS 940 computer used on a time sharing basis. At all points of testing, the consistency of time, test conditions, subject designation, and data were compared for accuracy. The results obtained and presented in this report have been cross-checked with all pertinent control points to ensure proper comparative data. The computer output all data required for interpretation or subsequent analysis, whether or not these data were required for the computations.

The various equating analytical computations and subsequent statistical analyses were performed as described in NASA CR-1102.

RESULTS

Internal Pressure Suit Conditions

The ranges of observed values for both monitored and controlled suit conditions are shown in table IV. The suit gas flow, pressure, and inlet temperature were controlled parameters. Suit inlet gas temperature, flow, and pressure were maintained within narrow limits. Suit outlet temperatures reached similar levels regardless of exercise (as reported previously, refs. 1 and 2). Since cryogenic air was used as the gas source for ventilating the suit, the inlet dew point was always zero. Outlet dew points were low at the 2- and 4-kph velocities, but reflected the mild sweating that occurred in all subjects at 6 kph.

All tests were performed outdoors over a 12 day period. The ambient temperature during the test period ranged from 60° to 78°F. The barometric pressure ranged from 759.3 to 761.2 mm Hg.

Exercise Data Before and After Testing to Investigate Potential Training Effects

Metabolic rate measurements were made for each subject at rest and when walking at 2- and 4-kph at 1 g to determine if there were any significant training effects on the data obtained with pressure suited subjects. These tests were performed with the subjects in coveralls and tennis shoes before the experiment proper and after the completion of all tests. Oxygen consumptions were monitored with a Goddard Pulmonet. The data are presented in table V. The data before and after testing do not differ significantly, which indicates there was no training effect over the experimental period.

Resting Values, Suited

Resting data were obtained prior to each exercise mode with each subject dressed in the pressurized suit and suspended at simulated 1/6 g. The tests were randomized within each simulation but not between simulators. The TOSS hard-surface testing was performed first, followed by the inclined-plane tests, with the TOSS simulated lunar surface tests performed last. There were no statistical differences within each variable between the means of any cell shown in table VI. These resting data are a summation of rest prior to any exercise and between exercise modes, which indicates that the subjects had returned to resting levels between tests. The equivalence of the rest values before tests and between tests is shown also by the relatively small variance in the data. The difference between the two most divergent means (2 kph, TOSS, hard surface and 6 kph, inclined plane, hard surface) approached, but did not reach, statistical significance for both metabolic rate and heart rate. The mean of all resting values within a given simulator is used in the graphic presentation of metabolic rates discussed below.

TABLE IV

SUMMARY OF THE RANGE OF VALUES FOR A7L INTERNAL SUIT CONDITIONS FOR ALL EXPERIMENTAL MODES

Simulator	Ventilated mode	Gas flow, cfm	Pressure, psig	Temperature		Dew point	
				Inlet, °F	Outlet, °F	Inlet, °F	Outlet, °F
1/6-g inclined plane	Pressurized	12	3.3 to 3.7	50 ±3	76 to 83	0	15 to 33
1/6-g TOSS/gimbal hard surface	Pressurized	12	3.5 to 3.6	50 ±3	75 to 83	0	12 to 34
1/6-g TOSS/gimbal lunar soil	Pressurized	12	3.5 to 3.6	50 +3	76 to 83	0	11 to 31

TABLE V

EXERCISE METABOLIC RATES FOR UNSUITED SUBJECTS BEFORE AND AFTER TESTING

Period	Metabolic rate					
	Rest		2 kph		4 kph	
	kcal/min	Btu/hr	kcal/min	Btu/hr	kcal/min	Btu/hr
Before testing	1.50 ± .12	356.4 ± 16.6	3.15 ± .45	748.4 ± 28.5	4.20 ± 54	997.9 ± 64.2
After testing	1.62 ± .22	384.9 ± 21.4	3.01 ± .37	715.2 ± 38.0	3.82 ± .41	907.6 ± 30.9

Mean $(\overline{X})$ ±1 standard deviation

TABLE VI

RESTING METABOLIC RATE AND HEART RATES OBTAINED DURING SUITED TESTING

Subsequent test velocity, kph	Turbine operated suspension simulator						Inclined plane, hard surface		
	Hard surface			Simulated lunar soil					
	kcal/min	Btu/hr	beats/min	kcal/min	Btu/hr	beats/min	kcal/min	Btu/hr	beats/min
2	1.45	345	70.7	1.13	268	72.2	1.21	287	60.5
	±.17	±40	±10.4	±.24	±57	±13.1	±.22	±52	±5.1
4	1.31	311	70.5	1.26	299	70.2	1.24	295	61.2
	±.31	±74	±7.0	±.13	±31	±13.5	±.25	±59	±6.7
6	1.26	299	69.2	1.19	283	74.7	1.10	261	51.8
	±.33	±78	±10.5	±.15	±36	±9.7	±.21	±50	±3.8

Metabolic Rates

The metabolic cost of self-locomotion at 1/6 g in a pressurized A7L at 3 different velocities in 3 different simulations is shown in table VII. Metabolic rates increased significantly with velocity ($p < .001$) for each simulator. There was no difference between metabolic rates for locomoting on the simulator lunar soil and the hard surface on TOSS. Differences in energy utilization were expected for locomoting on the two surfaces reported earlier with the G-2C pressure suit (ref. 1).

The energy cost of locomotion on a hard surface in TOSS was higher than for a similar surface on the inclined-plane simulator, but the difference between means did not reach significance ($p = .08$). A difference was expected and likely would have been found if (1) the sample variance had been less or (2) a larger sample had been studied. Self-locomotion on the simulated lunar surface had a statistically higher cost than for locomotion on the inclined plane simulator with a hard surface ($p < .05$).

A summary of metabolic rates is presented in table VIII. Row 1 presents the data as shown in table VII; row 2, these data normalized for body surface area; row 3, the data normalized for the subjects' nude weight as measured at 1 g; and row 4, the data from row 1, normalized for the subjects' lunar weight equivalent. The equivalent lunar weight was derived from the subjects' nude weight plus the weight of the pressure suit assembly divided by 6.

Physiologic Response

The physiologic response during the various exercise modes is summarized in table IX. The effects noted above for changes in metabolic rates, including statistical differences, are reflected in the expired minute volumes, oxygen consumptions, carbon dioxide productions, and heart rates. Heart rates showed one additional significant difference. Even though metabolic rates were not different between the two surfaces with the TOSS, heart rates were significantly increased when the subject walked on the simulated lunar soil as compared to the same locomotive rates on the hard surface. No significant differences were expected or noted in respiratory rates or rectal temperatures. Rectal temperatures varied on a day to day basis, both within and between subjects, but the greatest change during any test was 0.1°F.

Figure 13 shows the typical physiologic response with time of a subject dressed in an A7L pressure suit and running at 6 kph on the hard surface of an inclined-plane lunar gravity simulator. At the beginning of the test, the subject stands on the treadmill surface suspended at 1/6 g while his resting metabolic rate, heart rate, and other parameters are measured. At time zero, the treadmill is turned on and the speed adjusted to the appropriate velocity, in this case 6 kph. These adjustments usually take 1 to 2 min. The subject immediately begins running, and his physiologic response is recorded every minute. The lower curve in fig. 13 is for the measured metabolic rate. The curve is slightly sigmoid as a result of the treadmill speed adjustments, which causes a lower rate of increase during the first 1 to 2 min. After this time, the

TABLE VII

METABOLIC RATES AS A FUNCTION OF VELOCITY IN SIMULATED LUNAR GRAVITY
WEARING A PRESSURIZED A7L SUIT

Velocity, kph	TOSS simulation				Inclined plane, hard surface	
	Hard surface		Lunar soil simulant			
	kcal/min	Btu/hr	kcal/min	Btu/hr	kcal/min	Btu/hr
2	3.94 ±.86	912 ±204	4.15 ±.56	986 ±133	2.92 ±.43	694 ±102
4	5.16 ±.74	1226 ±176	5.65 ±.61	1342 ±145	4.57 ±.90	1086 ±214
6	6.94 ±1.68	1649 ±399	6.97 ±.81	1655 ±192	6.39 ±1.14	1518 ±271

TABLE VIII

AVERAGE METABOLIC RATES FOR LOCOMOTION AT 1/6 G IN A PRESSURIZED A7L PRESSURE SUIT

		TOSS simulator						Inclined plane, hard surface		
		Hard surface			Simulated lunar surface					
		Velocity			Velocity			Velocity		
	Unit	2 kph	4 kph	6 kph	2 kph	4 kph	6 kph	2 kph	4 kph	6 kph
Metabolic rate	kcal/min	3.84	5.16	6.94	4.15	5.65	6.97	2.92	4.57	6.39
	kcal/min/m^2	2.02	2.72	3.65	2.18	2.97	3.67	1.54	2.41	3.36
	kcal/min/kg earth weight	.052	.070	.094	.056	.076	.094	.040	.062	.086
	kcal/min/kg lunar suited weight	.272	.365	.491	.293	.400	.493	.207	.323	.452

TABLE IX

PHYSIOLOGIC RESPONSE DURING LOCOMOTION IN A PRESSURIZED A7L PRESSURE SUIT AT SIMULATED LUNAR GRAVITY

Parameter	Turbine operated suspension system						Inclined plane, hard surface		
	Hard surface			Lunar soil simulant					
	2 kph	4 kph	6 kph	2 kph	4 kph	6 kph	2 kph	4 kph	6 kph
Expired minute volume, $\dot{V}_E$ (liter/min, btps)	16.636* ±2.716	21.800 ±1.876	27.206 ±4.205	19.642 ±1.934	25.969 ±2.111	31.029 ±4.401	13.742 ±1.923	20.101 ±3.346	27.378 ±5.416
Oxygen consumption, $\dot{V}_{O_2}$ (liter/min, stpd)	.794 ±.178	1.082 ±.166	1.488 ±.359	.856 ±.127	1.156 ±.137	1.433 ±.168	.607 ±.090	.955 ±.198	1.335 ±.234
Carbon dioxide production, $\dot{V}_{CO_2}$ (liter/min, stpd)	.583 ±.128	.828 ±.091	1.118 ±.243	.717 ±.096	1.002 ±.115	1.200 ±.192	.484 ±.078	.738 ±.139	1.054 ±.204
Heart rate, beats/min	75.7 ±8.0	90.8 ±12.2	85.0 ±8.4	83.5 ±9.4	95.3 ±14.7	108.0 ±15.9	74.8 ±7.9	85.7 ±7.5	98.3 ±13.3
Respiratory rate, breaths/min	16.7 ±2.2	17.5 ±1.4	19.3 ±1.5	19.2 ±1.7	20.3 ±1.1	21.5 ±1.1	17.0 ±1.5	20.0 ±1.5	20.5 ±2.2
Rectal temperature, °F	98.8 ±.6	98.8 ±.5	99.1 ±.6	99.3 ±.4	99.1 ±.5	99.3 ±.5	98.7 ±.4	98.7 ±.5	98.8 ±.5

*Mean ($\overline{X}$) ±1 standard deviation

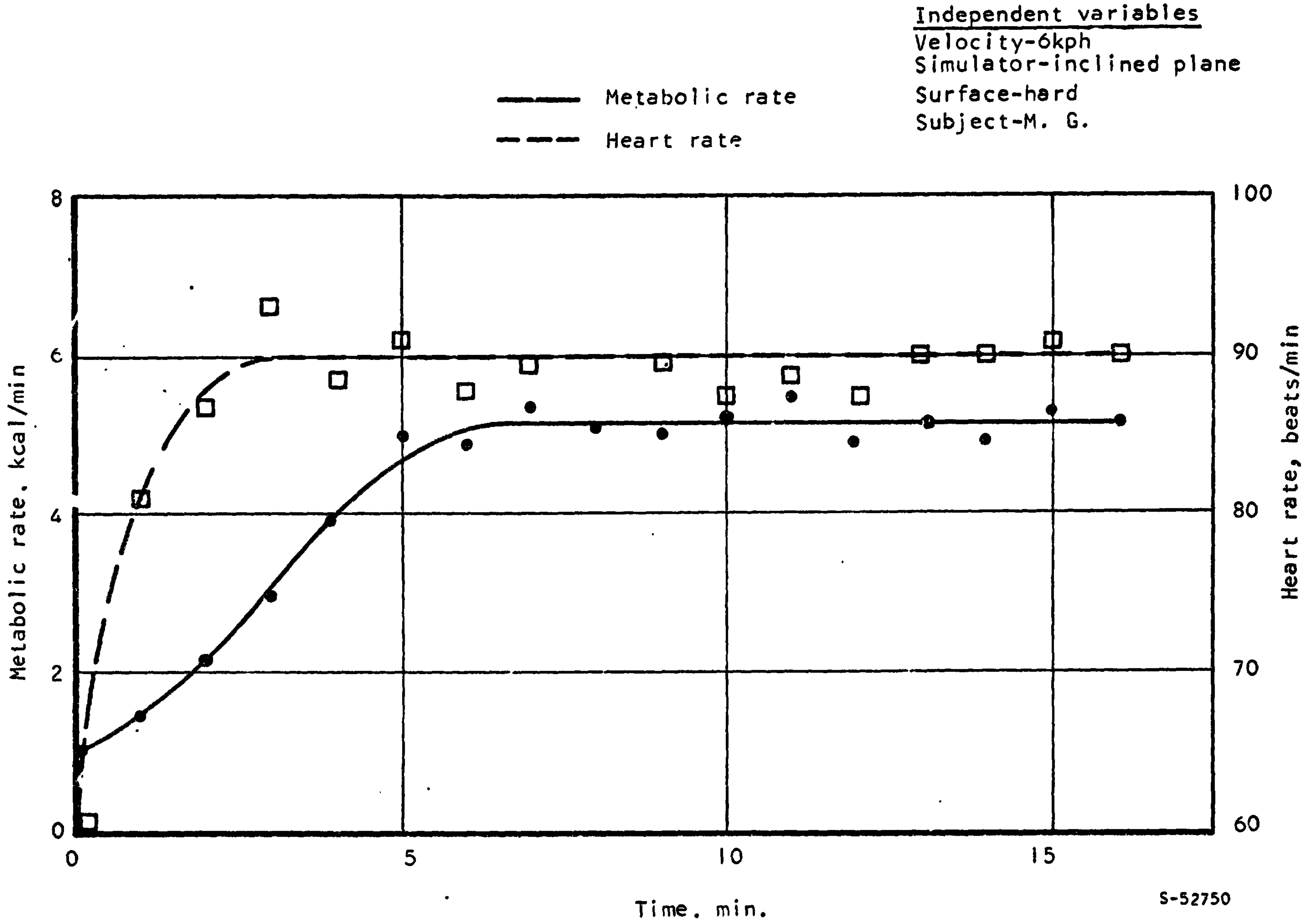


Figure 13. Heart Rate versus Metabolic Rate

metabolic rate essentially increases as a logarithmic function to a constant value (steady state value) between minutes 6 and 7. Once the treadmill is turned on, the energy requirement for a constant velocity should be a step function to the steady-state value noted after 6-1/2 min. The difference between the step function expected and the logarithmic curve obtained represents an oxygen debt which must be repaid when the exercise stops. The heart rate curve shows essentially the step function increase expected but is slightly displaced by the adjustment of the treadmill velocity. Heart rates also reach a steady-state value, providing there are no additional inputs such as emotional stressors. In this case, the heart rate deviated by ±3 beats/min.

DISCUSSION

This program represents another step in determining the anticipated energetic cost of self-locomotion on the moon and the differences between the various pressure suits and lunar gravity simulators that have been developed (refs. 1, 5, and 6). The results of this program describe the metabolic requirements for self-locomotion in an A7L pressure assembly using a turbine-operated-suspension simulator and an inclined-plane simulator to provide the artificial lunar gravity.

Fig. 14 is a graphic presentation of the data shown in table VII. The statistical influences drawn in the results section are readily apparent by a visual evaluation of this graph. The curves were drawn as connecting lines between the mean values within a given simulation. It is apparent that the mean values for the TOSS with a hard surface are consistently higher than the inclined plane data. These differences approached statistical significance ($p = .08$). The mean values for traversing on a simulated lunar soil in TOSS were consistently higher at each velocity when compared to locomoting on a hard surface in the same simulator. However, there were no statistical differences between these data. It should be noted that these data are for walking on horizontal surfaces.

Fig. 15 compares the A7L complete with ITMG with its precursor, the A5L; the RX-2, or hard suit; and the G-2C in several different simulators. The absence of difference between the A7L and G-2C is apparent. It is also obvious that the A7L data are higher than for the mobile suits tested earlier. The higher values for the A7L must be attributed to the presence of the ITMG. Many of the mobility characteristics designed into this series of suit must have been degraded by the addition of the ITMG. These data indicate that the design of the ITMG should be reviewed and that characteristics for the garment which would enhance the operation of the basic pressure suit assembly should be considered.

Table X compares the metabolic rates obtained as a function of velocity for self-locomotion in the A7L pressure suit with the values for mufti data presented in table 5-10 of NASA CR-1402 (ref. 1). These comparisons show that increases for use of the A7L pressure suit are less for the inclined plane than for the TOSS with a hard surface; the differences are even greater when compared to locomotion on a soft surface.

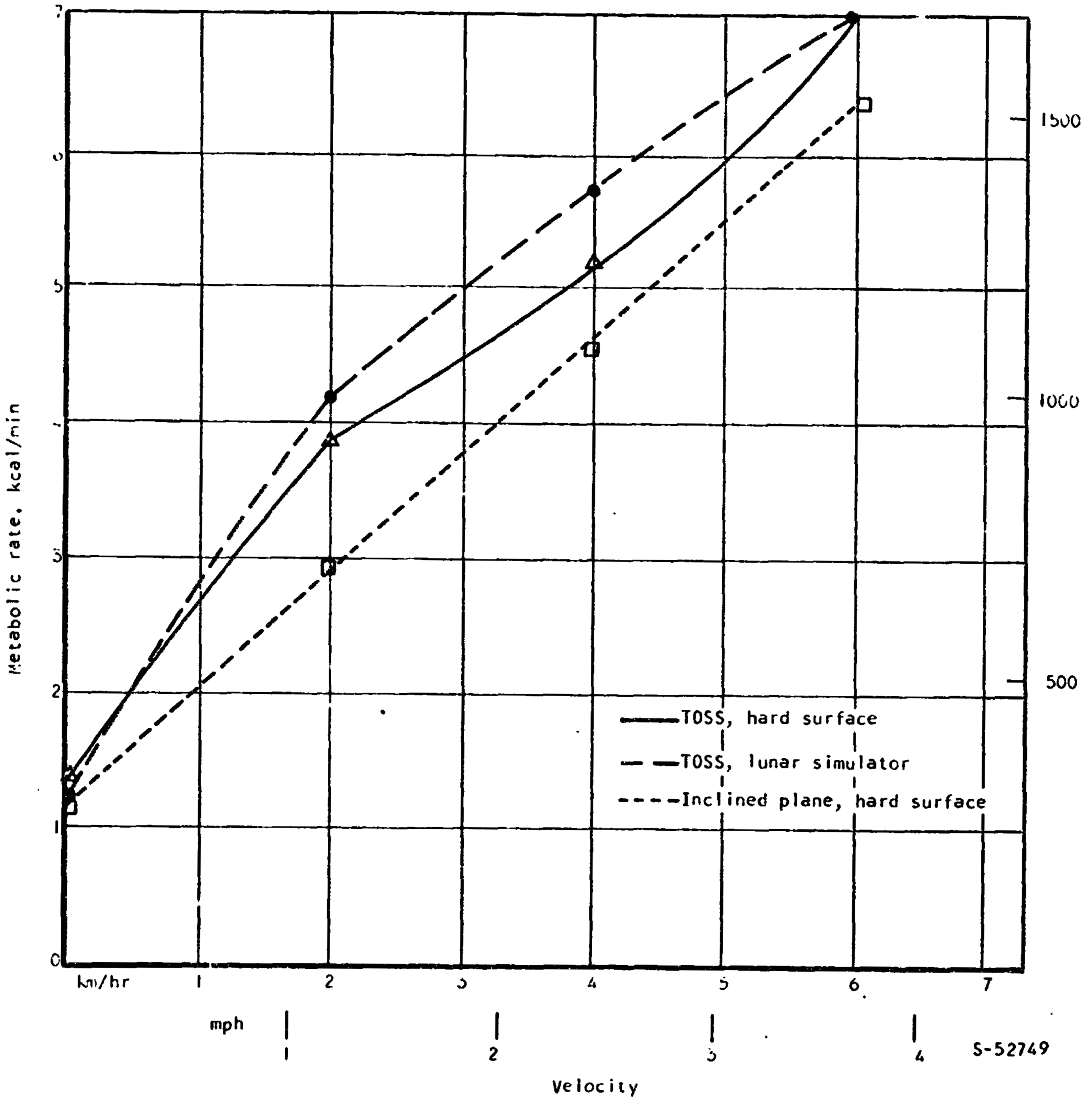
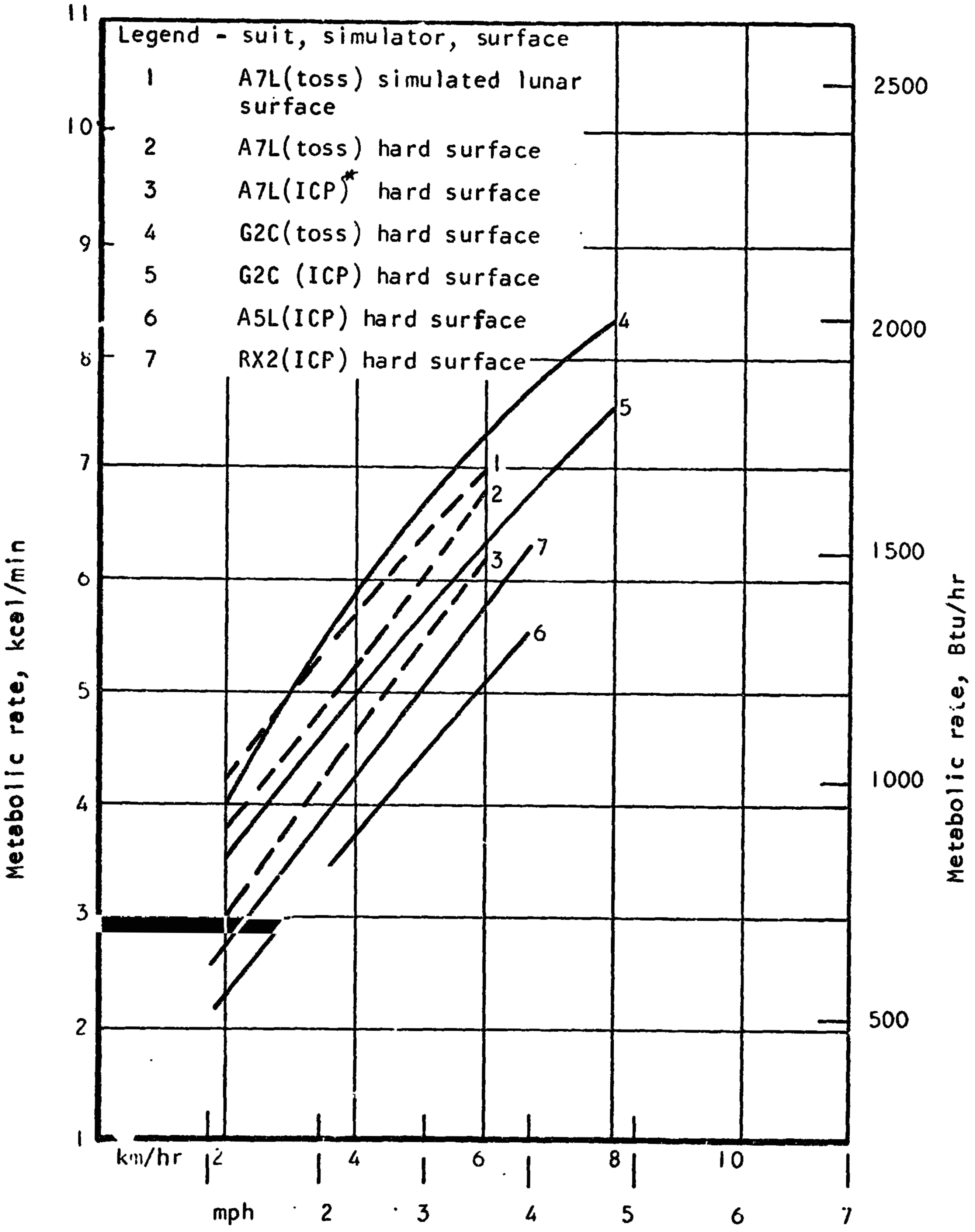


Figure 14. Metabolic Rate Versus Treadmill Velocity



* Inclined plane

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Figure 15. Comparison of A7L, G2C, A5L, and RX2 Pressure Suits

TABLE X

INCREASE IN METABOLIC RATES FOR SUBJECTS USING AN A7L PRESSURE SUIT AS COMPARED TO AN MUFTI DATA SHOWN IN NASA CR-1402

Simulation	Increase with velocity, percent			Average increase, percent
	2 kph	4 kph	6 kph	
TOSS, hard surface	16	303	132	151
TOSS, lunar soil simulant	184	341	133	300
Inclined plane, hard surface	100	300	113	113

CONCLUSIONS

1. Metabolic rates for walking on simulated lunar soil at simulated lunar gravity in the A7L average 986 Btu/hr, 1342 Btu/hr, and 1656 Btu/hr for velocities of 2 km/hr, 4 km/hr, and 6 km/hr, respectively.

2. Although not statistically significant, walking on a simulated lunar soil consistently increased the energy required for this task from 7 to 10 percent over that required for a hard surface.

3. Walking in a six-degree-of-freedom lunar gravity simulator requires between 10 and 30 percent more energy than with a three-degree-of-freedom simulator.

4. System design for mobility should be carried through ITMG design to ensure there is no performance degradation.

5. Differences in walking energy expenditure between various space suits are markedly diminished at simulated lunar gravity.

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