NASA CR-1403

MAN'S CAPABILITY FOR SELF-LOCOMOTION ON THE MOON

Volume II - Summary Report

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ABSTRACT

This document presents the results of a comprehensive study of man's self-locomotive capabilities in simulated lunar gravity. An inclined-plane and a gimbal-vertical simulator equipped with treadmills were used to simulate lunar gravity. Man's locomotive characteristics and the metabolic costs of walking, running, and loping at velocities from 2 to 12.8 km/hr were determined for subjects in pressurized Gemini-4C suits. The results showed that the energy cost of locomotion in simulated lunar gravity is considerably less than that in earth gravity. Ascending grades caused large increases in metabolic cost over that of level walking where the magnitude of the cost depends on the simulation technique used. Increasing the load carried from 75 to 400 earth-pounds had a small and inconsistent effect on metabolic costs. Changing the smooth, hard walking surface to sandy soil caused a large increase in the metabolic cost at the higher locomotion rates.

FOREWORD

This report was prepared by the Department of Life Sciences, AiResearch Manufacturing Company, Los Angeles, California. The technical assistance of M. Gafvert, N.J. Belton, A. Camacho, S. Salzberg, W. Price, R.A. Diaz, W. Pepper, and G. Raynes is gratefully acknowledged. The dedicated efforts of the test subjects that performed throughout this program are also gratefully acknowledged.

PREFACE

This research on man's capability for self-locomotion on the moon is part of the Human Factors Systems Program, Walton L. Jones, M.D., Director. In this contractor report, the investigators describe a comprehensive data gathering study to provide predictive information on the ability of man to walk on level and sloped terrain, utilizing a one-sixth gravity simulator. This study is included in the Man-Systems Integration research program. It was performed under the technical monitorship of Mr. William Letko, Langley Research Center.

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SECTION I

INTRODUCTION

This report summarizes the results, methods, procedures, and apparatus of an extensive study to evaluace man's capability for self-locomotion on the surface of the moon which is reported in full in NASA CR-1402. This program was conducted for the Langley Research Center of the National Aeronautics and Space Administration under Contract NAS I-7053.

The objectives of this program were to investigate systematically the effects of space suits, pack weights, slope grades, lunar surface conditions, gaits used for locomotion, velocity of traverse, and methods of simulating lunar gravity on self-locomotive performance. The effects of these independent variables were primarily evaluated by physiological and kinematic measurements.

Prior investigation at Langley Research Center on the effects of lunar gravity on a wide range of activities had indicated that walking, running, climbing, and other activities on the lunar surface would be substantially improved over that to which we are accustomed on Earth. (References I, 2, and 3). The lunar gravity conditions have indicated a high probability of a corresponding substantial decrease in the metabolic cost of walking compared to rates for Earth gravity conditions (References 4, 5, and 6)

The amount of research conducted on energy levels prior to the program reported in this document has been quite limited, and the level of confidence for generalization to the actual lunar surface has been uncertain. Among the reasons for this were the uncertainty about the adequacy of the various simulation techniques, the lack of data with space suits, and the uncertainty concerning lunar surface conditions. The primary reason, however, for the lack of sufficient confidence for predictive purposes has simply been the paucity of data. The program summarized in this report represents a major step toward correcting these deficiencies.

The test conditions for the experiments conducted in this program are presented in Table I. The table lists all the independent variables tested, including subjects, simulators, locomotion velocities, locomotion gaits, walking surface characteristics, the weights of packs carried, the inclination

TABLE I

EXPERIMENTAL DESIGN

Experimental conditions						
Simulator and suit mode	Slope, deg	Surface condition	Pack	Number of velocities	Number of subjects	Total tests
Inclined plane, pressurized (press.) suit	0 (horiz)	Hard	I, 75 lb	4 each; walk, lope and run	6, with 2 repeating once	96
Inclined plane, pressurized suit	0	Hard	I	1 each; walk, lope, and run	6, with all repeating twice	36
Inclined plane, subject in mufti (without press. suit)	0	Hard	I	4 each; walk, lope, and run	2	24
Incl plane, mufti	0	Hard	I	Fatigue test	6	24
Inclined plane, pressurized suit	0	Hard	I	Fatigue test	2	8
Inclined plane, pressurized suit	0	Hard	II, 240 lb	4 each; walk, lope, and run	6	72
Inclined plane, pressurized suit	0	Hard	III, 400 lb	4 each; walk, lope, and run	2	24
TOSS (6-deg-of-freedom), pressurized suit	0	Hard	I	4 each; walk, lope, and run	6	72
TOSS, press. suit	0	Smooth lunar	I	4	6	24
TOSS, press. suit	0	Coarse lunar	I	4	6	24
TOSS, pressurized suit	7.5	Hard	I	4	6	48
TOSS, pressurized suit	7.5	Smooth lunar	I	4	6	48
TOSS, pressurized suit	15	Hard	I	4	6	48
TOSS, pressurized suit	15	Smooth lunar	I	4	6	48
TOSS, pressurized suit	30	Hard	I	4	6	48
Inclined plane, pressurized suit	7.5	Hard	I	4	6	48
Inclined plane, pressurized suit	7.5	Hard	II	4	6	48
Inclined plane, pressurized suit	15	Hard	I	4	6	48
Inclined plane, pressurized suit	30	Hard	I	4	6	48

of the slope traversed, and suiting. The experimental program tested the effects of these independent variables on dependent variables such as metabolic rate, total energy expenditure, heart rate, respiratory rate, and kinematic characteristics of gait. The combinations of experimental conditions selected for testing resulted in a program of 836 tests. In addition, training and baseline testing were conducted under this program on the inclined walkway at Langley Research Center.

A series of statistical treatments were made on the data collected (dependent variables) to define more precisely the effects of the independent variables. These statistical calculations included both descriptive and inferential techniques. The descriptive techniques were limited to the determination of the mean (average) value and the standard deviation of grouped data. The inferential statistical techniques were primarily the product moment coefficient of correlation and analysis of variance.

SECTION 2

FACILITIES AND APPARATUS

GENERAL FACILITIES

The facilities and apparatus used in this program can be categorized into simulators, treadmill systems, lunar surface simulators, pressure suits, physiological and metabolic apparatus, and miscellaneous equipment such as digital data systems, weighing equipment, and environmental control systems.

Most of the tests conducted in this program were performed at an outdoor facility especially designed for this purpose. The general layout of the facilities used in this program is depicted by a photograph of the primary test area, Figure 1.

LUNAR GRAVITY SIMULATORS

The simulators used in this program were extensions of techniques developed during previous programs. The inclined-plane simulator was built from the data and design provided by Hewes and Spady and reported in NASA TND-2176 (Reference 7) with modifications in the method of holding the subjects due to the constraints of the pressure suits and backpacks used in thi program. The vertical suspension (TOSS, turbine-operated suspension system) is described in subsequent paragraphs.

Inclined-Plane Simulator

The inclined-plane simulator consists of a treadmill, a suspension system, and a tower for the suspension system. The treadmill was installed integral with and parallel to the plane upon which the subject stands. This plane is 9-1/2 deg from vertical with respect to the point of suspension. The test tower, shown in Figure 1, provides a suspension height of 136 ft for the inclined-plane simulator. This structure, a modified oil derrick, provides twice the minimum elevation specified under the contract. The suspension cabling is attached at one end to foam-rubber filled slings that hold the subject and at the other end to a trolley on the 40-ft-long horizontal beam 136-ft from the base of the tower. The backpack, gas meter and associated harnesses required to suspend the subject are shown in Figure 2. Suspension of the subject vertical to the 9-1/2 deg treadmill surface results in an effective acceleration to the feet of the suspended subject almost equivalent to that on the lunar surface.

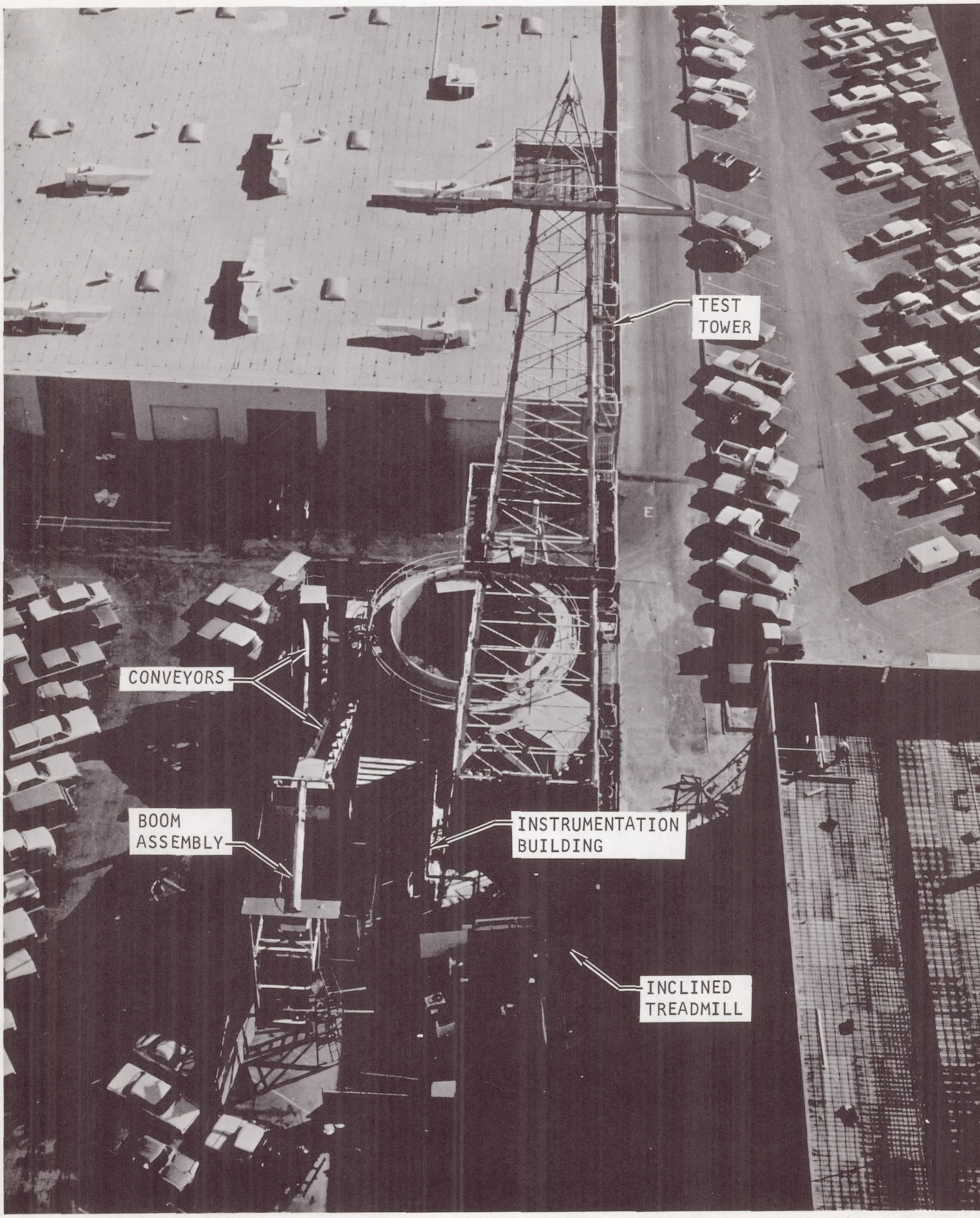

Figure 1. Primary Test Area

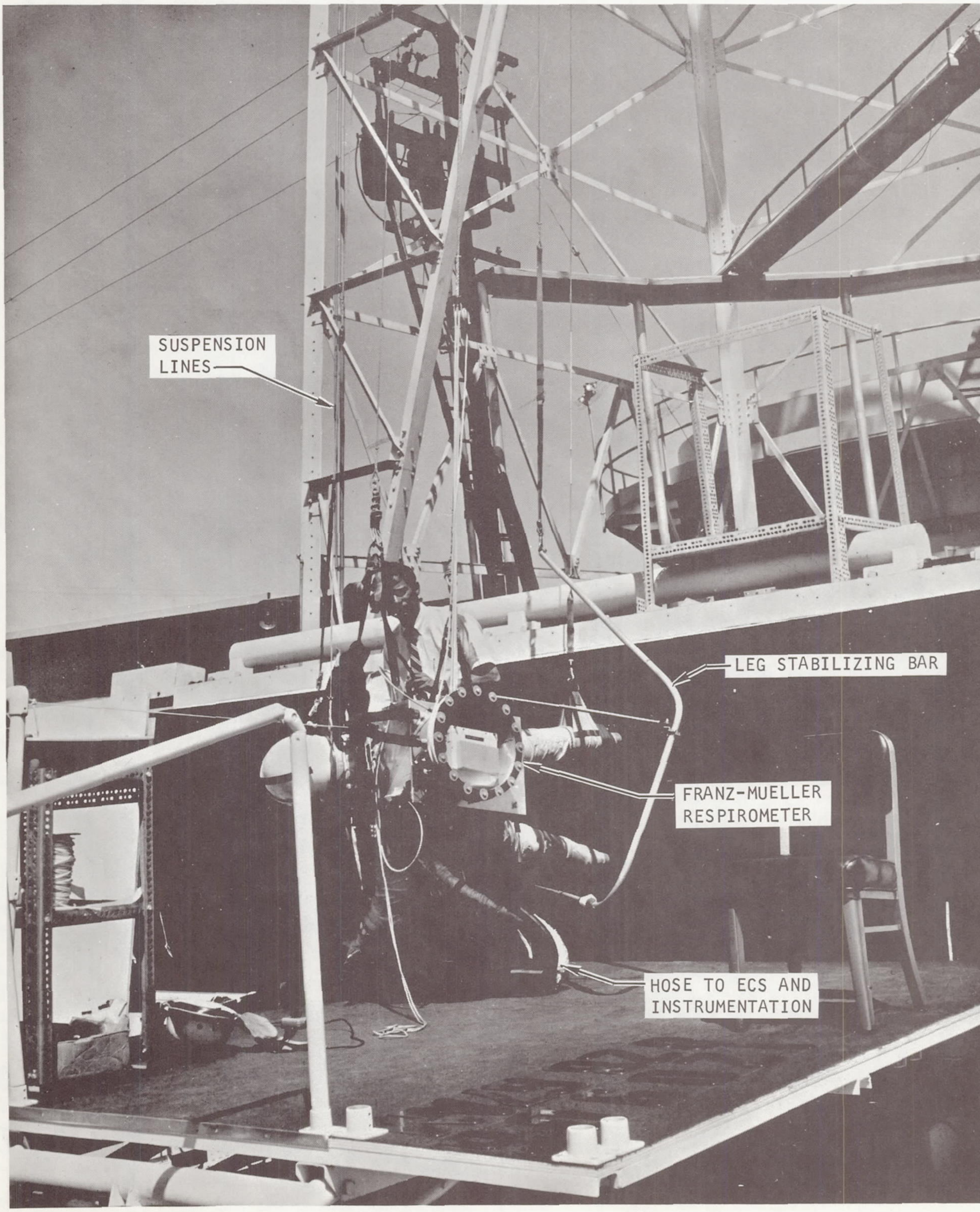

Figure 2. Inclined Plane Test Configuration Showing Backpack, Gas Meter, and Harness Assembly

Vertical Suspension Simulators

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 that observed for negator spring systems used for the simulation of reduced gravity in manned testing.

The basic system, illustrated schematically in Figure 3, consists of a "C" brace gimbal, a swivel, a yoke with air pad bearing, a cable and pulleys, a lightweight beam, and a turbine take-up pulley. The air turbine acts as a constant tension device winding up the vertical cable during upward movements of the subject and providing 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 2.

The variable-surface treadmill system, shown in Figures 4 and 5, is a system containing four conveyer 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. In this 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. Control of this function is effected by a manually positioned valve which determines the position of the hydraulically operated gate door.

LUNAR SURFACE SIMULATION

The materials for simulating the lunar surface were selected based on data from the Surveyor program (References 8 and 9) 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 the 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 by the push-off of the subject whether the soil fails in bearing or shear.

A sandblasting type of sand was chosen as one of the most likely candidate soils to simulate a smooth lunar surface. In a comparison of the test data with the selection criteria, this material compared favorably with the reported lunar surface properties.

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

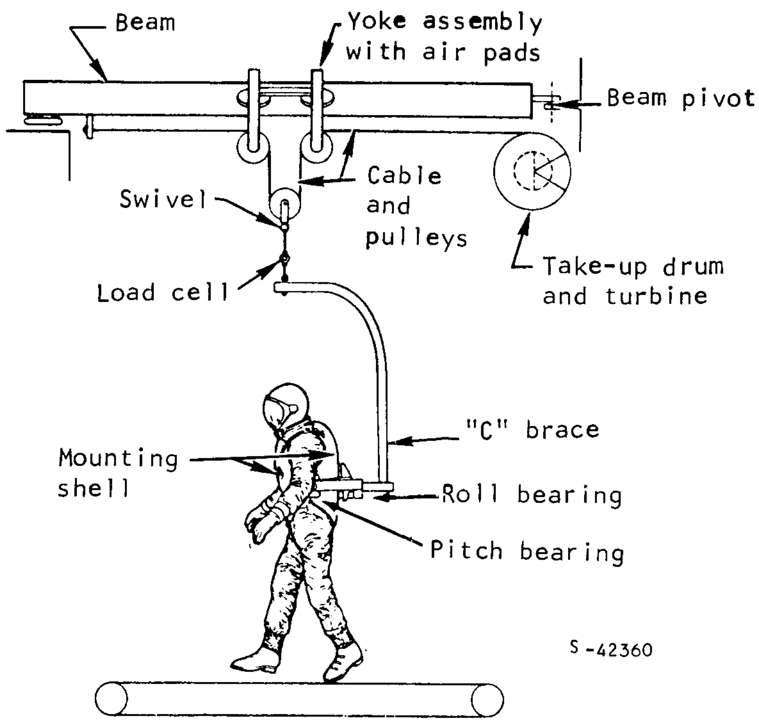

Figure 3. Turbine-Operated Suspension System (TOSS)

TABLE 2

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

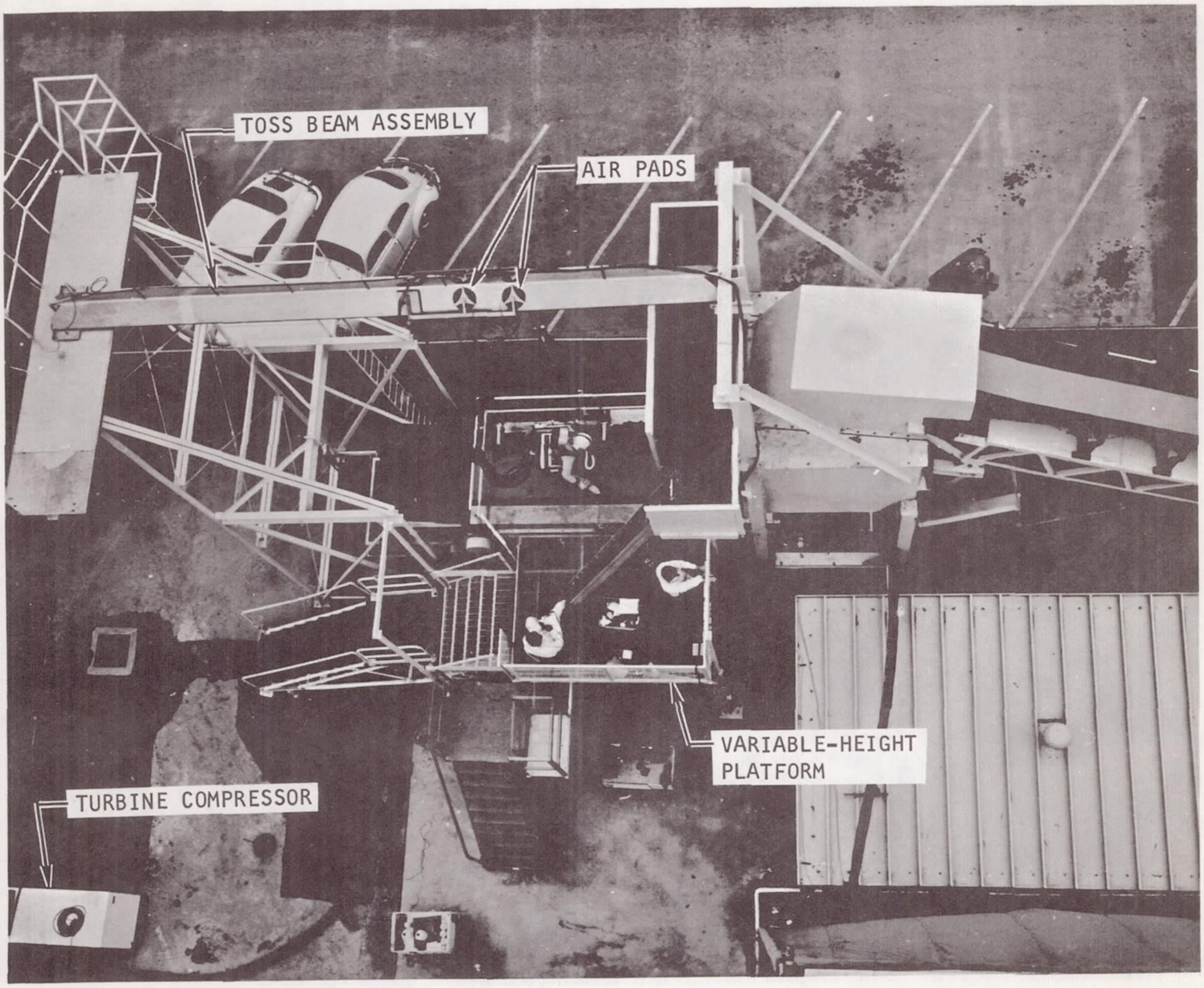

Figure 4. TOSS and Lunar Surface Simulating Treadmill (Viewed from above)

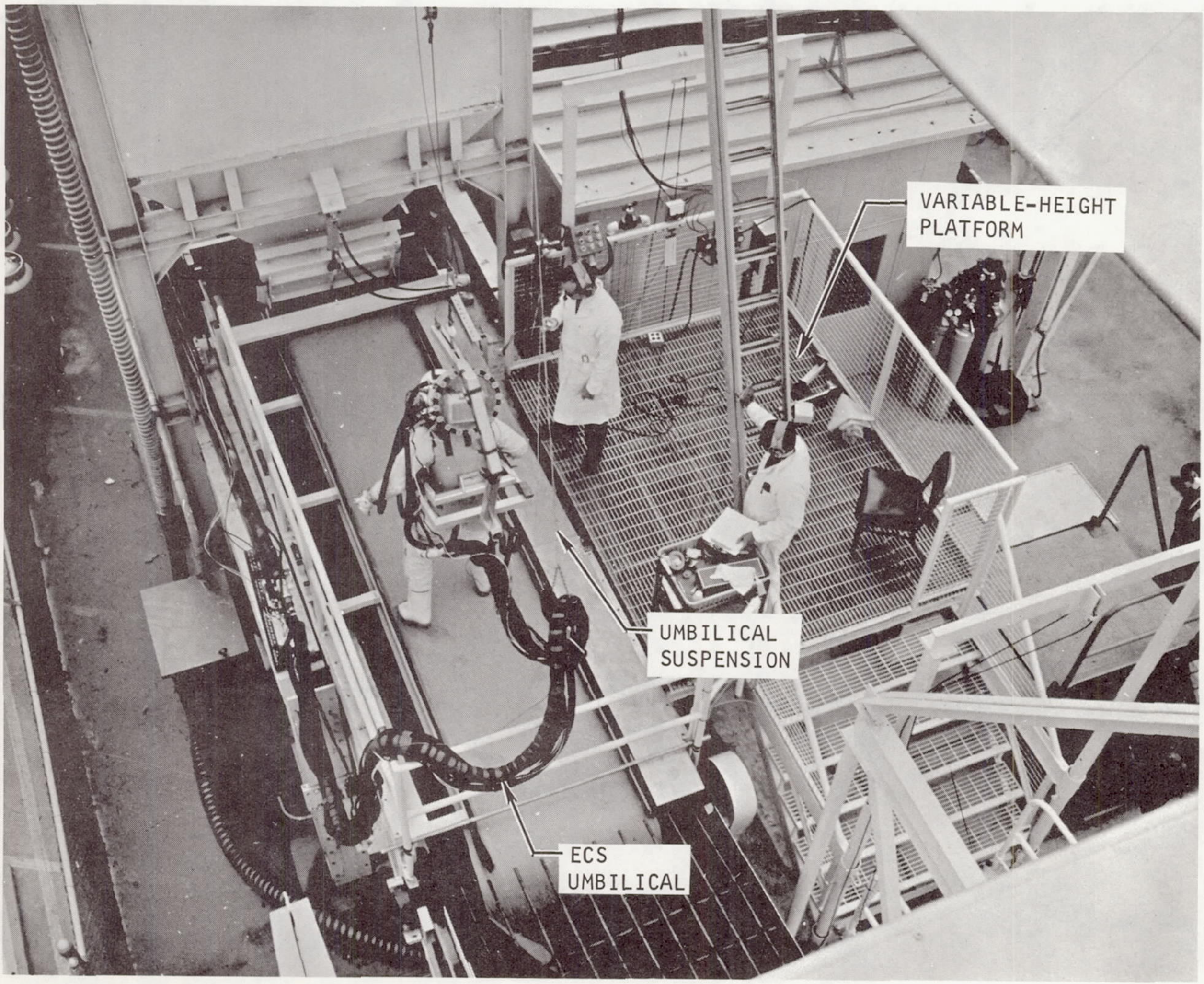

Figure 5. Test Configuration for Walking Tests on Simulated Lunar Soil

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 is illustrated in Figure 6, taken from the Surveyor V report. The figure shows that the area immediately adjacent to Surveyor V does not contain as many of the larger particles as the areas around Surveyor I and III. However, there is good general agreement.

The equation for this particle size distribution, taken from the Surveyor I report, is

$$N = 3 \times 10^5 y^{-1.77}$$

where N = cumulative number of grains in 100 m^2

y = diameter of grains in mm

To simulate the rough surface condition, concrete aggregate and crushed granite in sizes ranging from 4.8 mm (0.187 in.) to 62 mm (2.5 in.) were mixed with the surface material used for simulating the smooth lunar surface. The distribution of the particle size is illustrated by the vertical lines shown in Figure 6 between lines 1 and 2. The line marked 3 is the upper limit of the particle size used to simulate the smooth surface. The distribution was obtained by adding the coarse aggregate volumetrically to the sand.

PHYSIOLOGICAL AND METABOLIC APPARATUS

The physiologic instrumentation used to determine the various parameters for these experiments is listed in Table 3. In addition to the analog data collection system, provisions were made for an analog-to-digital conversion system with an automatic recording of all the digital data on punched paper tape.

Metabolic rates were measured by indirect calorimetry. The basic respiratory system for the suited tests is shown in Figure 7. In this system, inspired air is drawn from the right side of the helmet through a hose connected to a port in the faceplate. The hose leads externally to the bifurcated mouthpiece. The expired gases pass from the bifurcated mouthpiece through a second external hose leading to a Franz-Mueller-type respirometer which is attached to the subject's backpack. The expired volume is measured by the respirometer. A third hose conducts this gas back to the left side of the helmet where it passes through a port in the faceplate and is then deflected downward into the airstream from the helmet to the trunk of the suit.

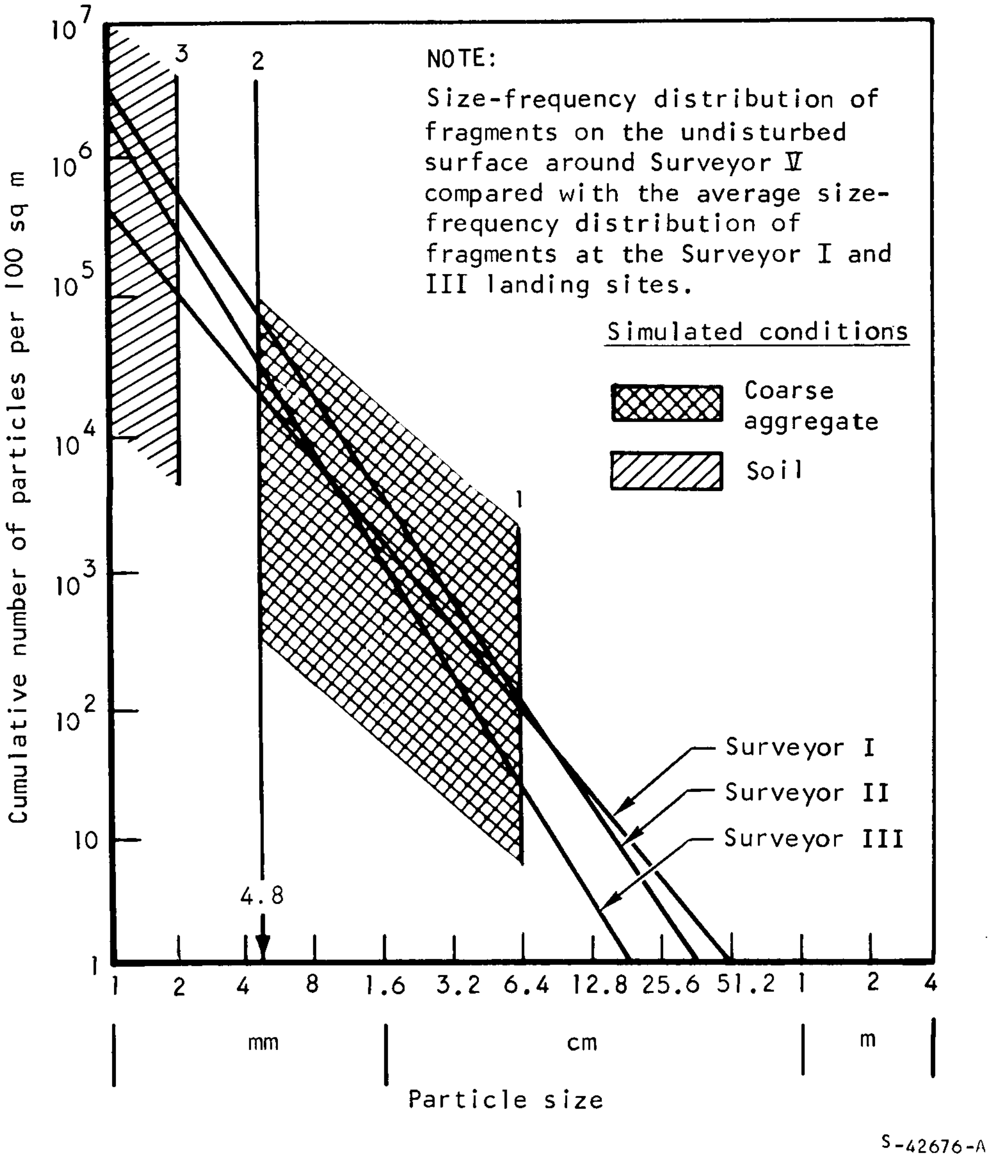

Figure 6. Lunar Surface Particle Size Distribution

TABLE 3

PHYSIOLOGIC 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 ±0.75%	Brown Multipoint Recorder ±1%
Suit temperature out	Cu-Co Thermocouple ±0.75%	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 ±0.75%	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 ±0.75%	Brown Multipoint Recorder ±1%
Ambient pressure	Mercury barometer, Wallace and Tiernan Gauge ±0.25%	Manual recording
Ambient temperature	Cu-Co Thermocouple ±0.75%	Brown Multipoint ±1%
Treadmill velocity	Tachometer ±5%	Offner Dynograph ±1%
Subject weight	Buffalo Scale ±0.25%	Manual recording
Subject height	Meter stick ±0.1%	Manual recording
Surface area	Dubois Nomogram	Manual recording
Gravity gradient	Load cell ±5%	Manual recording

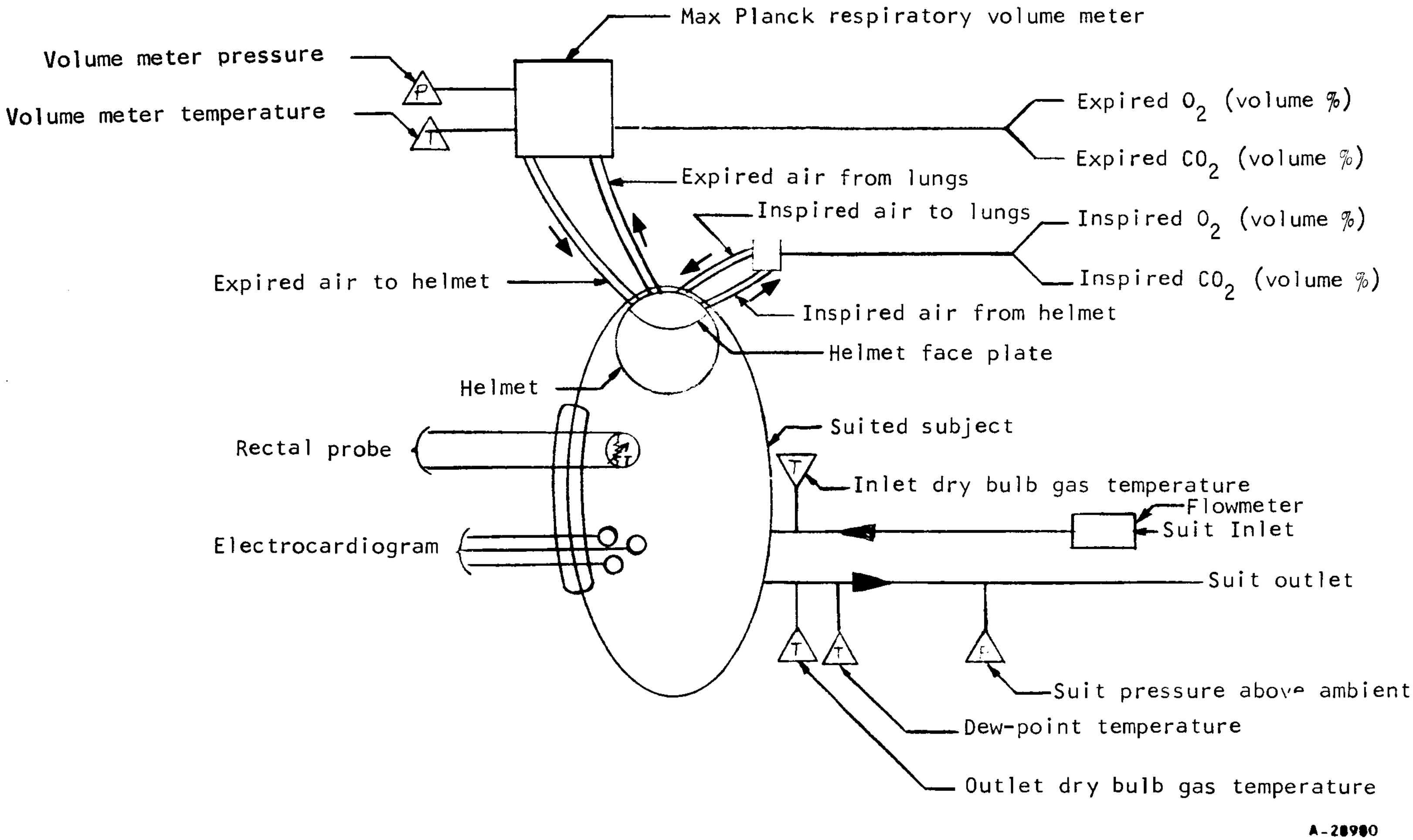

Figure 7. Basic Respiratory System

ENVIRONMENTAL CONTROL SYSTEM

The environmental control system (ECS) used in this program was designed as an open loop suit pressurization and ventilation system. It controlled the suit ventilation flow rate, suit inlet dry bulb temperature, and suit-to-ambient 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 Figure 8.

BASIC BACKPACK AND RESPIROMETER

The backpack shown in Figure 9 is the basic backpack which was used for all tests on the inclined-plane simulator. The total Earth weight of the pack, including the weight of the shell and other equipment, is adjustable by placing lead weights as shown in the pack. These weights can be placed so that the pick-up suspension point of the pack is at the c.g. of the pack for any weight.

LIQUID AIR BACKPACK

Two liquid air backpacks used to ventilate and cool protective suits were modified to provide the ventilation, cooling, and pressurization of the suited subject for the basic training at Langley Research Center (LRC) and in initial subject orientation and training at AiResearch. Figure 10 shows the pack being worn by a subject undergoing training on a small inclined-plane simulator.

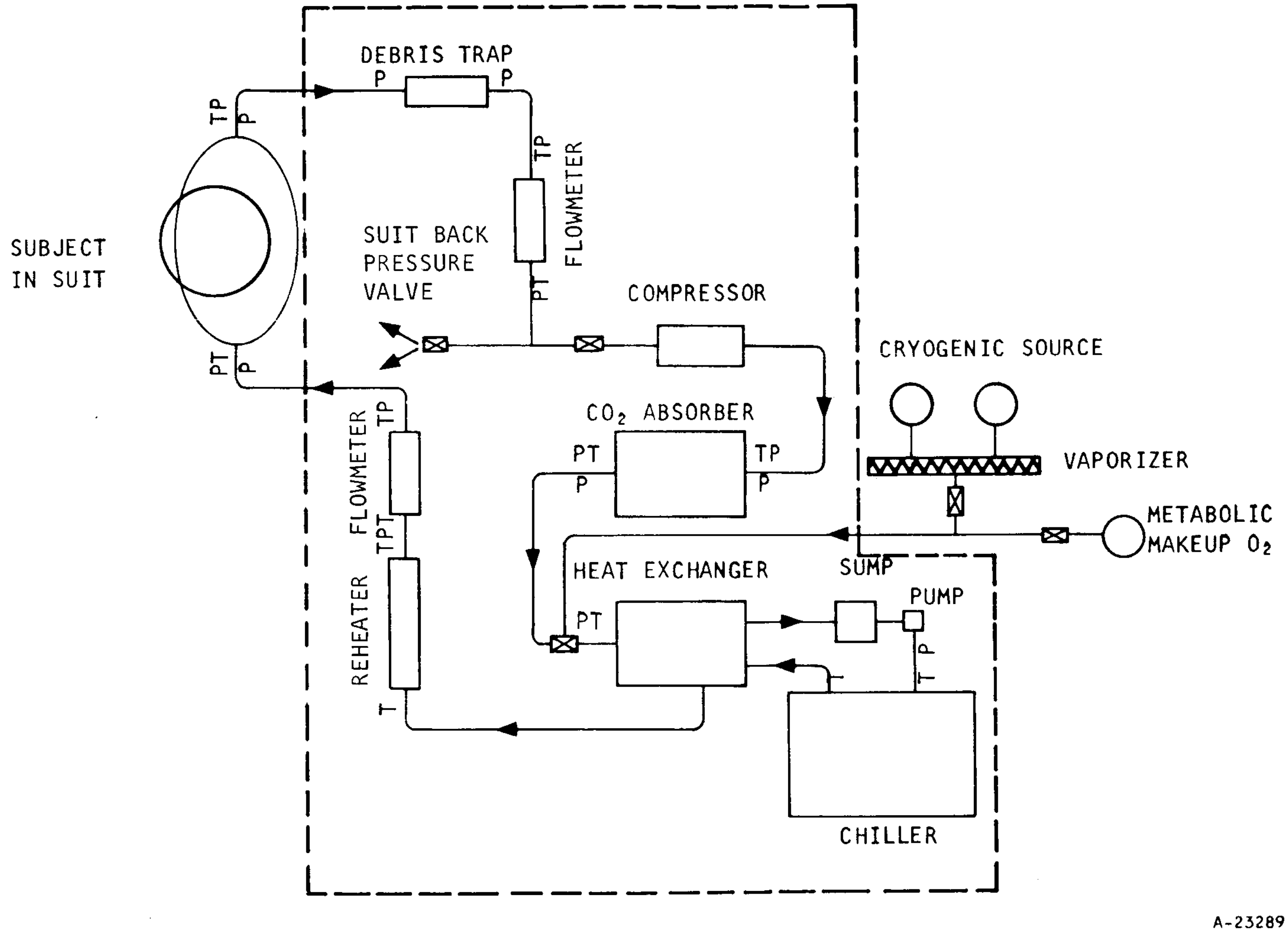

Figure 8. Mobile ECS Schematic

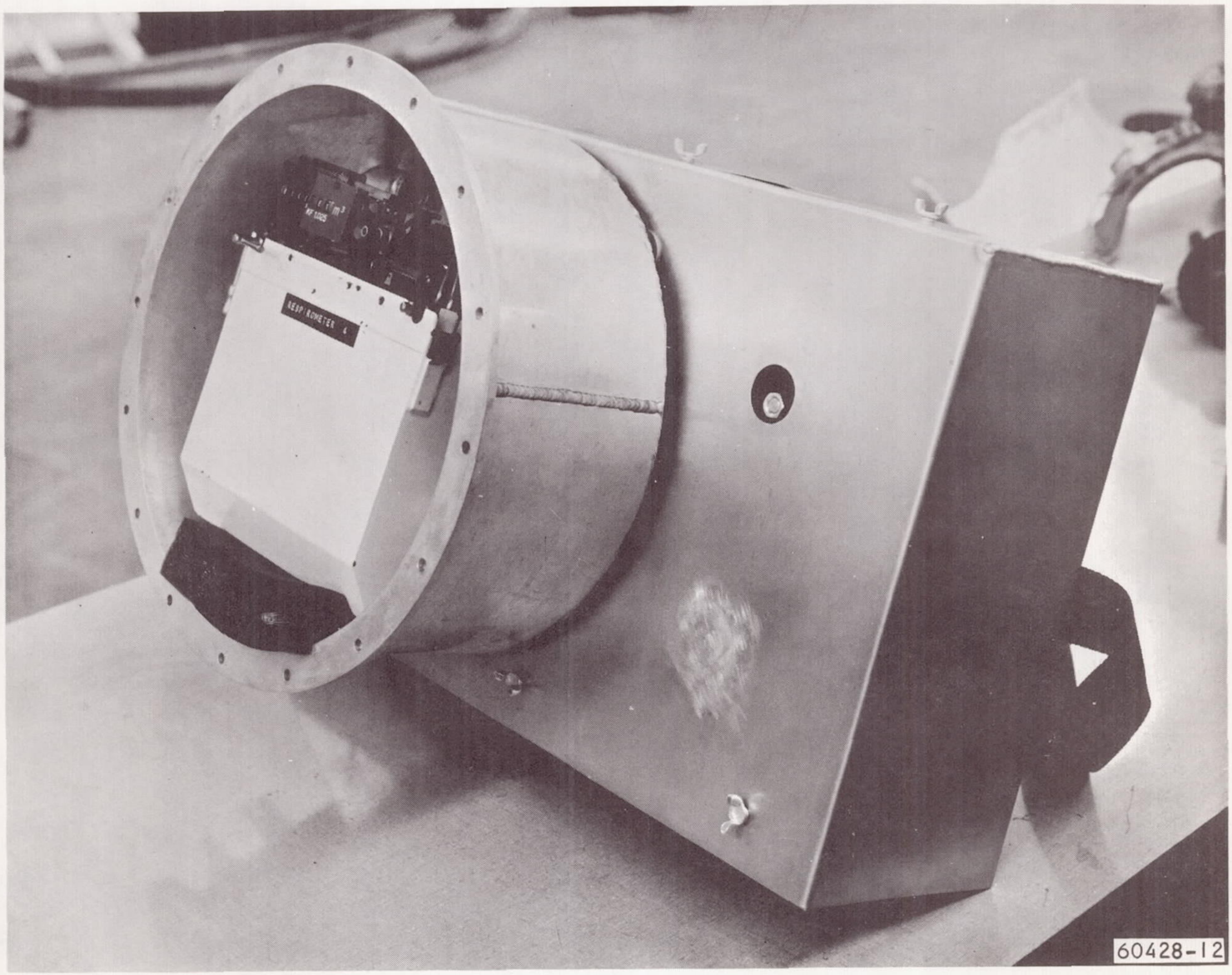

Figure 9. Weight Pack and Mounting of Respirometer

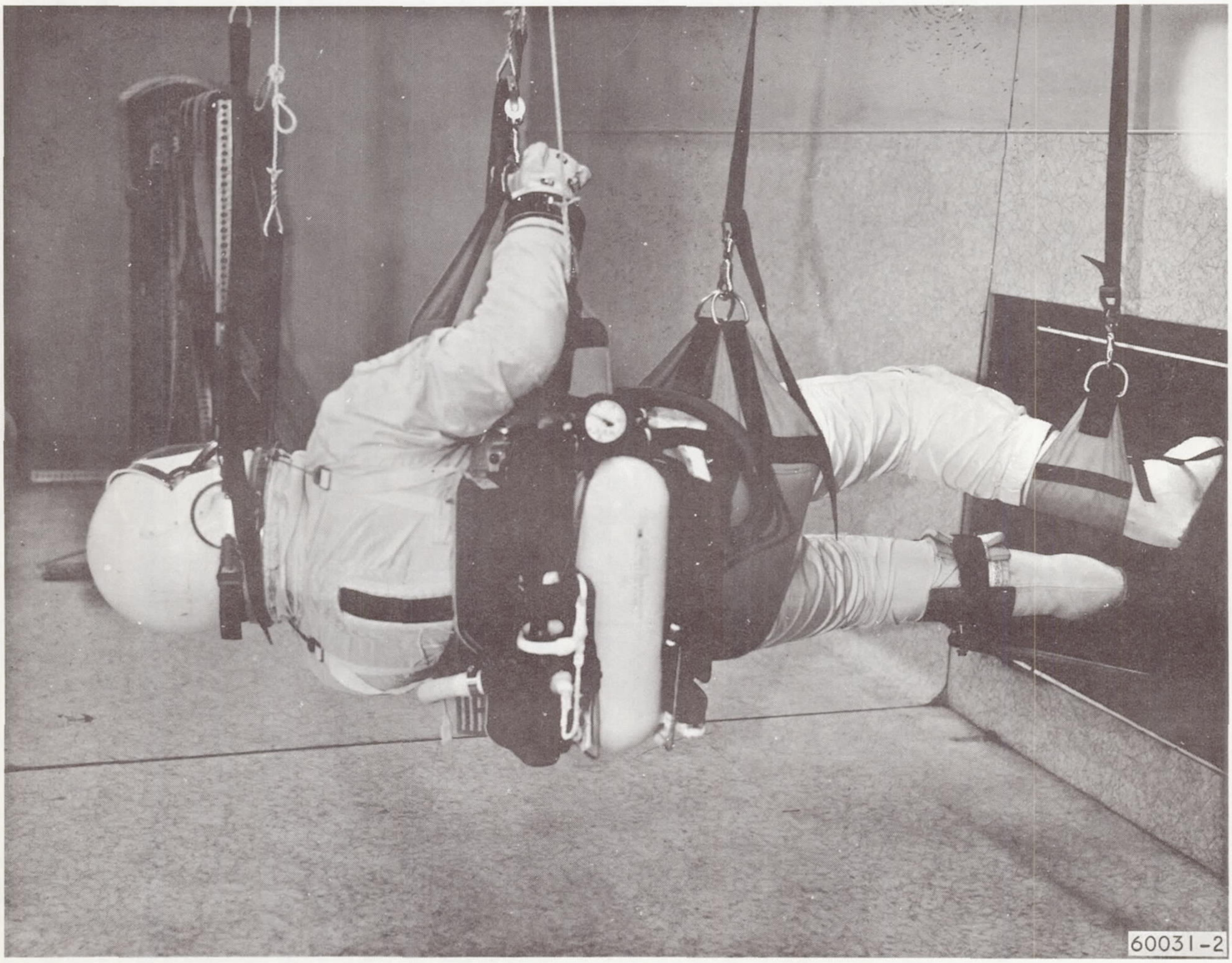

Figure 10. Liquid Air Backpack on Subject in Training

SECTION 3

SUBJECTS AND TRAINING

SUBJECT SELECTION

Six healthy male subjects were selected from the AiResearch test subject panel. Selection criteria were based on suit fit, psychological and physiological reaction to stress-inducing situations, an ability to pass an FAA Class I flight physical, and physical fitness testing. The subjects chosen all had extensive experience in suit testing in conjunction with a modified Hewes and Spady inclined-plane simulator and a 6-deg-of-freedom vertical suspension simulator.

The anthropomorphic data for the six subjects that participated in this program are given in Table 4. The obvious uniformity among the subjects is a result of the size requirements to fit the pressure suits available for this program. These subjects compare very closely to the body characteristics of the astronaut population for this same reason. The only deviation from the characteristics of the astronauts is that the subjects in this program were younger.

Basal and resting metabolic rates were determined to evaluate the possibility of any aberrations in the general condition of the body. In addition, a Harvard Step Test, lean body mass determinations, and a Balke Test were performed on each subject.

TRAINING

All subjects had previously participated in studies requiring the use of a modified Hewes and Spady inclined-plane lunar gravity simulator. All subjects were given a minimum of three training sessions on three different days, both in mufti and in pressurized suits, to reorient them to this type of simulator. Normally three days of training is adequate for walking or running on an inclined-plane simulator.

Two subjects who had also performed locomotion tasks on the Hewes and Spady inclined-plane simulator located at Langley Research Center found the training on the inclined treadmill quite adequate for performing on the stationary inclined board located at LRC. They performed quite well after only 4 to 8 training trials on the 191-ft board. Figure 11 shows a subject in a Gemini suit pressurized to 3.5 psi walking through the measurement grid in the LRC simulator. The only subjective differences noted were the push-off necessary to reach a given traversing velocity, the minor problems associated with maintaining a constant velocity and gait going through the measurement grid, and the problems of decelerating and stopping.

TABLE 4

ANTHROPOMORPHIC CHARACTERISTICS
OF TEST SUBJECTS

Subject	Age, years	Height,		Weight,		Body surface area, M^2	Lean body mass, kg
		in.	cm	lb	kg		
A (Billman)	24	68	172.7	149.3	67.73	1.81	56.46
B (Chidsey)	29	70	177.8	133.3	60.45	1.75	58.65
C (Gafvert)	24	68-3/4	174.6	147.3	66.82	1.82	52.01
D (Kern)	22	70-1/2	179.1	164.9	74.77	1.93	59.37
E (Paige)	31	70-1/2	179.1	148.3	67.27	1.85	57.18
F (Wallenius)	24	70	177.8	152.3	69.09	1.86	50.59

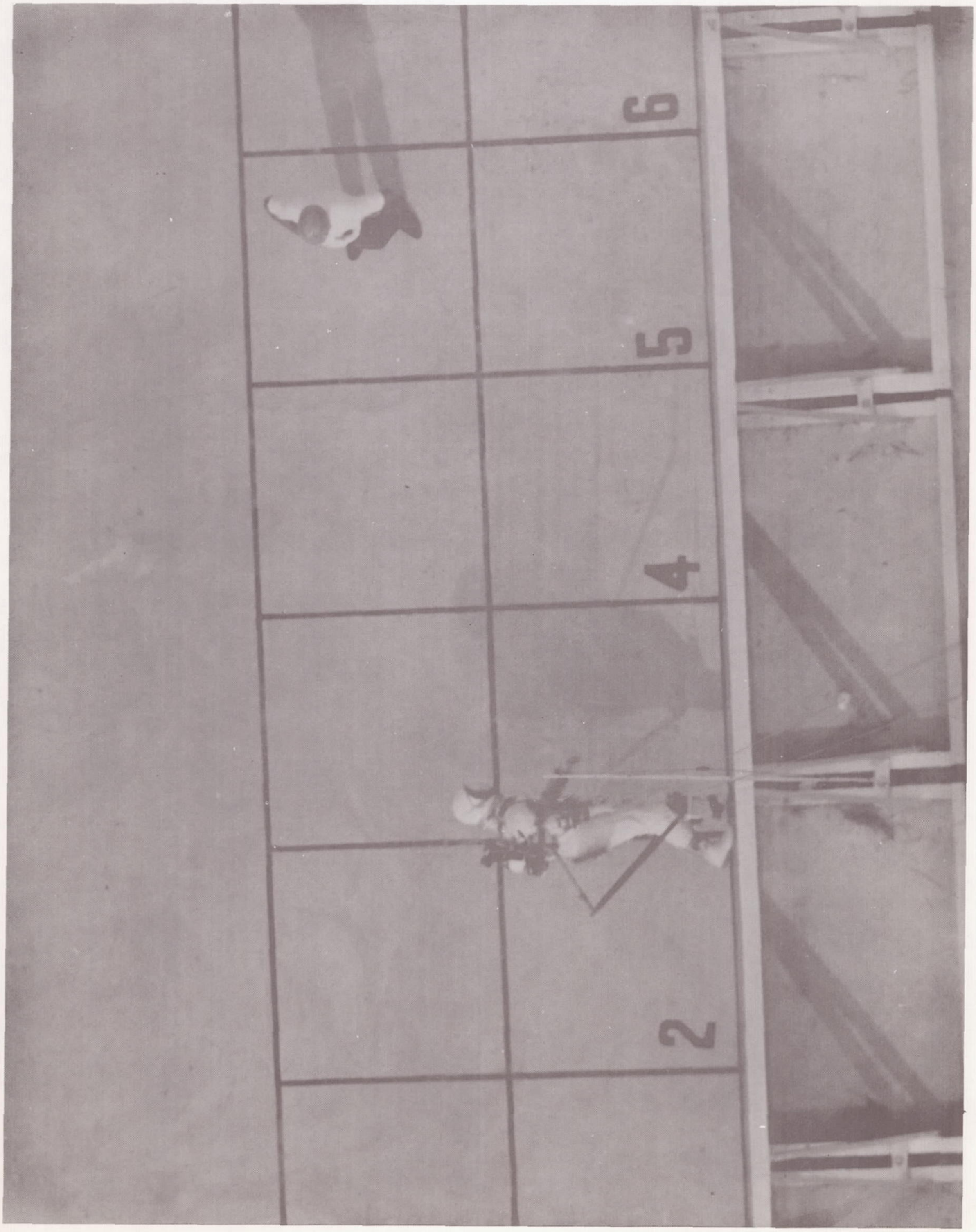

Figure 11. Test Subject on LRC Inclined-Plane Simulator with Pressurized Suit

The subjects made the transition from the inclined-plane simulator to the vertical suspension simulator with approximately three days of training for each man. This added time was needed to adjust to problems of directional stability in the decreased traction field. The directional instability occurs mainly in the yaw degree-of-freedom. The subjects had to learn to impart approximately the same amount of force with each foot to keep from rotating either to the left or to the right. This effect was even more pronounced with the loping gait. All subjects were adequately trained within the three-day period. It must be noted that each time a new series of tests was started (e.g., slope traversing, different loading, and surface changes), the subjects were given a brief period of training to ensure they could perform the modes requested and that the data would not be biased by a training effect. This procedure was used for each simulator.

SECTION 4

RESULTS

The results of this program are summarized by the data presented in the following pages. Unless otherwise indicated, all data points described or discussed are mean values of observations on six subjects. The use of the term "significant difference" in this report is reserved for cases in which differences observed are statistically significant (i.e., the differences are considered real differences as determined by statistical tests).

This section is divided into two major subsections, physiological results and kinematic results, followed by a discussion of range computation.

PHYSIOLOGICAL DATA

The principal physiological dependent variable determined during this experimental program was metabolic rate. Other physiological variables evaluated included heart rate, respiratory rate, oxygen consumption, carbon dioxide production, and expired minute ventilation. The individual data and evaluation of those data are presented in the detailed report for this program. Only portions of the metabolic data, the interrelations between heart rate and metabolic rate, and comparisons of the metabolic rate data from this program with other pertinent data are discussed in this summary document.

Metabolic Rate

During this program, emphasis was placed on the steady-state energy cost for performing each test mode, since the steady-state metabolic rates were the best predictive measures for evaluating man's performance. All test modes were repeated to increase the validity of the data. Data from repetitions of the same test modes were analyzed to evaluate the reliability of the data.

Three series of tests were conducted to analyze the differences between repeated tests at the same conditions. The steady-state metabolic rates for the initial tests performed on the horizontal inclined-plane simulator with a hard surface and with a 75-lb pack (Pack I) are shown graphically in Figure 12. Statistical analysis of these tests and the data of the two repeat series revealed no significant differences. The data were pooled across all three test series; the results are presented in Figure 13. Comparison of Figures 12 and 13 shows that the data are from the same population of values. The general forms of the curves obtained are as expected. If the subjects had been able to choose their gait to perform any given velocity, however, the curve for walking would probably have led directly into the curve for running to produce a straight line. The curve for the loping data lies above this imaginary line.

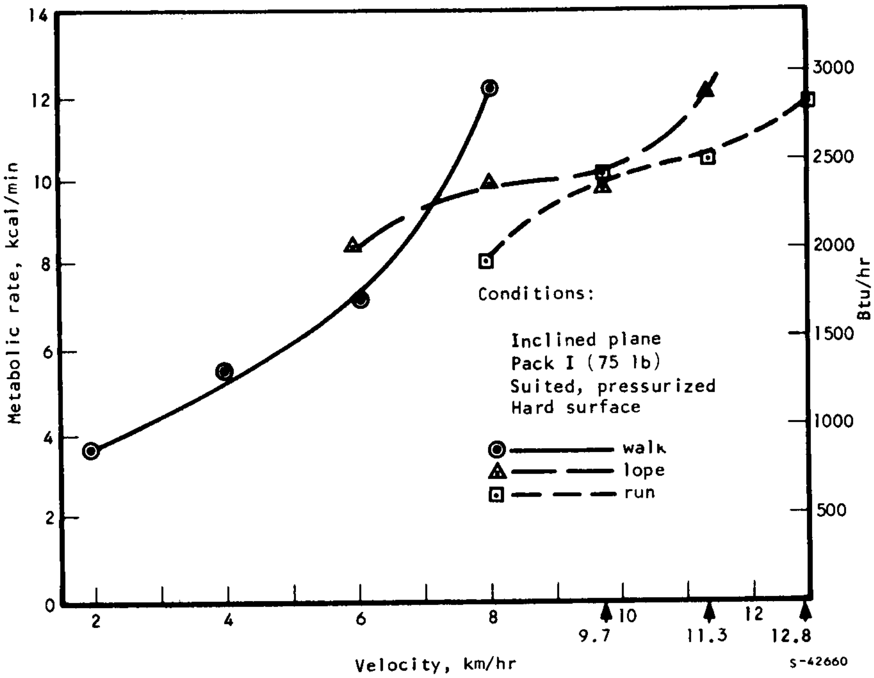

Figure 12. Steady-State Metabolic Rates for Initial Trials on the Horizontal Inclined-Plane Simulator, Subject Carrying Pack I

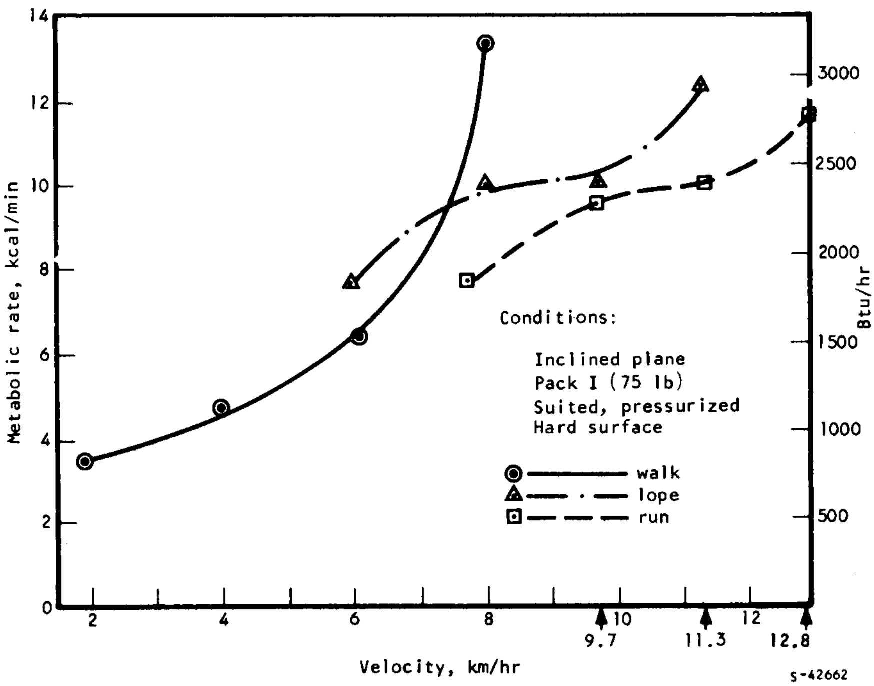

Figure 13. Steady-State Metabolic Rates for All Trials (Pooled Data) on the Horizontal Inclined-Plane Simulator with Pack I

The metabolic costs for walking were increased significantly by velocity ($p<0.01$), with the energy cost for the 8-km/hr walk being disproportionately high. In trying to walk at this velocity, the subjects were forced to use an unusually long stride while striving to maintain the double support required for walking. Hogberg (Reference 10) reported in 1952 that for running, the most economical stride length lies in the region of a freely chosen one, while an increase of stride length over this optimum yields a larger increase in energy cost than a corresponding shortening of the stride. Although Hogberg's studies were performed at 1 g, the same phenomenon has been demonstrated by Sanborn (Reference 11) in a 1/6-g environment. This effect, coupled with the physical characteristics of the suit which impose undue stress in performing the walking task, accounts for the exceptionally high energy cost of the 8-km/hr walk. The metabolic costs for loping at 1/6 g increased with velocity, but the increases were not significant. The running modes resulted in an increase in energy cost with velocity ($p<0.05$).

The data shown in Figure 14 for subjects in shirt sleeves are significantly lower ($p<0.01$) for each velocity than the data in Figure 12 for subjects in pressurized suits. The loping gait required significantly higher energy levels than either of the other gaits regardless of velocity ($p<0.05$). The higher energy cost for loping is undoubtedly due to the requirement for performing more antigravity work than is the case for walking or running. Benedict and Murchauser (Reference 12) report that the energy requirements are higher for running than for walking at the same speed at 1 g due to the greater elevation of the body with the increased cost required to perform antigravity work. Supporting evidence has been presented by Fern (Reference 13) and by Cavagna (Reference 14). Extrapolation of their conclusions to the 1/6-g environment supports the data obtained during this program and offers a probable explanation for the higher energy cost for loping. The energy cost for raising the body would be lower in the 1/6-g condition, but proportional changes should be similar to the 1-g condition. Raising the body may be only a portion of the change in the total cost of loping, since the body must be decelerated with each step and must require additional energy cost with higher elevations of the body. Subjectively, the subjects all reported that if they had their preference, they would always choose a locomotive gait that could be performed with minimal excursion from the walking surface. This is in contrast with the comments of Langley Research Center personnel performing as subjects.

In a 1967 presentation to the Seventh International Symposium on Space Technology and Science, Margaria (Reference 15) reported that on a theoretical basis loping should not have a higher metabolic cost than running at the same velocity. Margaria did not provide data to substantiate his analysis. However, the data of Kuehnegger tends to give credence to Margaria's work (Reference 16). Kuehnegger's data, however, is based on tests performed with only two subjects. As a result, the comparisons between the metabolic costs for the two gaits are purely subjective comparisons. In contrast, the data of the current study were derived for six subjects, and the higher cost loping as compared to running at the same velocity was derived by statistical inference ($p<0.05$). This analysis indicated that there are only 5 chances in 100 that the difference is not real. Similar confidence statements on the reliability of the work of Kuehnegger on the adequacy of Margaria's model cannot be made.

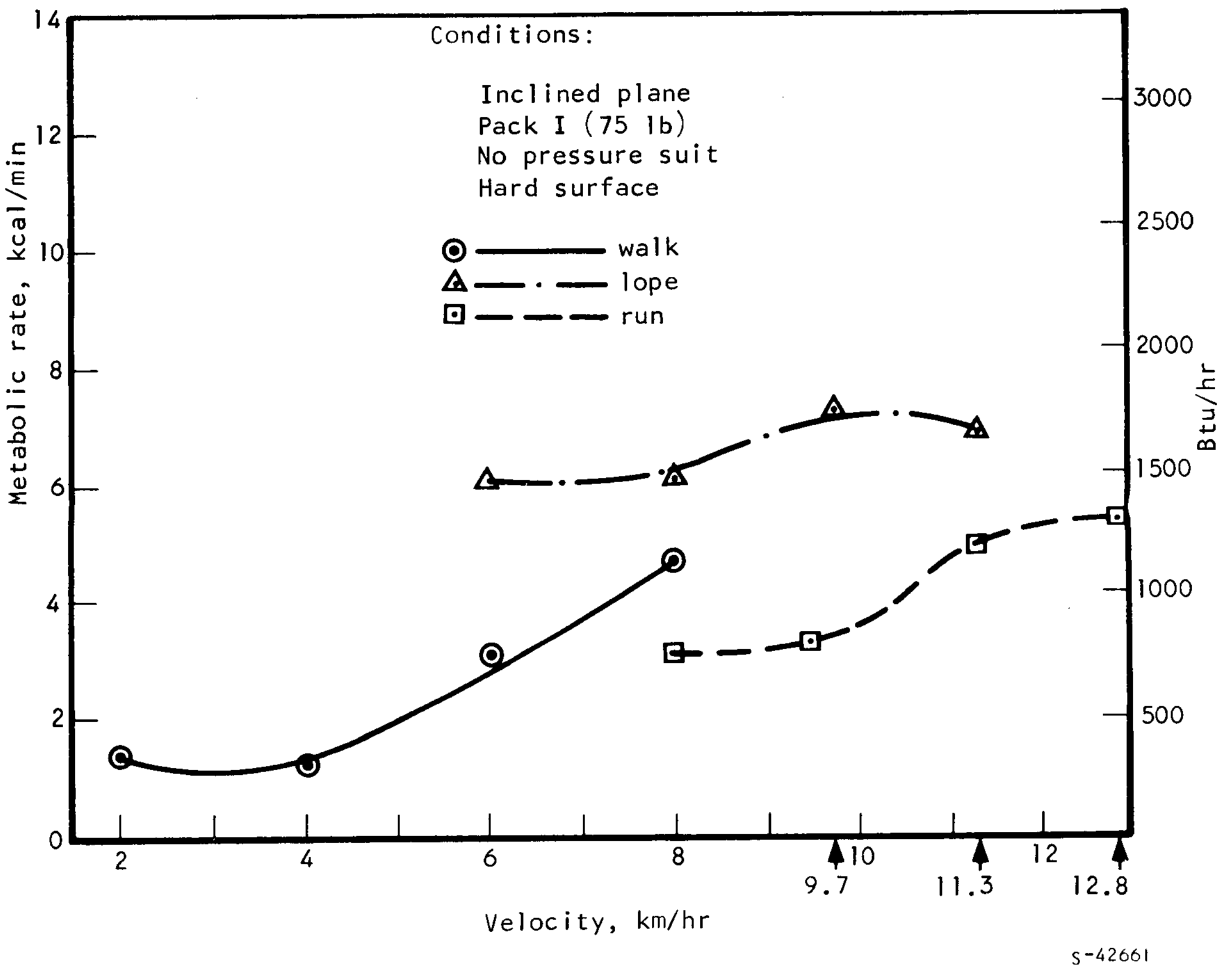

Figure 14. Steady-State Metabolic Rates for Locomotion on the Inclined-Plane Simulator, Pack I, Without Pressure Suit

The steady-state metabolic rate data are shown in Figures 15 and 16 for carrying the 240-lb (1-g) Pack II, with the resulting effect that the subject is carrying a 40-lb load at 1/6-g, but is still having to work against the inertial forces of the 240-lb mass. There were no differences between the initial Pack II data and that obtained in repeat testing.

Statistical inferences indicate a significant increase in metabolic rate with velocity for walking with Pack II ($p<0.01$). There were no differences with velocity for either the loping or running gaits.

Locomotion with Pack III required the subjects to transport a 400-lb (1-g) load which resulted in the subject carrying 66-2/3 lb in the 1/6-g environment while still affected by the inertial mass of 400 lb. Since only two subjects were used in these tests, and the variance between only two subjects tends to mask differences between mean values, the statistical analyses were not particularly meaningful.

A comparison of Figure 17, which shows the results of testing with Pack III, with Figure 16 indicates that except for the two highest lope and the two highest run velocities, the data between Packs II and III were quite similar. The points of inflection in the 8-km/hr lope and the 9.7-km/hr run curves would infer that these velocities were better for locomotion than the other lope or run velocities.

A multiple analysis of variance to test the effects of pack-carrying was performed on all the data for Packs I and II across the three gaits. Pack III was not included because those tests were performed by only the two special subjects. This analysis showed the velocity effects noted above within gaits and failed to demonstrate any differences between the data obtained for Packs I and II.

A multiple analysis of variance of the data for the two special subjects across the three gaits, with the three packs, showed that the energy cost for walking increased with velocity ($p<0.05$).

The lack of significant increases with load-carrying infers that the subjects were performing more work at essentially the same energy cost. Thus, the subjects were performing more efficiently. This effect was probably due to the subjects obtaining better traction as their total weight was increased by adding weight with a pack load. Since tne subjects were supported in the missing degrees-of-freedom in the inclined-plane simulator, the inertial effects of carrying these loads are not clear.

The data for the metabolic cost of locomotion in the TOSS are presented graphically in Figure 18. Steady-state metabolic rates were increased by velocity within the walking gait ($p<0.01$), but were not changed by velocity within the loping or running modes.

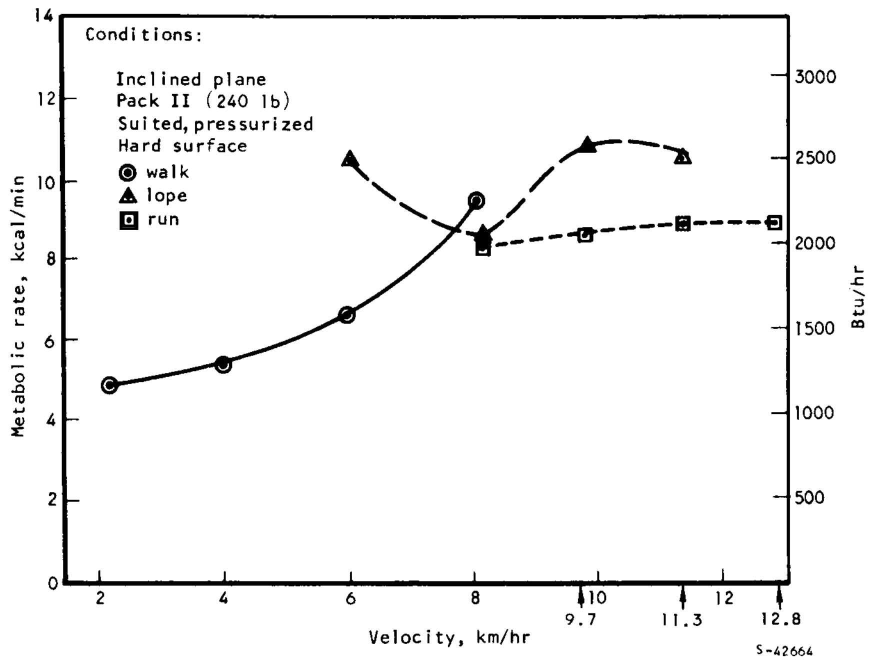

Figure 15. Steady-State Metabolic Rates for Initial Trials on the Inclined-Plane Simulator, Pack II

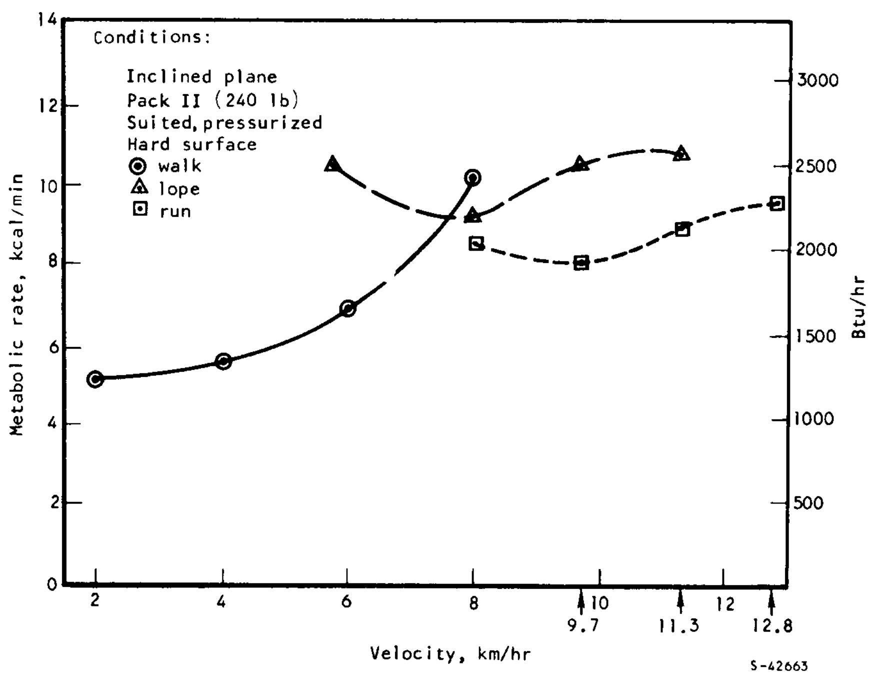

Figure 16. Steady-State Metabolic Rates for All Trials (Pooled Data) on the Inclined-Plane Simulator, Pack II

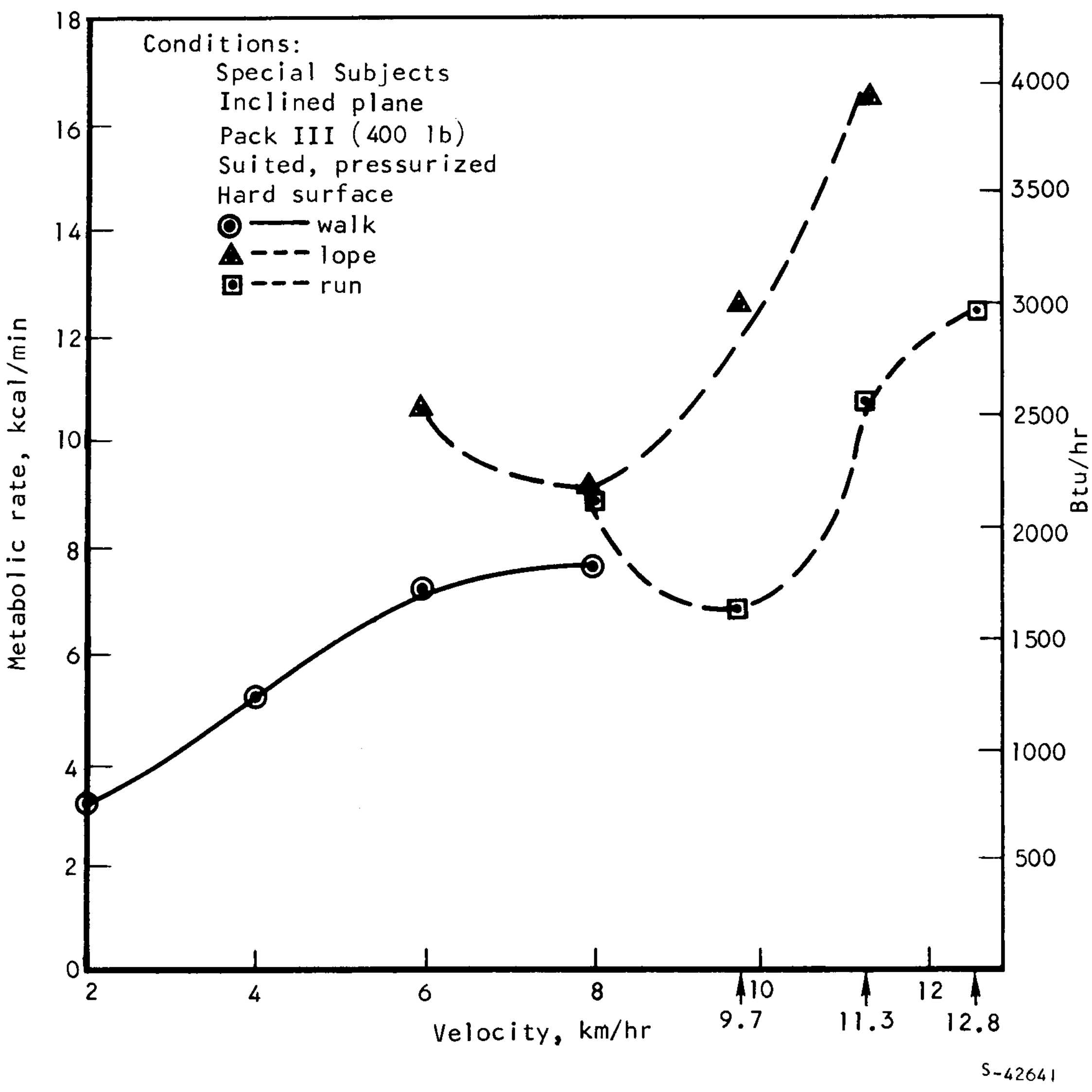

Figure 17. Steady-State Metabolic Rates for Locomotion on the Inclined-Plane Simulator, Pack III

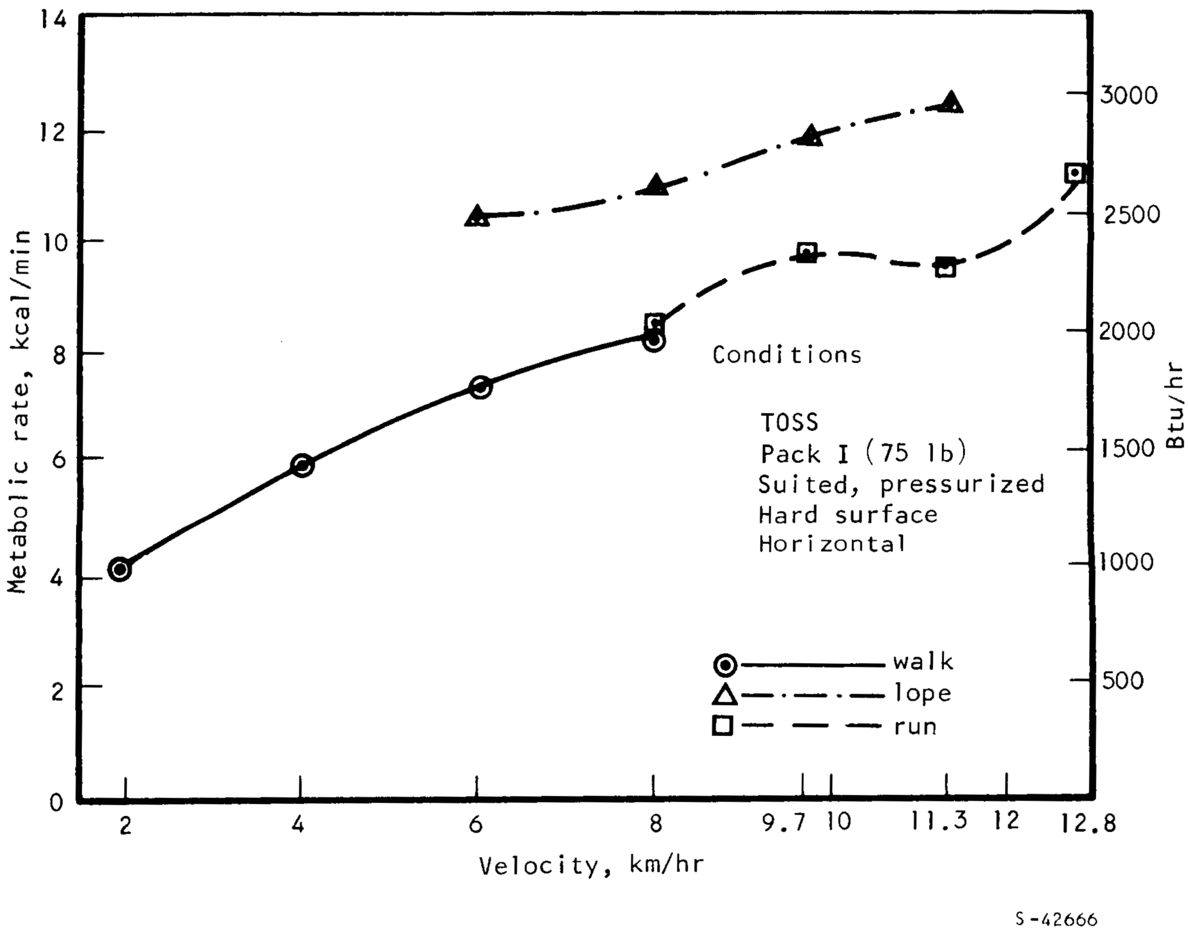

Figure 18. Effect of Gait and Velocity on Steady-State Energy Cost of Locomotion with the TOSS Simulator

It is interesting to note that the curve in Figure 18 for walking leads directly into the running curve, and the total points could be fitted with a straight line. This was also noted on the Pack I data for the inclined plane. Loping values are completely above this curve, indicating the very high energy cost for performing the loping gait with TOSS.

The energy costs for ascending and descending slopes on a hard surface with the inclined-plane and TOSS simulators, and on simulated smooth lunar soil in the TOSS simulator are shown in Figures 19, 20, and 21. For locomotion on the inclined-plane simulator (Figure 21), the energy costs for ascending a 7.5-deg slope increased with velocity ($p<0.01$). There was no change with velocity for descending the same grade. Energy cost for uphill locomoti,n was higher than for downhill locomotion ($p<0.01$).

The energy required for traversing a 15-deq slope increased with velocity ($p<0.01$) and was higher than for ascending a 7.5-deg slope ($p<0.05$). No subject was able to traverse the 15-deg slope at 8 km/hr. The energy cost for uphill locomotion was higher than for downhill. No difference was noted in downhill energy costs for either the 7.5-, 15-, or 30-deg slopes.

The metabolic costs for ascending and descending 7.5, 15, and 30 deg on a hard surface slope with the TOSS simulator are shown in Figure 20. A velocity effect increasing the metabolic cost of locomotion was noted between all 4 uphill velocities at 7.5 deg ($p<0.01$). An increased cost across all velocities was noted for downhill locomotion on both the 15-deg slope ($p<0.05$) and the 30-deg slope ($p<0.05$). The 2- and 4-km/hr ascending velocities at 15-deg were significantly different ($p<0.01$). Comparisons between requirements to navigate each slope showed that the oxygen needs for climbing a 15-deg slope were higher than for the 7.5-deg slope ($p<0.01$). Traversing downhill slopes indicated that the 7.5-deg slope required more energy than either the 15-deg or 30 deg slope ($P<0.01$), and there was no difference between the 15-deg and 30-deg data. Climbing uphill had a higher cost than going downhill at all velocities with both slopes ($p<0.01$).

Figure 20 summarizes the slope data for tests performed with the TOSS simulator and is comparable to the presentation made in Figure 19 for the inclined-plane simulator tests. The effects described for Figure 20 fit equally well to these data, with only the magnitude of the data being different. The downhill data are lower than the horizontal data, which in turn are lower than for the ascending modes.

The differences between the data from the subjects in each of the simulators are demonstrated by the locomotive modes they could not complete. On the inclined-plane, the subjects were able to accomplish all of the descending modes and the 7.5-deg and 15-deg ascending modes. When attempting to ascend the 30-deg slope on the inclined plane, the subjects were able to complete the 2- and 4-km/hr velocities with little difficulty. At the 6-km/hr velocity, however, only one subject completed the standard 14-min exercise period. The

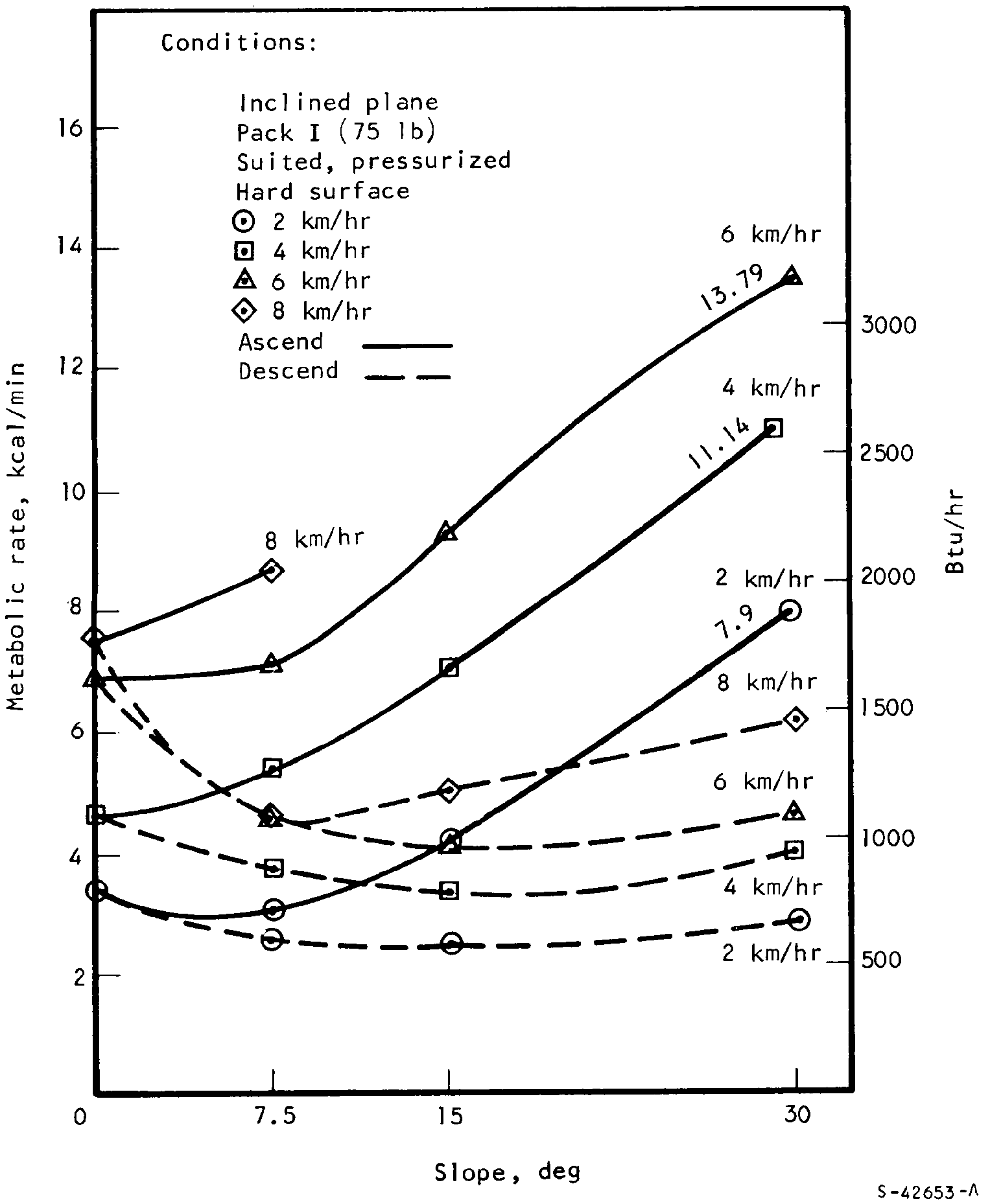

Figure 19. Summary Curves of Steady-State Energy Cost for Locomotion on Slopes with the Inclined-Plane Simulator

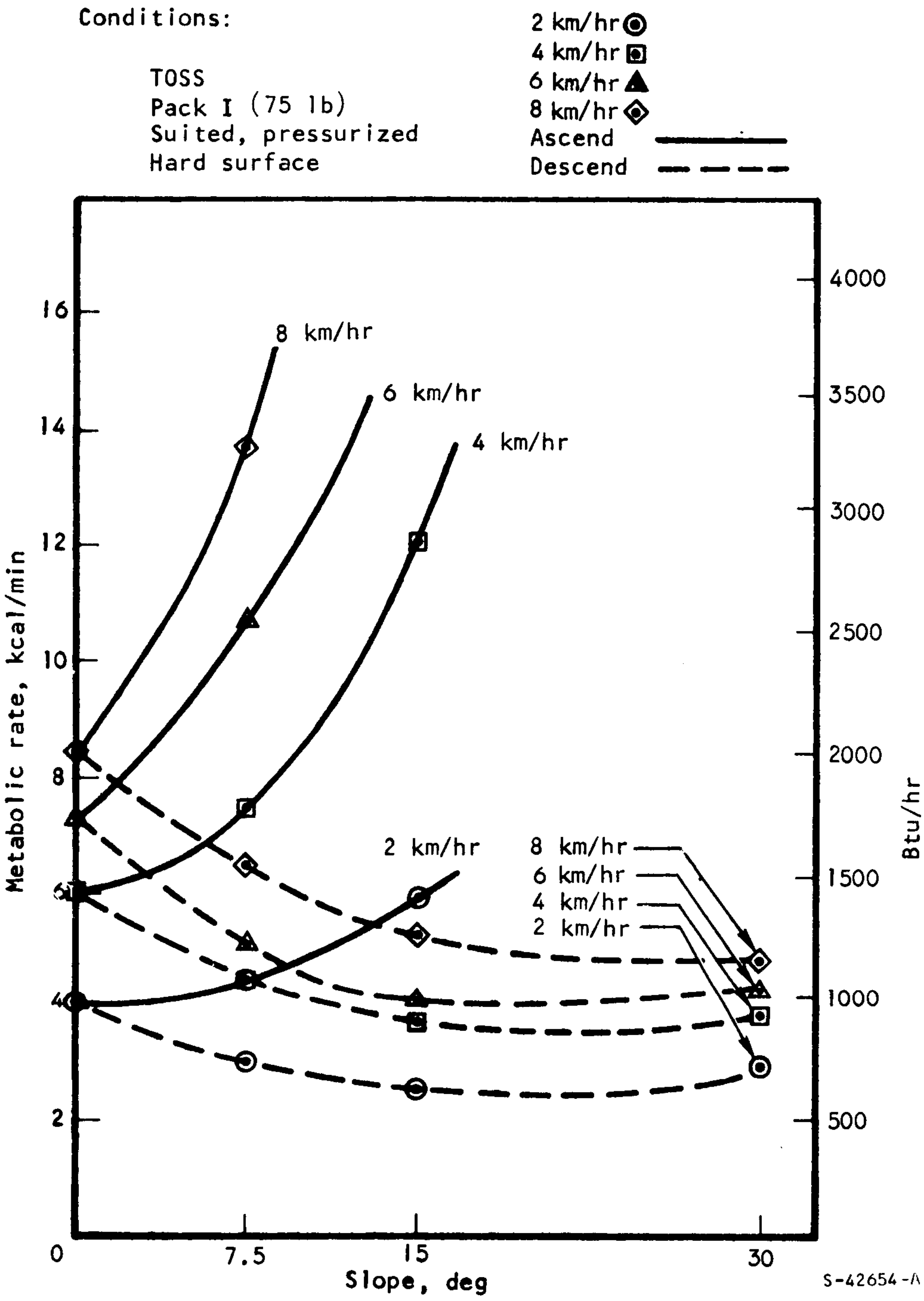

Figure 20. Summary Curves of Energy Cost for Locomotion on Hard-Surface Slopes, TOSS Simulator

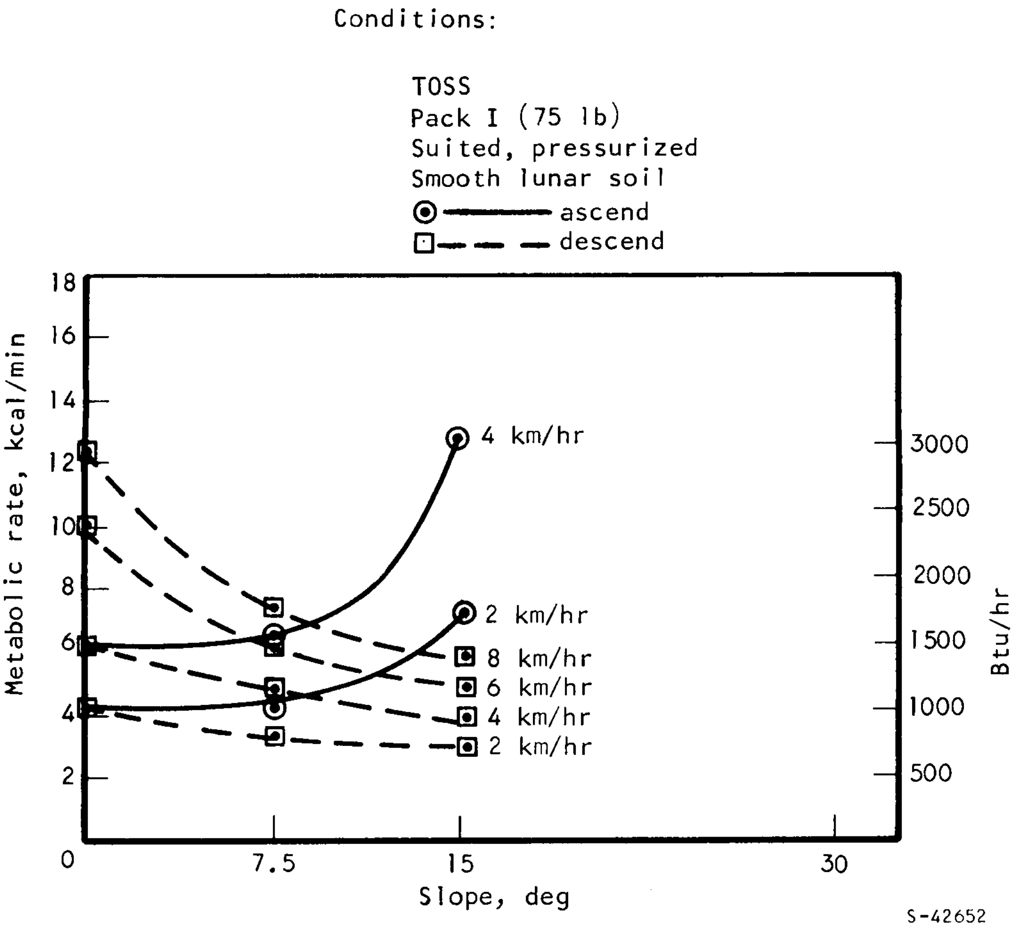

Figure 21. Summary Curves of Energy Cost for Locomotion on Slopes; Smooth Lunar Soil, TOSS Simulator

other subjects completed between 2 and 5-1/2 min of exercise before the tests were stopped because their heart rates had exceeded the established limits for safety. At 8 km/hr, none of the subjects were able to perform on the 30-deg slope. The major reason for this was the inability of the subject to maintain traction and position (inability to keep up) on the treadmill. On the other hand, with the TOSS simulator, the subjects were able to perform all of the descending-slope tests and the 7.5-deg ascending tests. On a 15-deg ascending slope, the subjects were able to perform only the 2- and 4-km/hr velocities. In the 6- and 8-km/hr tests, they each exceeded a heart rate of 180 beats/min prior to reaching a steady-state condition. Only one of the six subjects could perform the 2-km/hr velocity while ascending the 30-deg slope, and he was only able to maintain the exercise for 5 min before his heart rate reached test cutoff limits.

Figure 21 shows the comparative data for self-locomotion with the TOSS simulator and smooth lunar soil conditions, on a horizontal surface and on ascending and descending slopes. Metabolic costs increased with velocity for the horizontal tests ($p<0.01$). For 7.5- and 15-deg ascent, the cost was increased by velocity ($p<0.05$), while for descending modes, velocity increased the cost at 7.5 and 15 deg ($p<0.05$). Energy costs for descending modes were lower than for either locomotion on a horizontal surface ($p<0.01$) or the ascending modes ($p<0.01$). The uphill values at 7.5 deg were not different from the data on the horizontal smooth lunar surface, but the 15-deg values were different from the data obtained for tests both on the 7.5-deg slope and in the horizontal plane ($p<0.01$).

Testing with the TOSS simulator included three surface conditions: hard, simulated smooth lunar soil, and simulated coarse lunar soil. The multiple analysis of variance used to compare the values obtained from testing with the three surfaces showed that the simulated smooth lunar surface effected a greater increase in metabolic rates than did the hard surface ($p<0.01$). This analysis also revealed an interaction between velocity and slope incline ($p<0.01$) and between velocity and slope direction ($p<0.01$) for the hard surface.

These interactions are descriptive of the curvilinear relationship shown in Figure 20. A similar interaction was found between velocity and slope with testing on the smooth soil. The resulting curvilinear relationship is shown in Figure 21. Tests with the simulated coarse lunar soil showed an increase in energy cost when compared to the same tasks on the hard surface ($p<0.01$). There were no differences, however, between the values for testing on the smooth and coarse surfaces.

Walking or sprinting on a horizontal hard surface resulted in metabolic rates which were not different for the inclined-plane and TOSS simulators. Loping produced a higher energy cost with TOSS than with the inclined-plane simulator ($p<0.05$).

Locomotion on the various slopes pointed out other effects related to the simulators. Ascending and descending a 7.5-deg slope produced metabolic rates that were systematically higher for TOSS than for the inclined-plane simulator ($p<0.01$). The presence of the roll and yaw degrees-of-freedom with TOSS allowed motion in these planes and may affect the cost of locomotion. Statistical treatment pointed out the significance of the interaction between direction on the slope and the simulator, indicated by the data plots in Figures 20 and 21. Locomotion on the 15-deg slope again produced higher values on TOSS than on the inclined-plane simulator ($p<0.01$). The interactions at 15 deg, however, were very pronounced, with interactions being found between velocity and simulator ($p<0.05$), velocity and slope direction ($p<0.01$), and simulator and slope direction ($p<0.01$), and finally an interaction between velocity, slope direction, and simulator ($p<0.05$).

The effects noted here are mainly a function of differences between data for the two simulators for uphill slope locomotion. Locomotion downhill on slopes up to 30 deg showed no differences for tests performed on the two simulators. Uphill slopes resulted in exceptionally higher data with the TOSS simulator than with the inclined-plane simulator ($p<0.01$).

The general absence of differences between the data from the simulators was rather unexpected. This lack of difference is in direct conflict with data reported previously with a counterweight 6-deg-of-freedom simulator (References 4 and 17). The absence of differences between the data for the two simulators may be due in part to the highly immobile suit used in this study. If one of the relatively mobile Apollo suits had been used, it is probable that many more differences would have been noted, including information on the effects of the presence or lack of the various degrees-of-freedom.

In addition to analysis of the steady-state metabolic rate data, the time course changes in metabolic rates over a test mode were evaluated. Figure 23 shows the typical form of the changes in metabolic rates with time. The curves shown are developed as the average of the data for each interval for the six subjects studies. The curves have been faired to conform to the theories of physiology and are representative of the data. When several of the manually faired curves were checked against a computer-fitted curve, there were no appreciable differences; the manually faired curves were determined acceptable for graphing purposes.

The total energy requireo to perform each task was determined by integrating the area under each metabolic-rate-vs-time relationship curve as the average over the six subjects.

Areas were determined using Simpson's rule of integration which states that the area under a curve can be estimated by adding up the area of polygons fitted under the curve. Thus, the total area (energy) for the typical energy cost curve shown in Figure 22 is the sum of the area under the portion of the curve from the start of exercise (2 min) to the end of exercise (16 min) noted as "a," plus the logarithmic decay portion of the curves during recovery, noted as the cross hatched area from the 16th min to the 22nd min.

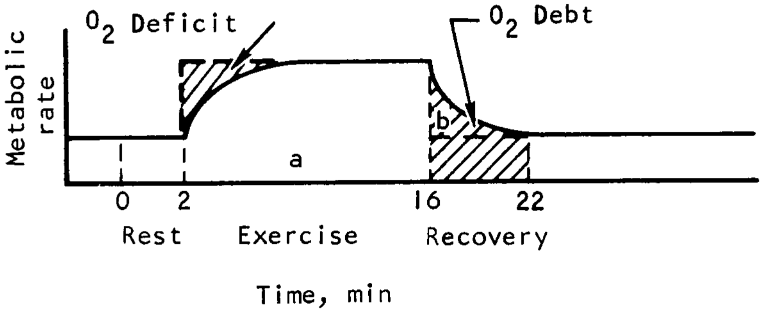

Figure 22. Typical Total Energy Cost Curve

Table 5 presents typical observations for total energy and proportional energy required for locomotion at 1/6 g carrying a 75-lb pack load (12.5 lb at 1/6 g) on the inclined plane simulator with the treadmill horizontal. The data represent the 3 locomotive gaits used, over the 12 velocities studied. Column I contains the total energy required during the work phase and the recovery period (total area under the curve from the 2nd to the 22nd min (Figure 22). It is an average of the six subjects studied. Column II gives the average energy used by the subjects during the work period (area a," under the curve from the 2nd to the 16th min). Column III shows the average of the total energy during the recovery period following exercise (the cross-hatched area under the curve from the 16th to the 22nd min). Area "b," the so-called oxygen debt, represents the energy required to repay the oxygen deficit acquired during the work phase. Column IV gives the ratio of post exercise metabolism to the total energy requirement (ColumnIII/Column I). Column V shows the average total energy cost of the work performed (Column VI x 14 min). Column VI gives the average energy cost per minute for the exercise task, (area "a" plus "b") divided by 14 min. Finally Column VII shows the actual average steady-state metabolic rate measured during the last portion of the exercise period.

Several other facts can be derivea from the table of total and proportional energy (Table 5). The fourth column of the table shows that the ratio of the oxygen repayment period energy to the total energv for performing the exercise is relatively constant even though the metabolic cost is increased three to four times. This phenomenon is not understood at this time. Another factor of importance in the table lies in the comparison of the fifth and sixth columns.

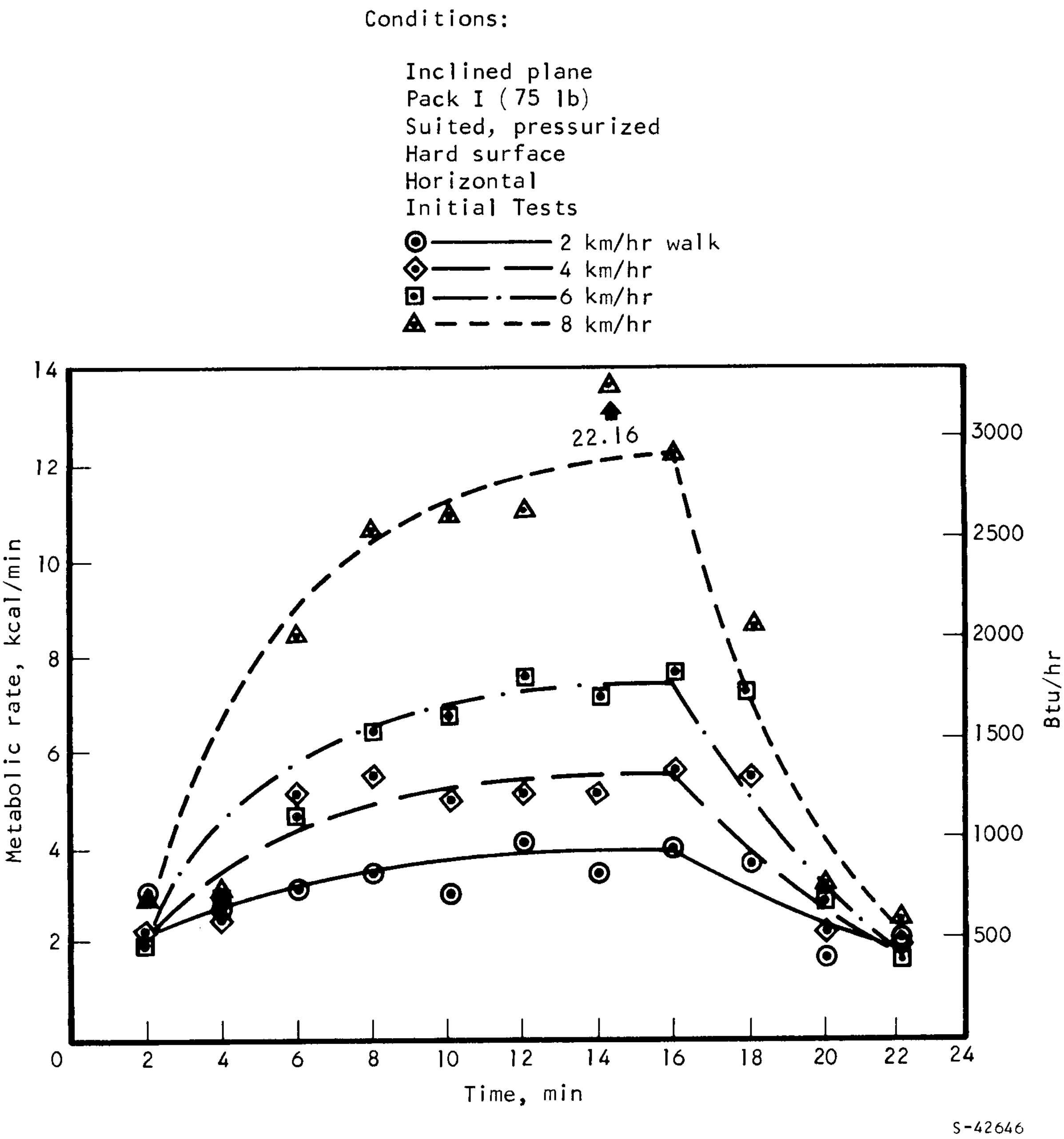

Figure 23. Time Course Changes in Metabolic Rates for Walking on the Inclined-Plane Simulator

TABLE 5

TOTAL ENERGY AND PROPORTIONAL ENERGY REQUIREMENTS

LOCOMOTION ON HORIZONTAL INCLINED-PLANE SIMULATOR
WITH PACK I AND PRESSURIZED SUIT

Gait	Velocity, km/hr	Average total energy, kcal (Col I)	Average energy for work, kcal (Col II)	Average energy post-work, kcal (Col III)	Ratio of Col III/Col I (Col IV)	Total Energy During Work, kcal (Col V)	Average energy cost, kcal/min (Col VI)	Steady-state energy cost, kcal/min (Col VII)
Walk	2	62.90	47.78	15.12	0.240	645.5	3.25	3.67
	4	83.49	62.75	20.74	0.248	71.7	5.12	4.63
	6	99.65	74.18	25.47	0.256	90.0	6.43	6.42
	8	168.69	134.36	34.33	0.203	150.3	10.93	13.32
Lope	6	126.09	98.86	27.23	0.216	113.0	8.07	7.63
	8	153.26	122.06	31.20	0.204	142.5	10.18	9.96
	9.7	148.88	119.45	29.43	0.198	133.7	9.55	10.08
	11.3	179.45	143.64	35.81	0.200	173.6	12.40	12.31
Run	8	128.51	100.50	28.00	0.218	116.6	8.33	7.57
	9.7	120.58	95.30	25.28	0.210	108.2	7.73	9.56
	11.3	166.15	132.97	33.17	0.200	153.0	10.93	9.99
	12.8	181.12	145.66	35.46	0.196	167.6	11.97	11.37

The fifth column is derived by dividing the total energy required to perform each task by 14 (the number of minutes the subjects exercised). This provides a measure of the average energy per unit time (kcal/min) used to perform each mode and is comparable to the steady-state metabolic rates shown in the sixth column. Comparison of the values shown in these columns indicates that the total energy for performing a test can be evaluated simply by measuring the steady-state value and multiplying by the total time the exercise is performed. It must be noted that this consideration would only hold for a task repeated long enough for the individual to reach a true steady-state. Table 5 is replicated for all such data in the detailed report of this program.

Although it was initially thought that the energy cost of locomotion would be increased on the lunar surface (Reference 18), the use of artificial-gravity simulators has proven it will be less (References 4, 5, 6, and 19). Current test results support this latter thesis.

Figure 24 presents most of the data available, including those obtained by this effort on the energy cost of locomotion during simulated 1/6 g in mufti. The summary data for the 1-g data is prepared after Passmore and Durin (Reference 20). The curves shown are trend lines drawn by visual averaging. It is readily apparent that the lower curve drawn for the 1/6-g data is a reasonable fit for all the data from the three different test series. It is significant that the data for these tests were obtained by different techniques.

The data shown in Figure 24 dramatically point out the decrease in metabolic rate with decreased gravity. When considering locomotion in the reduced-gravity environment, several parameters such as gait and traction are relevant. A simplified view of the problem is to consider locomotion as analogous to walking while carrying weights. As gravity is reduced, the weight carried is reduced concomitantly, and the energy required for comparative locomotive tasks is similarly reduced. Wortz (Reference 1) described a series of experiments that confirmed the above by adding weights to the subjects to return them to their 1-g equivalent weight with metabolic rates that were similar to 1-g tests. These results substantiate the concept that weight reduction is a primary mechanism in producing metabolic costs for locomotion that are lower at reduced gravity than at 1 g.

The factors of traction are also important. This is amply demonstrated by a significant decrease in the efficiency of locomotion even though the total energy expenditure is dramatically reduced with reduced gravity. This relationship was cogently illustrated by the data of Robertson and Wortz (Reference 16), which show that the energy cost per kg of body weight at lunar gravity is significantly higher than for comparative tasks at 1 g, indicating a substantial reduction in efficiency.

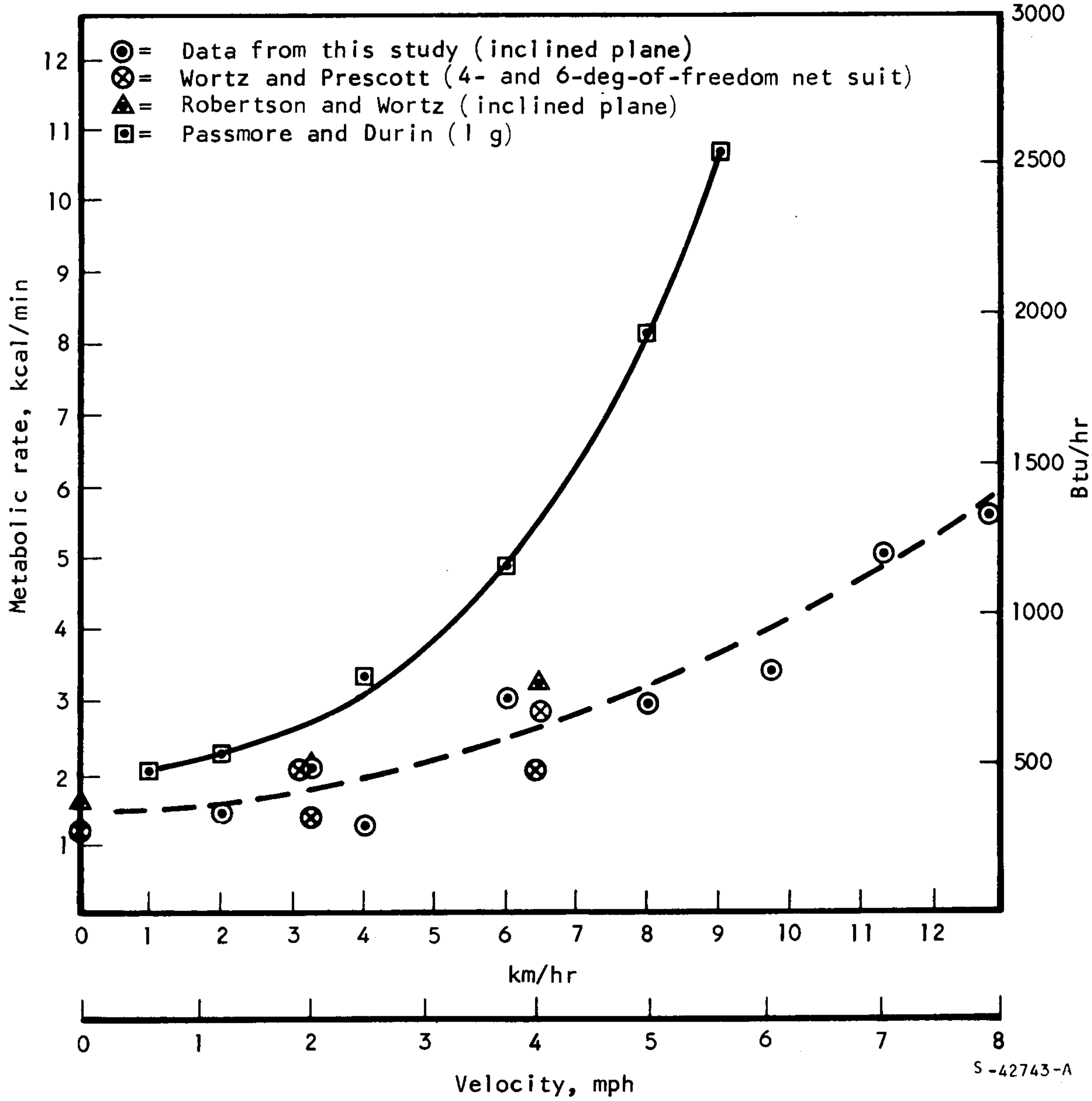

Figure 24. Energy Cost for Walking and Running at 1 G and 1/6 G, Horizontal, Without Pressure Suit

Figure 25 summarizes the data available for the metabolic cost of locomotion in various pressure suits at 1 g (References 17, 21, and 22). These data are shown to indicate the mobility characteristics of the various suits and for comparisons with the 1/6-g data shown in Figure 26. Three of the suits characterized in Figure 25 were developed as early-generation Apollo suits. These suits are the Litton RX-2A, the International Latex Corporation pre-prototype suit ILC, and the A5L. The G-2C manufactured by David Clark, the ILC, and the A5L suits all represent approximately the same weight penalty to the subject. In contrast to this, the RX-2A weighed 83 lb, a penalty of approximately 50 lb over other suits.

The curves shown for these data are faired curves. The values are so diverse between suits, however, that certain conclusions can be drawn. First and most important, the development of mobile joints has lead to the evolution of suits which allow locomotion at greatly reduced metabolic cost. The A5L, the latest ILC suit, is by far the most mobile design based on the present criteria. The G-2C suit is the least mobile of the soft-suit concepts. The RX-2A is a hard suit, weighing 83 lb. The extremely high metabolic cost of locomotion with the RX-2A suit was a function of carrying that excessive weight, rather than being related to the mobility of the suit.

Comparing the shirt-sleeve data of Passmore and Durin (Figure 24) with the suited data of Figure 25 at the 1- and 2-mph velocity intervals shows that the three relatively rigid suits increased the metabolic cost 250 percent. The more mobile A5L suit increased the cost of locomotion by only 150 percent. It should also be noted that the data for suited subjects reached 8.4 kcal/min (2000 Btu/hr) at a velocity of only 2 mph, while in mufti this level was not reached until 5 mph.

Figure 26 reviews the metabolic cost of locomotion in pressurized suits in simulated lunar gravity environment (References 5 and 17) including the data from this effort. When compared to the 1-g data from Figure 26, the decreased total energy cost of locomotion for suited subjects is obvious. The evaluation of the shirt-sleeve data shown in Figure 24 explains this decreased energy cost. When compared to the shirt-sleeve data for 1/6-g tests in Figure 24, the data for suit tests show similar increments in metabolic costs as reported for the 1-g data as a function of the suit worn.

The upper curve in Figure 26 presents the data contained elsewhere in this report for both the inclined-plane and the TOSS simulators. As shown by the fit of the faired curve and the analysis of variance, there is no statistically significant difference between the data from the two simulators with the Gemini pressure suit. From these data, it must be concluded that the Gemini pressure suit imposed the greatest restriction to locomotion and incurred the highest metabolic cost of the suits shown here.

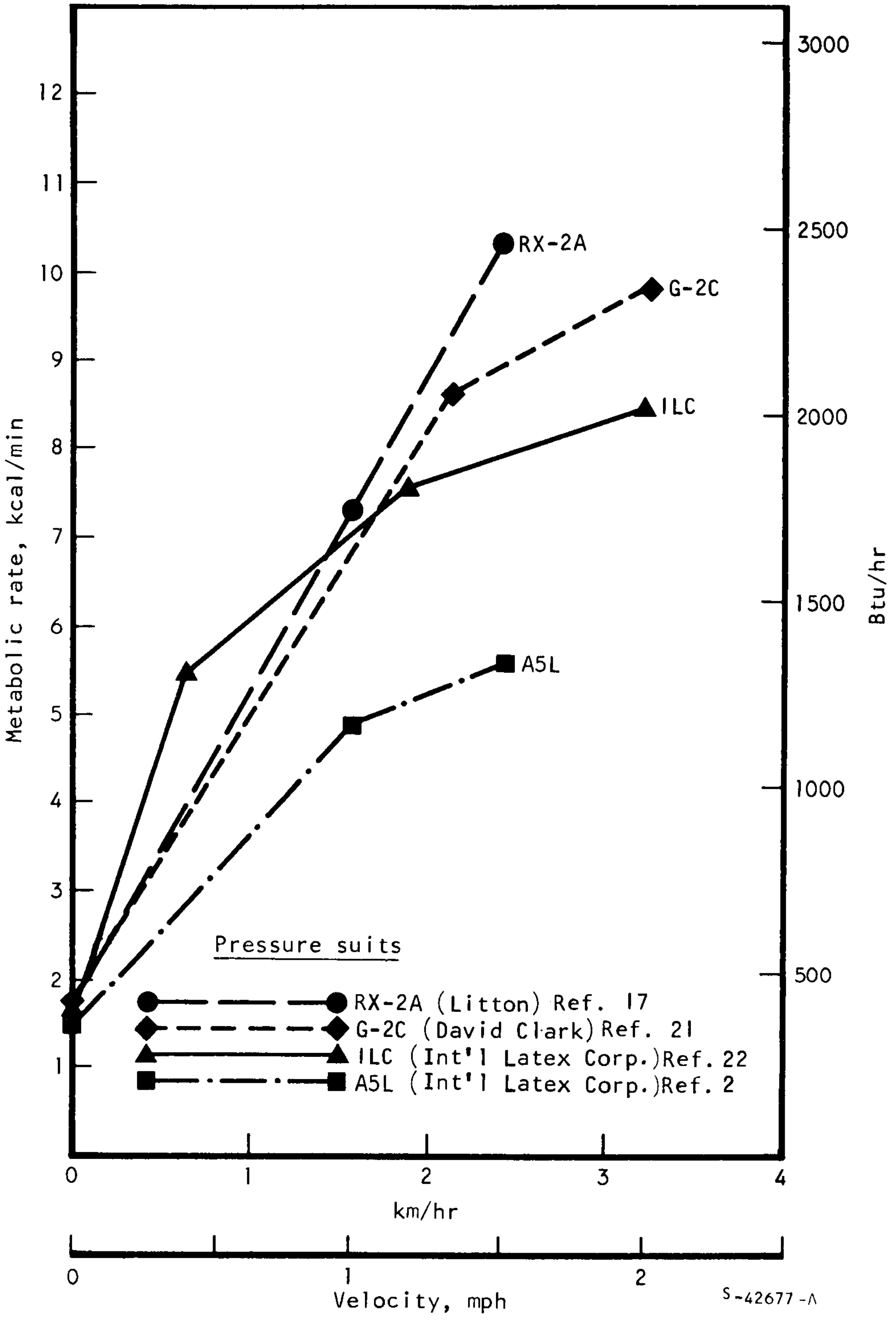

Figure 25. Energy Cost for Walking at 1 G, Horizontal, Various Pressurized Suits (No Pack)

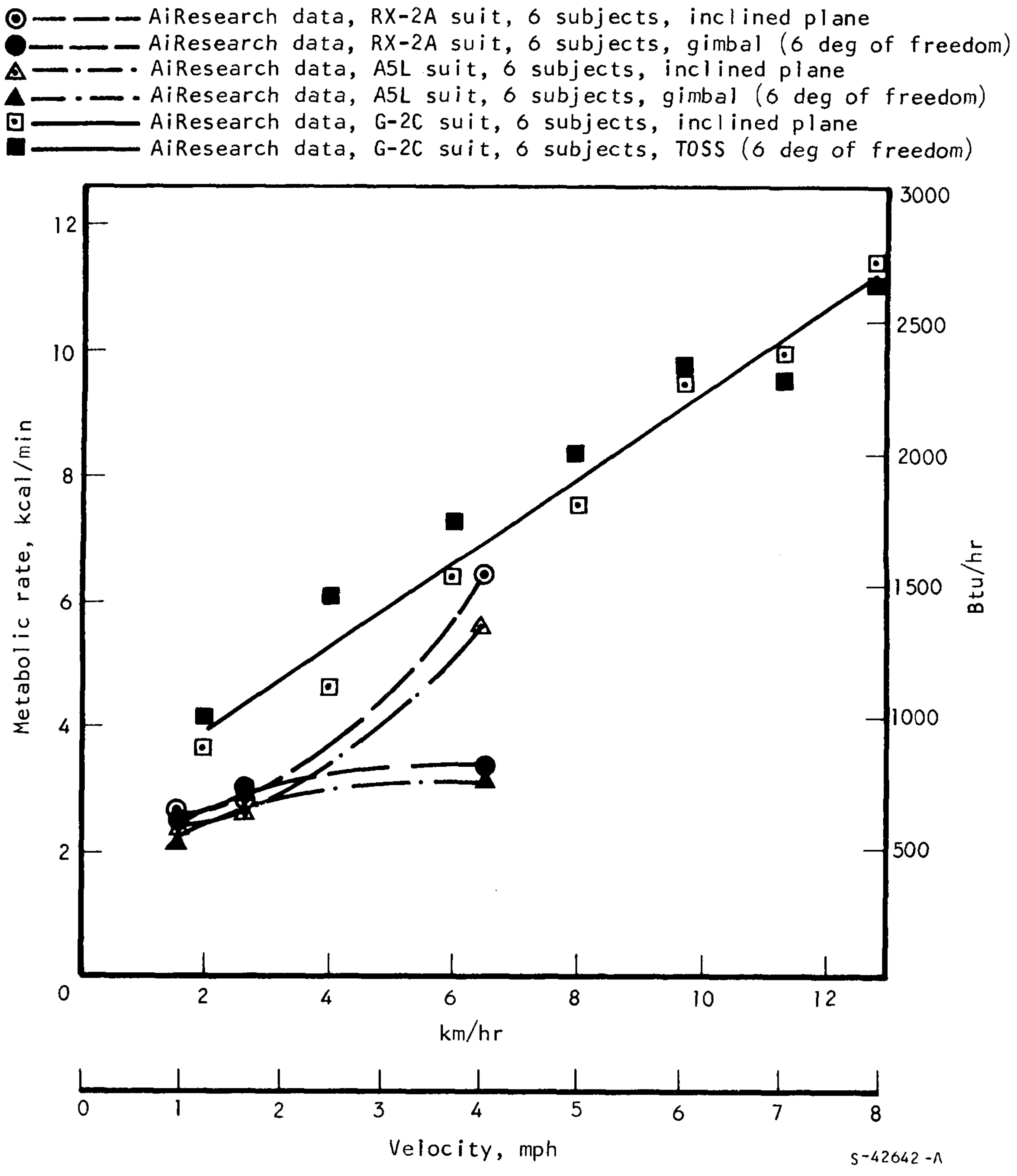

Figure 26. Energy Cost for Walking and Running at 1/6 G, Horizontal, Pressurized Suits, on a Level Hard Surface

The data for the A5L and the RX-2A suits have been described previously (Reference 17). In comparing data for the Gemini suit, the greater mobility of these suits is apparent. The differences between the inclined-plane and the gimbal data were originally attributed to the missing degrees-of-freedom in the inclined plane requiring energy (References 17 and 18). The lower data with the gimbal, shown in Figure 26, may have resulted from the subjects using the counterbalance of that simulator to their mechanical advantage. The conflicting evidence on the effects of degrees-of-freedom is not fully understood.

Relationship Between Heart Rate and Metabolic Rate

To evaluate the effect of data dispersion on the predictions of metabolic rate from heart rates, a large population of values was prepared. Figure 27(A) is a plot of 500 data points relating heart rate and metabolic rate. The mean ±1 standard deviation over the 500 heart rates is 117.6 ±30.7 beats/min, while for the metabolic rates the value was 7.01 ±3.56 kcal/min. The central solid line is the regression line with respect to y and is expressed by the equation $y = 69.24 + 69.1x$. The broken line on either side of this regression line is the value of two standard deviations from the mean regression lines. The regression line with respect to x is shown by the broken center line and is expressed by the equation $x = -2.11 + 0.08y$; the solid lines are ±2 standard deviations from this line.

A correlation of 0.80 was found for the relationship between heart rate and metabolic rate. This relatively high correlation in the presence of the obvious dispersion of data points is a result of the extensive range of both heart rate and metabolic rate.

A complete analysis of these curves yields a standard error in determining the heart rate from a given metabolic rate of 18.42 beats/min. The standard error of metabolic rate, given a heart rate, equals 2.14 kcal/min. These standard errors represent the utility of these data in predicting the value of either variable, having the value of the other. Individual subject variability is illustrated in Figure 27(B). The technique of predicting metabolic rate from heart rate leaves much to be desired.

Summary of Observations on the Physiological Parameters

The following list summarizes the general observations on the physiological variables evaluated during this program:

1. Metabolic rates for locomotive tasks are lower at simulated lunar gravity than at 1 g.

2. The forms of the curves for changes in metabolic rates with time conform to accepted physiological principles.

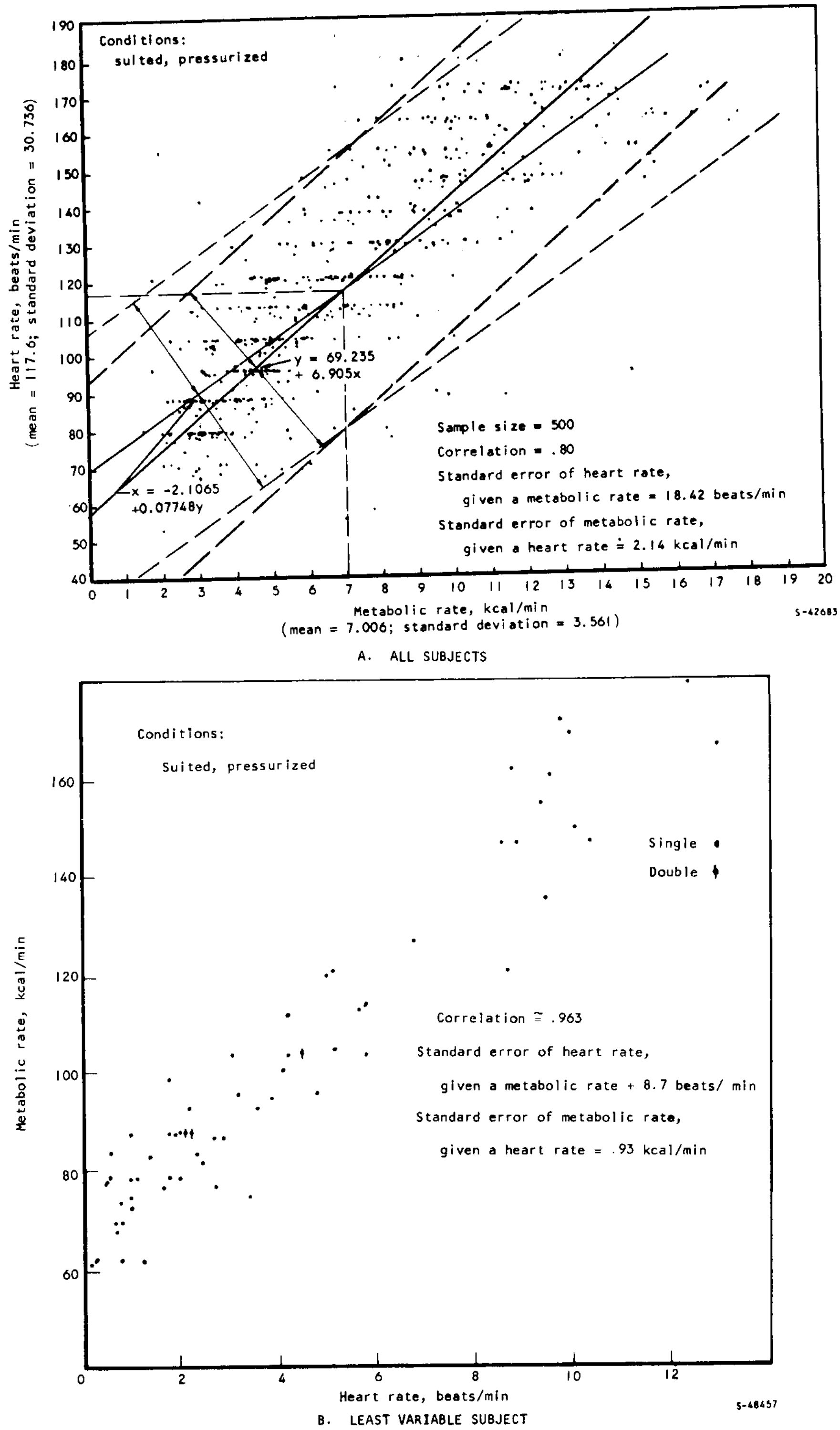

Figure 27. Plot of Data Points Relating Heart Rate and Metabolic Rate

3. The total energy cost of locomotion on the inclined-plane simulator increased with velocity for all gaits. There were no statistically significant differences in energy expenditure between gaits for performing a given velocity where such data could be compared.

4. As expected, the total cost of locomotion in mufti on the inclined-plane simulator is lower than for tests with pressure suits. With subjects in shirt sleeves, loping had a higher energy cost than the other locomotive gaits. The absence of differences for loping in a suit must result as an effect of the suit constraints masking this effect.

5. Total metabolic costs for load-carrying on the inclined-plane simulator increased as a function of velocity. However, there were no differences within gaits for the three loads carried. Thus, more work was being performed with the same energy, indicating an increase in efficiency as a result of increased weight. This increased efficiency may result from the increased traction gained by the added weight as the load is increased.

6. Total energy costs were higher for ascending slopes than for horizontal locomotion. Energy costs for ascending slopes and for horizontal locomotion were higher than for descending. An increased load further increases the cost of locomotion on slopes.

7. Testing on the TOSS simulator showed an increase in total energy as a function of velocity. In addition, the energy cost for the loping gait was higher than for either walking or running at the same velocities. This is in direct contrast to the inclined-plane results.

8. Ascending slopes in the TOSS simulator increased total energy requirements, which were further increased with each increase in velocity. Although velocity increased the total energy for descending slopes, the energy cost was lowered by descending slopes within a given velocity. The costs for going downhill were lower than for horizontal locomotion.

9. Subjects could not negotiate the 30-deg uphill slope in the TOSS simulator except at 1 km/hr, and then only four subjects could accomplish the test. None of the subjects could climb the 15-deg slope at 8 km/hr. In each case where the required mode could not be performed, the subject could not develop the required traction to keep up with the treadmill. Since these tests mandated constant-velocity locomotion, however, these data should not be interpreted as indicating that slopes up to 30 deg could not be negotiated. The conclusion that can be drawn is that locomotion on steep slopes has extremely high energy cost and should be avoided.

10. Locomotion on a simulated lunar soil increases the energy cost of locomotion over that observed with a normal treadmill surface.

11. Ascending or descending slopes on the simulated smooth lunar soil had a higher cost than the same modes performed on the hard surface.

12. The increased cost of locomotion on the simulated lunar soil results from the loss of traction due to shearing of the soil. Similar results were noted for horizontal locomotion on the simulated coarse lunar soil.

13. T‚e ratios of oxygen repayment to total oxygen cost for a given mode were reasonably constant even though the total metabolic cost increased three to four times. This phenomenon is not understood at this time.

14. The average energy per unit time in kcal/min closely corresponds to the steady-state values measured for each task. This would indicate that the total energy for a task can be simply evaluated by measuring the steady-state value and multiplying by the total time the exercise is performed. It must be noted that this consideration would hold only for a task repeated long enough for a steady-state condition to be reached.

15. Steady-state metabolic costs are significantly increased by velocity. Comparisons of requirements between gaits to perform the same velocity on the inclined-plane simulator indicate that based on metabolic rate alone, there would be little choice between gaits with a 75-lb (1g) pack.

16. Loping in mufti revealed a much higher steady-state cost than other gaits at the same velocity. This is undoubtedly due to the added cost to perform antigravity work.

17. There were no statistically significant differences between carrying the 75-lb or 240-lb packs on the inclined-plane simulator. Lower rates were noted with the 400-lb pack. These findings support the thesis of better efficiency of work due to increased traction as a function of increased weight.

18. All subjects could perform at velocities ranging from 8 to 12.8 km/hr on the hard surface with the inclined-plane simulator for periods of 1 hr either suited or in mufti at 1/6 g.

19. Fatigue tests of 4-hr duration were attempted while suited and pressurized, and only one subject was able to complete a 4-hr test. This test was run at 9.7 km/hr on a horizontal hard surface. The extreme fatigue of the subject indicated that such modes should be avoided.

20. Steady-state metabolic costs were higher for ascending slopes than for horizontal locomotion. Downhill locomotion decreased the metabolic cost below that required for horizontal locomotion.

21. The steady-state data with the TOSS simulator showed higher energy cost for loping than for other gaits at the same velocity.

22. Differences in data for walking and running on a horizontal hard surface were not statistically significant for the inclined-plane or the TOSS simulators. Loping produced a higher energy cost with the TOSS simulator than with the inclined-plane simulator.

23. Locomotion on the uphill slopes showed the TOSS simulator differing from the inclined-plane simulator because of the subjects' stability problems. Downhill slopes did not produce any differences between simulators.

24. The general absence of differences between simulators in this study may have resulted from the use of the highly immobile pressure suit used in these tests. Tests must be performed in more mobile suits or in mufti to properly evaluate any differences between simulators.

25. Testing with pressurized suits at 1 g will tend to differentiate between the suits, based on mobility, as long as the total system weight is similar.

26. The mobile A5L suit was shown in other studies to increase the cost of locomotion by 150 percent over the shirt-sleeve condition. In this study, the more rigid Gemini suit increased the metabolic rate by 250 percent.

27. Heart rates are positively correlated with metabolic rates, $r = 0.80$. Using the regression technique of evaluating metabolic rates from heart rates, the accuracy that could be obtained from 500 observations was ± 2.14 kcal/min for any measured heart rate. The utility of this technique is limited, and estimation of metabolic rates from heart rates has basic inherent errors.

28. Heart rate and minute ventilatory volume are positively correlated with $r = 0.79$.

29. Respiratory rates were of little use in these studies, other than to monitor the emotional state of the subject during rest periods as a check for hyperventilation.

KINEMATIC DATA

The fundamental considerations of Hewes, Spady and Harris (Reference 2) were used in the analysis of locomotion/gait characteristics. The principal locomotion gaits employed by man are walking and running. The generally accepted distinction between them is that in walking, there is double support (i.e., both feet are on the ground sometime during any given stride), and in running, double support is absent (i.e., both feet are simultaneously off the ground sometime during any given stride). Locomotion without double support can be further divided into loping and sprinting. The lope, typical of the lower running speeds, is characterized by a long, leaping stride, normally achieved with a relatively low stepping rate. The sprint, which utilizes a short stride with a fast stepping rate, achieves higher running speeds. These authors (Reference 18) provide a convenient method, termed locomotive index, η, and defined as the ratio of leg swing to leg stroke, to differentiate between walking and running. When the calculated locomotive index is less than 1, the subject is walking; when the index is greater than 1, the subject is running.

The Relation of Locomotive Index, Step Rate, and Stride Length

The three variables of locomotive index, step rate, and stride length are presented together in Figures 28 through 36, since changes in one parameter must also be reflected in changes in the other two.

Figure 28 shows the data for a pressure-suited subject carrying a 75-lb load on the horizontal inclined-plane treadmill. It can be seen in this figure that stride length, step rate, and locomotive index η all increase as velocity increases. It is also apparent that step rate and locomotive index distinctly differ between gaits, while the velocity effect on stride length for running is a continuation of that for walking. Locomotive index significantly increases with velocity for walking ($p<0.01$). The effect of velocity on locomotive index for the running or loping modes, however, is not statistically significant. Locomotive index is also significantly different for each of the gaits ($p<0.01$).

Step rate is significantly affected by velocity in the walking ($p<0.01$), and loping modes ($p<0.05$). Step rate was not significantly altered by velocity changes between 8 and 12.8 km/hr during the running gait. On the other hand, step rate is significantly different for each of the three gaits.

Figure 29 illustrates the effects on these parameters when a 240-lb pack is carried. Locomotive index significantly increased with velocity for both the walking and loping modes ($p<0.01$). There was no velocity effect on locomotive index during the running mode. The locomotive index between the three gaits with this pack, however, was significantly different ($p<0.01$).

The trend of step rate data with the 240-lb pack is similar to that with the 75-lb pack. Locomotive index is significantly different between gaits ($p<0.01$) and significantly increases by velocity for walking and loping ($p<0.01$). The change observed for the running mode was not significant.

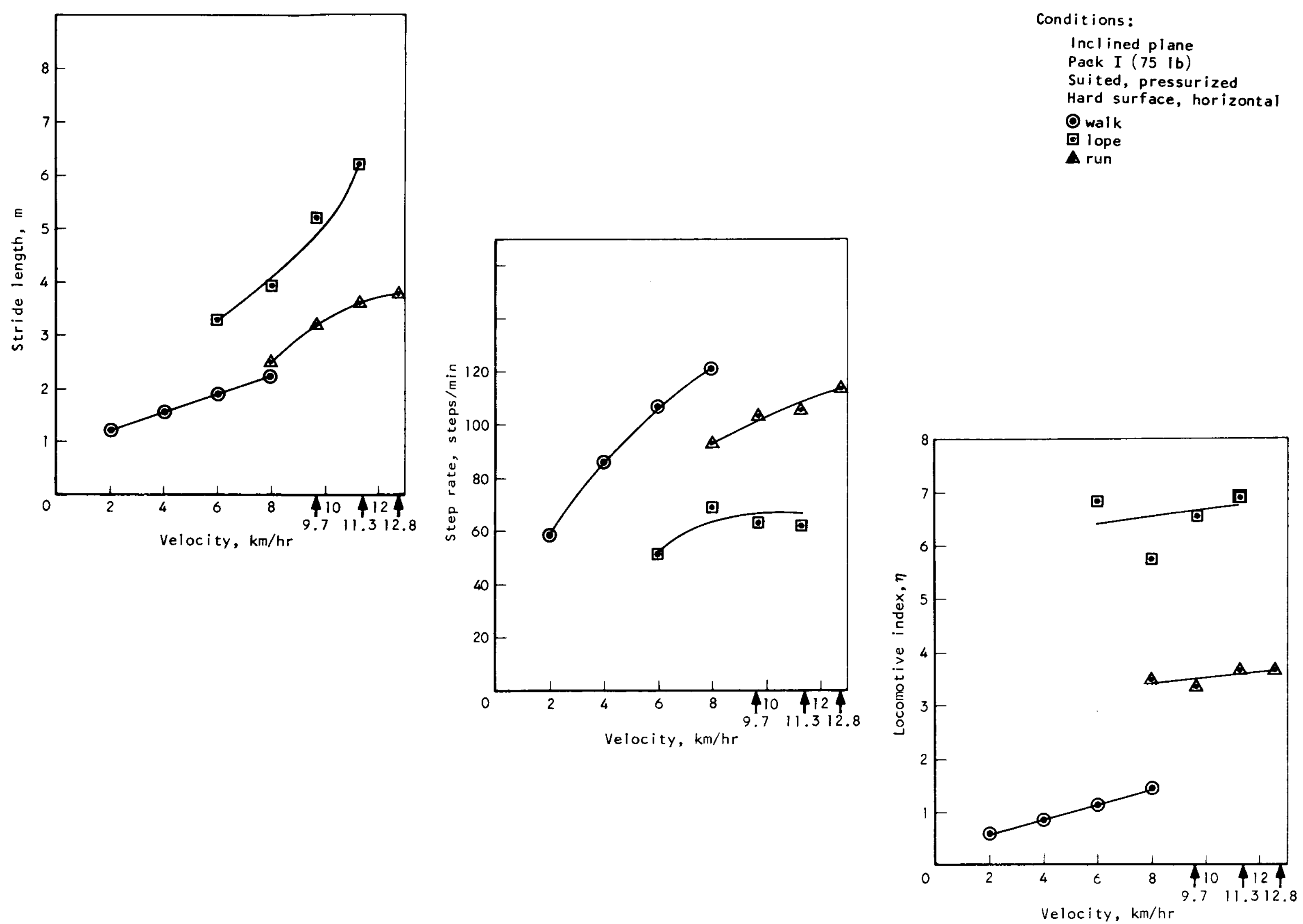

Figure 28. Locomotive Parameters vs Velocity on Inclined-Plane Simulator, Horizontal Hard Surface, Pack I

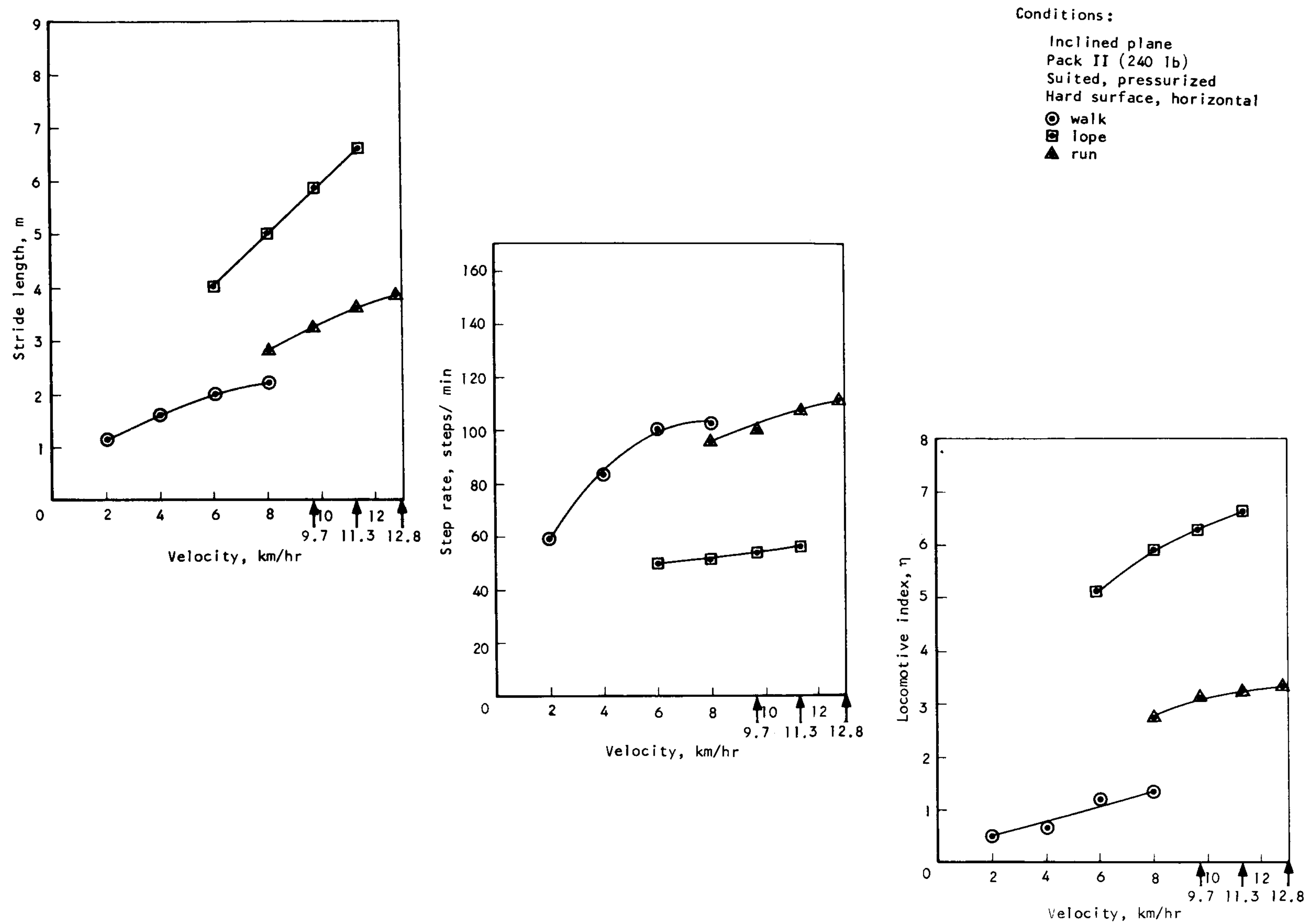

Figure 29. Locomotive Parameters vs Velocity on Inclined-Plane Simulator, Horizontal Hard Surface, Pack II

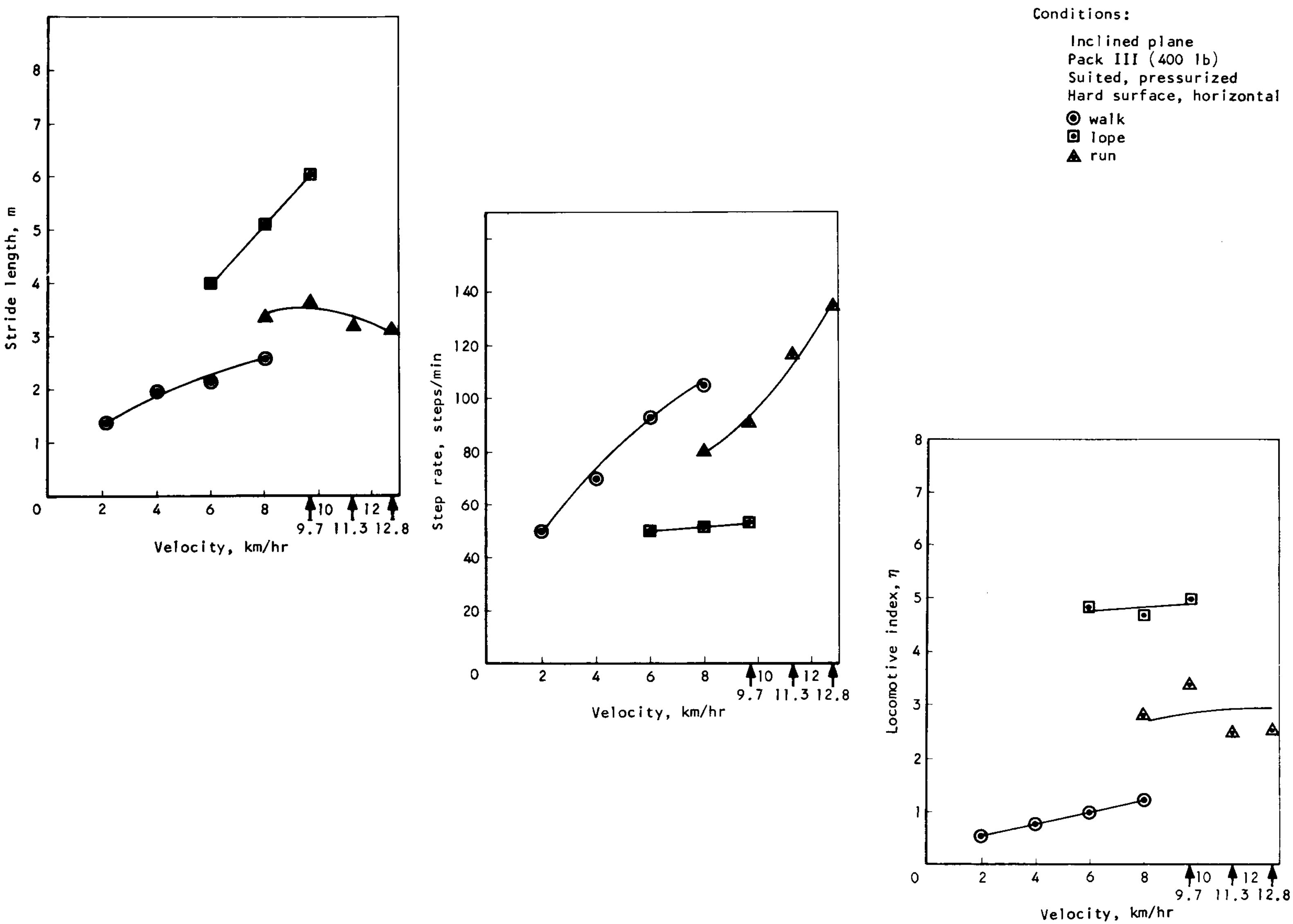

Figure 30. Locomotive Parameters vs Velocity on Inclined-Plane Simulator, Horizontal Hard Surface, Pack III

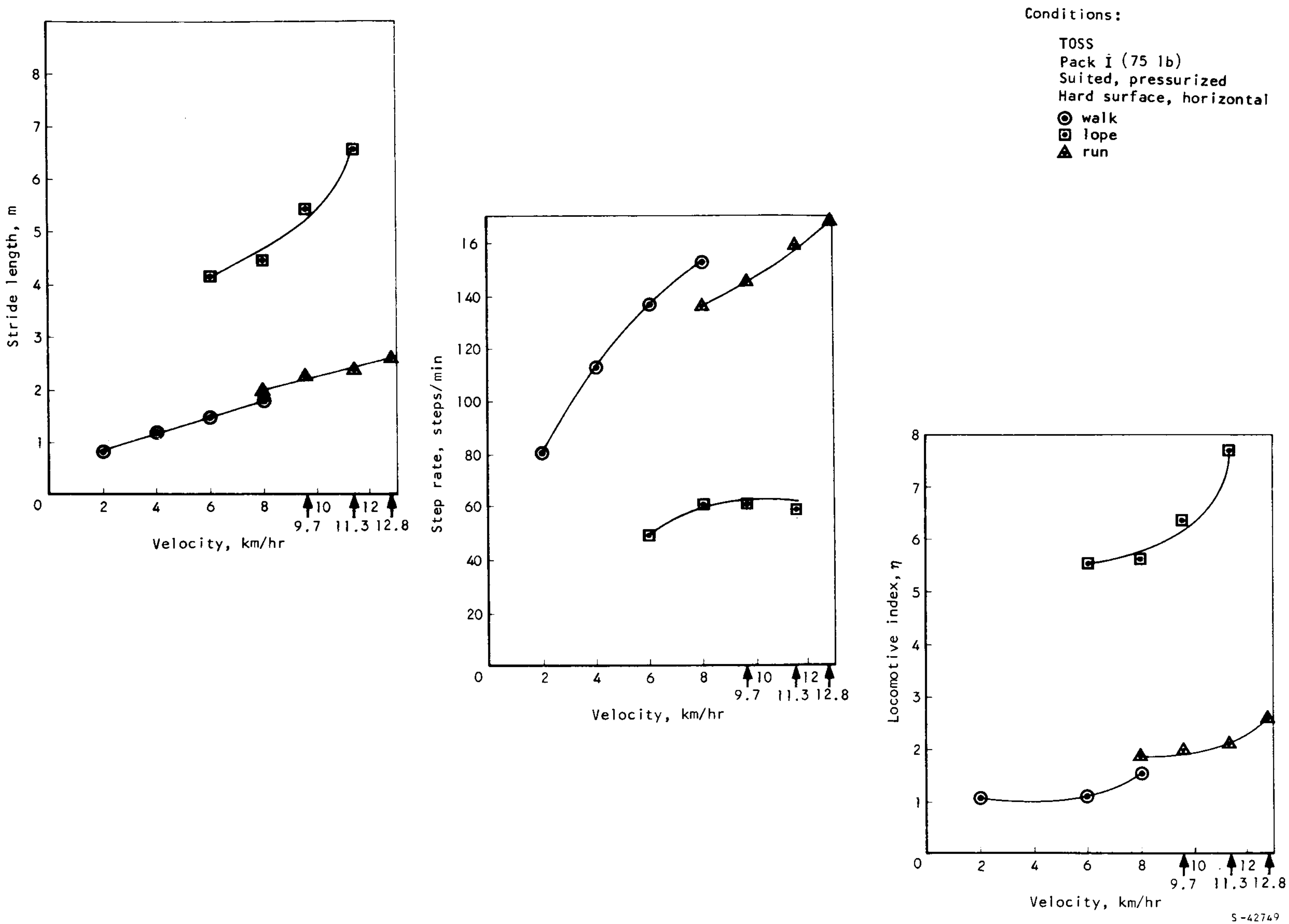

Figure 31. Locomotive Parameters vs Velocity on TOSS Simulator, Horizontal Hard Surface, Pack I

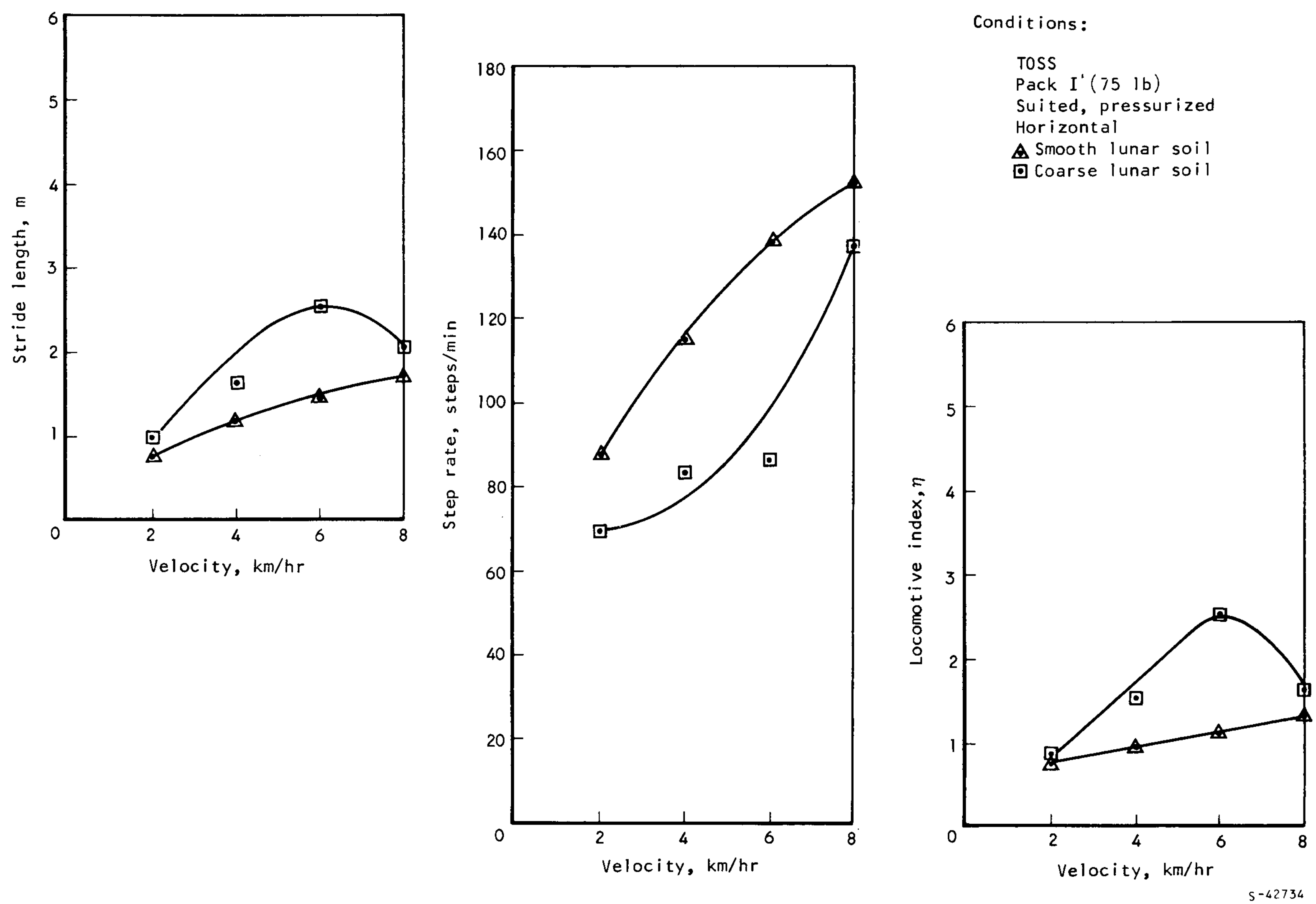

Figure 32. Locomotive Parameters vs Velocity on TOSS Simulator, Horizontal, Lunar Surface Conditions, Pack I

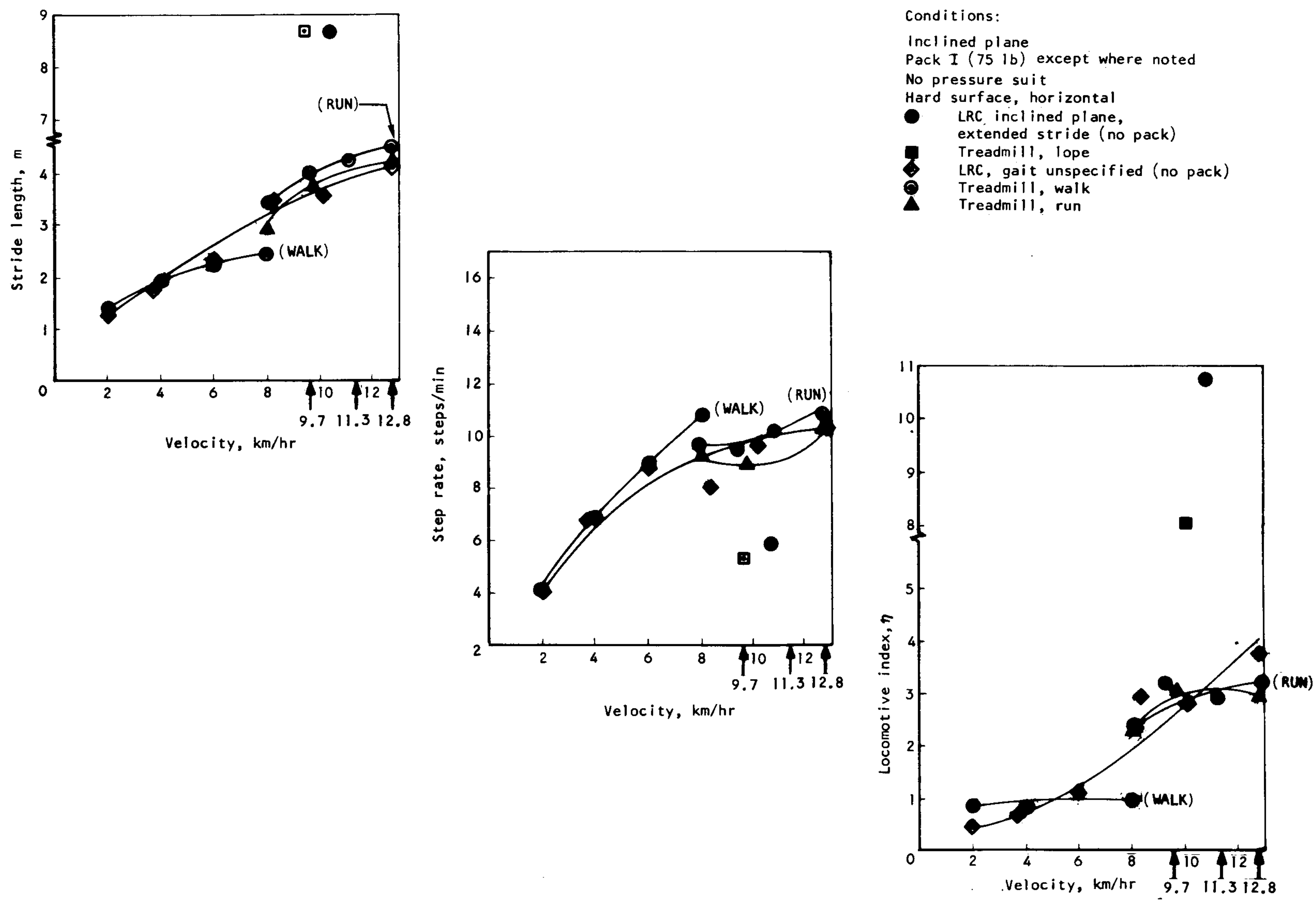

Figure 33. Comparison of Simulators Using Locomotive Kinematic Data, Horizontal Hard Surface, Without Pressure Suits

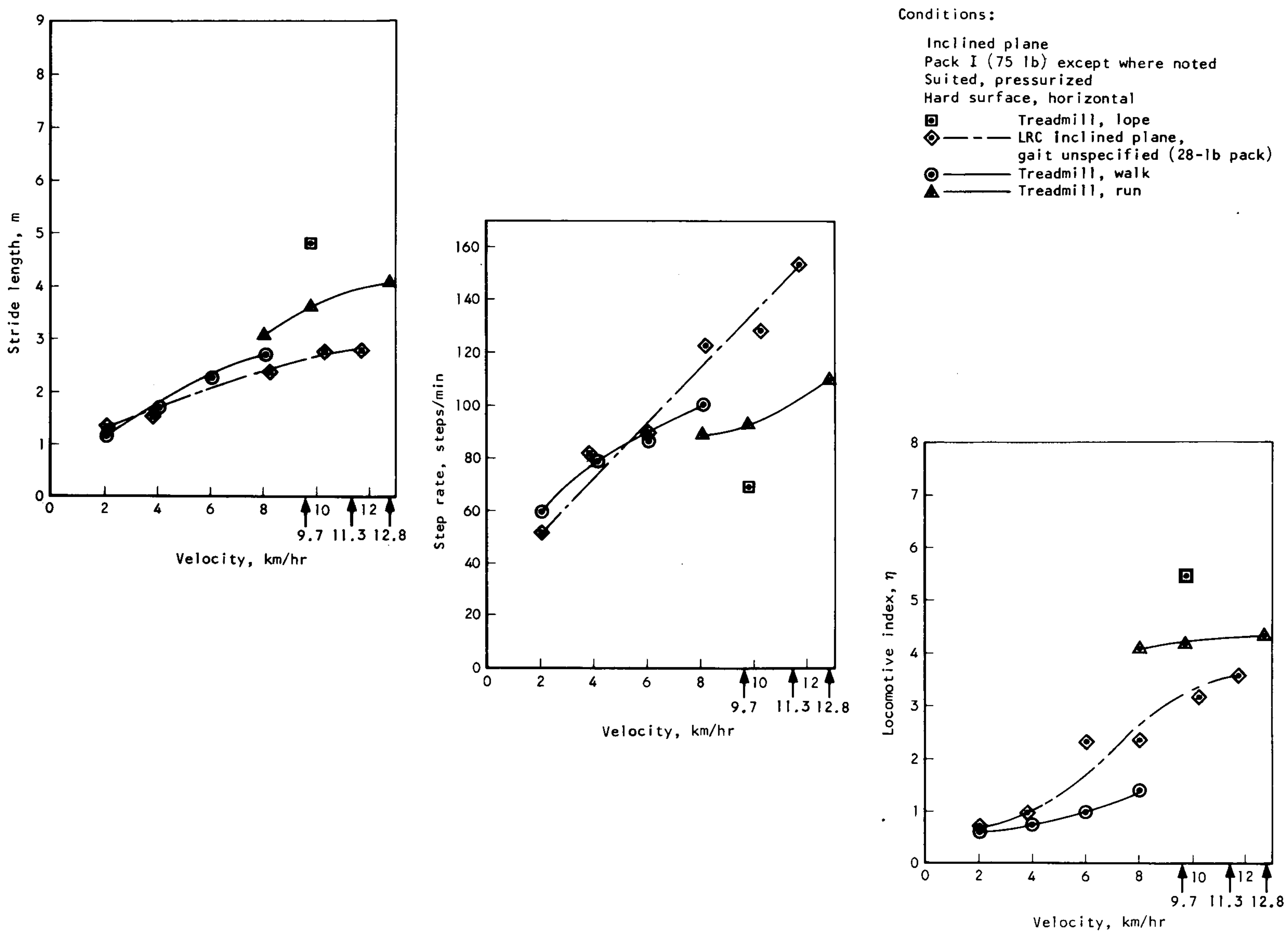

Figure 34. Comparison of Simulators Using Locomotive Kinematic Data, Horizontal Hard Surface, Pressurized Suits

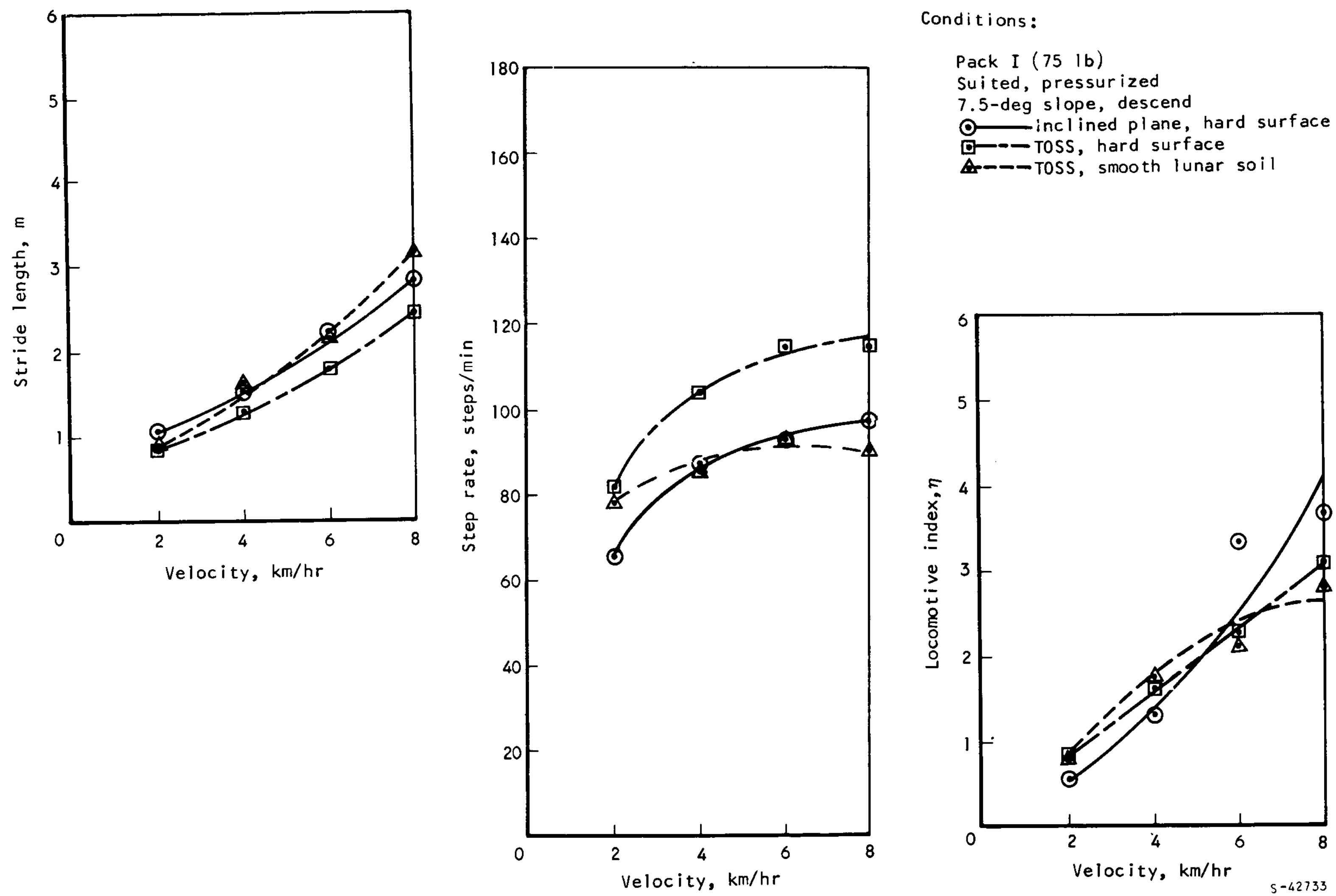

Figure 35. Comparison of Simulators and Surface Conditions Using Locomotive Kinematic Data for Descending a 7.5-deg Slope with Pack I

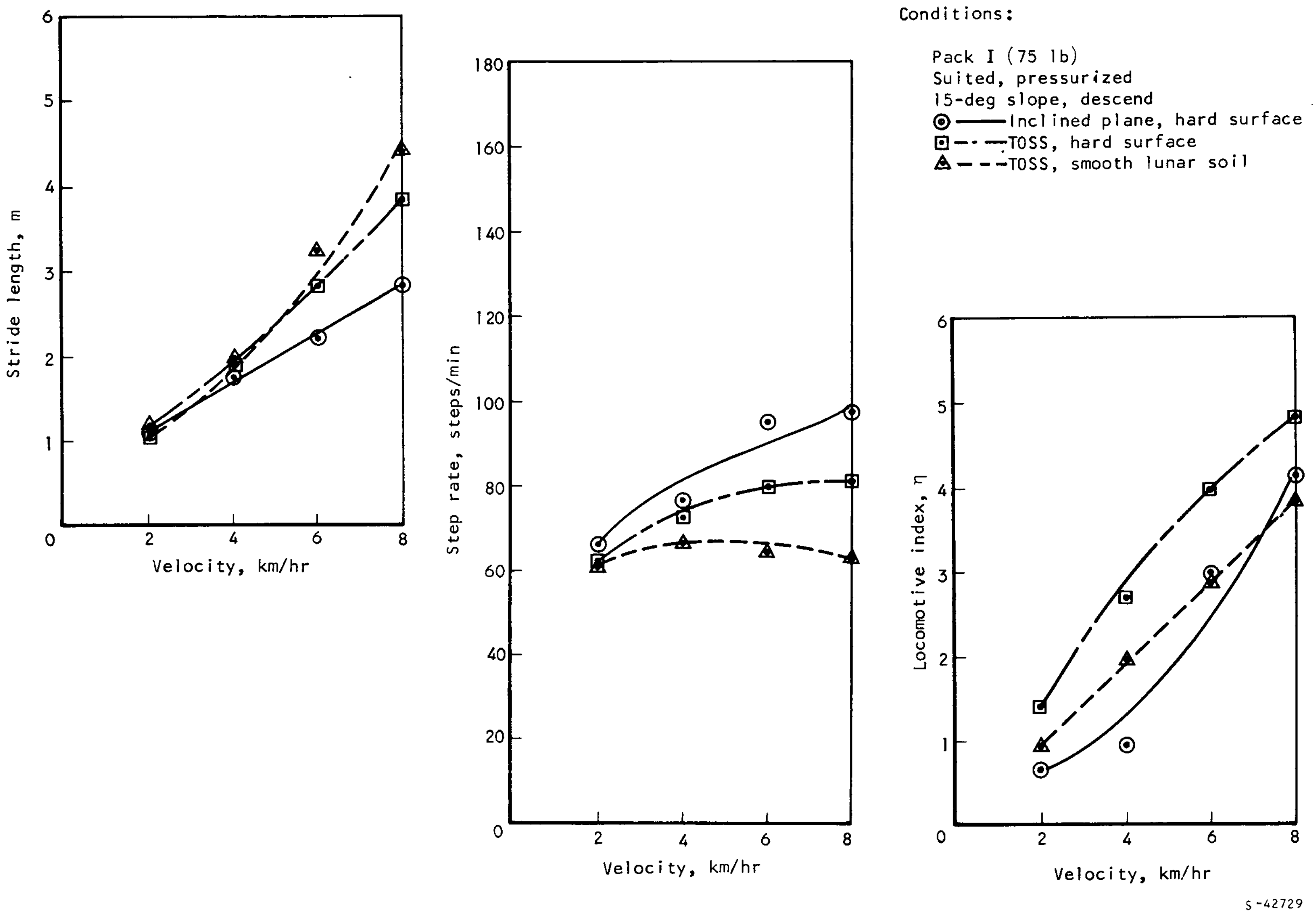

Figure 36. Comparison of Simulators and Surface Conditions Using Locomotive Kinematic Data for Descending a 15-deg Slope with Pack I

The data from tests with two subjects carrying 400-lb packs are presented in Figure 30. Because of the small number of subjects, statistical treatment of the data is not relevant. General observations from the 400-lb pack data, however, are similar to the 75- and 240-lb pack conditions. These are generally increases in step rate, stride length, and locomotive index with increasing velocities, and there are marked distinctions between all three gaits for these dependent variables.

With respect to differences between packs, the only significant effect of pack weight within gait is a significantly lower locomotive index during running ($p<0.01$) for the heavier pack. Also there was no statistically significant effect of pack weight on locomotive index as a function of gait, except at 6 km/hr where a significant interaction effect is observed between the walk and lope gaits with the 240- and 400-lb packs.

The only significant effect of pack weight on step rate was noted for the loping gait, in which the 240-lb pack produced a systematically ($p>0.01$) lower step rate than was observed for the 75-lb pack. This effect is reflected in stride length where again the only effect of pack weight was to affect the loping stride length by an increase for the 240-lb pack over that obtained with the 75-lb pack. A significant interaction effect between pack and velocity was also observed for the loping gait, which indicates that the extent of the effect of pack weight on stride length is altered by velocity ($p<0.01$).

The locomotive kinematic parameters for the TOSS simulator are plotted as a function of velocity in Figure 31. Velocity has a significant effect on each of the dependent parameters for each of the three gaits ($p<0.01$). In addition, the differences exhibited between each of the gaits are statistically significant ($p<0.01$). It should be noted, however, that the running stride length and locomotive index appear to be simple extensions of the walking data. This is probably due to the elimination of walking in the simulator at a velocity somewhere between 2 and 6 km/hr. These observations accurately reflect the energy expenditure data.

The effects of lunar surface conditions on stride length, step rate, and locomotive index are shown as a function of velocity in Figure 32. In general, each of these parameters increases with velocity for the simulated smooth lunar surface ($p>0.01$). With the simulated coarse lunar surface, however, stride length and locomotive index have a curvilinear relationship with velocity. This interaction effect is statistically significant for both parameters ($p>0.05$). In addition, the main effect of this surface on all three parameters is a significant increase in values as velocity increases ($p>0.01$).

Figures 33 and 34 provide comparisons of the data collected for horizontal locomotion on the inclined-plane simulators with subjects in pressurized suits and in mufti. Figures 35 and 36, on the other hand, compare the data on subjects descending 7.5-deg and 15-deg slopes. These figures also present comparisons between the different types of simulators employed. In general, correspondence between simulators is good; however, the differences between simulators are emphasized by increasing slopes.

Summary of Observations on Locomotive/Index, Step Rate, and Stride Length

The data described here are typical of the observations made during this program. The observations on locomotive index, step rate, and stride length may be summarized as follows:

1. In general, the values of stride length, step rate, and locomotive index η increase as velocity increases.

2. The walk, lope, and run gaits are definitely distinct in terms of locomotive index. Generally, the probability of distinguishing gait in terms of η is $p>0.90$. Mean values of η for the horizontal inclined-plane simulator at velocities less than 8 km/hr ranged from 0.625 to 1.16 for walking, 3.49 to 3.68 for running, and 6.83 to 6.90 for loping. On the TOSS simulator these values ranged from 0.77 to 1.09 for walking, 1.14 to 2.53 for running, and 5.56 to 7.67 for loping. In this simulator, loping is distinct from either walking or running. Walking phases into running between 4 and 6 km/hr. Walking in the TOSS simulator is not the same as in the inclined plane. The inclined-plane simulator provides freedom for the subject to pitch, to walk forward and backward, and to displace himself vertically. No freedom is allowed for moving from side to side or for roll and yaw motions. The suspension is such that the distance between the feet is relatively fixed. This makes it possible for the subject to maintain a desired leg position without exerting muscular forces. Subjects in the TOSS simulator did not have this advantage. On the faster lope velocities, it was necessary for the subject to extend the foot as far forward as possible when coming down onto the treadmill surface. To achieve this, it was also necessary to use the thigh muscles to hold the suit legs closer together. This action was tiring and sometimes painful. For one subject, heart rate increased more than 20 beats/min for standing with legs held together, as compared to standing relaxed with the legs apart. The preferred gait for subjects in the TOSS simulator included a yaw motion while walking and running. The yaw action reduces the period during which both feet can be on the surface at the same time.

3. The subjects encountered difficulty in obtaining a consistent gait for the 6-km/hr lope and the 8-km/hr run, indicating that these velocities may have been somewhat low for the gaits.

4. Heavy pack loads reduce the variance in kinematic parameters and may well aid stability during locomotion under lunar gravity conditions.

5. Treadmill and walkway kinematic data are quite similar for the inclined-plane technique of simulation.

6. Kinematic data are also similar for the inclined-plane and the TOSS simulators at velocities under 6 km/hr.

7. Stride lengths for walking and running in the TOSS simulator appear to increase almost linearly with velocity. The stride lengths for the loping gait show the same effect, only much greater. Stride length is consistently less for walking and running in the TOSS simulator than for those gaits with the inclined-plane simulator. For loping, stride length is greater in the TOSS simulator than in the inclined plane.

8. In comparing the step rate curves with the locomotive index curves, a consistent relationship of decreasing step rate with increasing locomotive index within velocity and pack is shown. For example, the comparison of the locomotive indexes for the different gaits at the 8-km/hr velocity show the walking gait as the lowest, followed by the running gait, with the loping gait as the highest. The plotted step rates for the 8-km/hr velocity show the loping gait as the lowest step rate, followed by running, with the walking gait as the highest. This relationship is also brought out by comparison of the gait curves across all the velocities. The two highest locomotive indexes for suited subjects loping with 75-lb packs occur at 6 and 11.8 km/hr, with the lowest occurring at 8 km/hr. The two lowest step rates for suited subjects loping with 75-lb packs occur at 6 and 11.3 km/hr, with the highest occurring at 8 km/hr.

9. Comparison of the walking data for the two simulators shows that step rates are higher and stride lengths are lower for the TOSS simulator.

10. Locomotive index, step rate, and stride length increased with velocity for the simulated smooth lunar soil condition. This was also the case for the coarse lunar soil condition, with the exception of the locomotive index and stride length at the 8-km/hr velocity. At this velocity, it was necessary to increase the step rate to improve stability after stepping on the rocks. The curves for the smooth lunar soil condition are almost linear. When compared to the data for the smooth lunar soil, the locomotive index and stride lengths were greater for the coarse soil condition at all velocities, and step rates were lower.

11. On the TOSS simulator, the step rate is greater for the hard surface than for the simulated smooth lunar soil and becomes increasingly greater as velocity increases. This effect may be due to the decreased traction on the smooth lunar soil, with increasing velocity as a function of the shearing of the soil. Sensory feedback as to when the foot has touched the surface arises sooner when stepping on a hard surface than when stepping on a yielding surface. The shear strength of the soil provides the subject poor traction with lowered feedback at the higher velocities; consequently, the time taken to end one step and start another increases, resulting in a decreased step rate. The depth of penetration into the soil increases the duration of application of both decelerating and accelerating forces by the foot. The penetration of the foot into the soil makes it difficult to determine from photographic data, exactly when the foot left the surface. This probably resulted in some errors in data reduction.

12. Values of locomotive index, step rate, and stride length are almost identical for the shirt-sleeve and pressurized suit conditions.

Body Position Data

Figure 37 compares stride length and step rate between programs for subjects without pressure suits, and Figure 38 provides comparisons of tests with subjects in pressurized suits. It can be seen from these figures that although the number of comparative test conditions between programs are few, these parameters show substantial consistency among the different programs.

Other kinematic data measured during this program were back angle δ_b, hip angle δ_h, and knee angle δ_k. These angles are defined by Figure 39. The reliability of the back angle and hip angle measurements were determined by test-retest techniques and were found to be 0.86 and 0.79, respectively. The ability of these measurements to discriminate between the test conditions is in the same sequence. All of the kinematic data on body angles reveal changes with increasing slopes.

Figure 40 illustrates the mean back angles observed for horizontal locomotion and for ascending and descending slopes. It can also be seen that little difference is exhibited in back angle between simulators. Figures 41 and 42 present similar data for hip angle δ_h and knee angle δ_k.

Summary of Observations on Body Angles

The observations made on body positions during this program may be summarized as follows:

1. There is no significant change in back angle δ_b with velocity changes for horizontal locomotion.

2. The type of gait, however, does influence back angle. There is an increase in back angle between the walk and run gaits and between the walk and lope gaits on the inclined-plane simulator. Back angle is different for all gaits in the TOSS simulator.

3. When the 240-lb pack is substituted for the 75-lb pack, back angle does not change for walking on the inclined-plane simulator, but does increase with lope and run gaits. Back angle increases for all gaits when the 400-lb pack is substituted for the 75-lb pack.

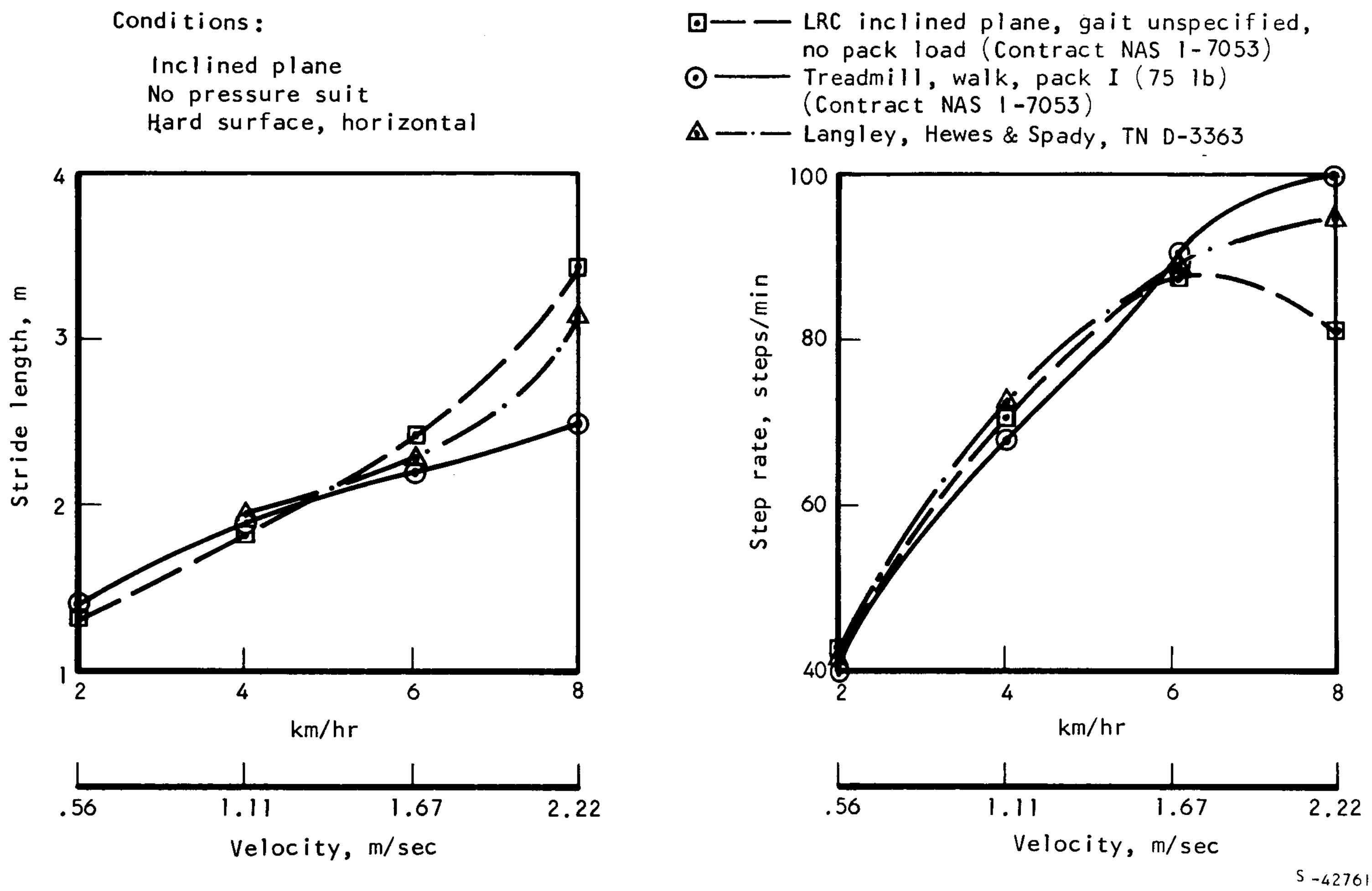

Figure 37. Comparison of Stride Length and Step Rate Between Programs, Without Pressure Suits

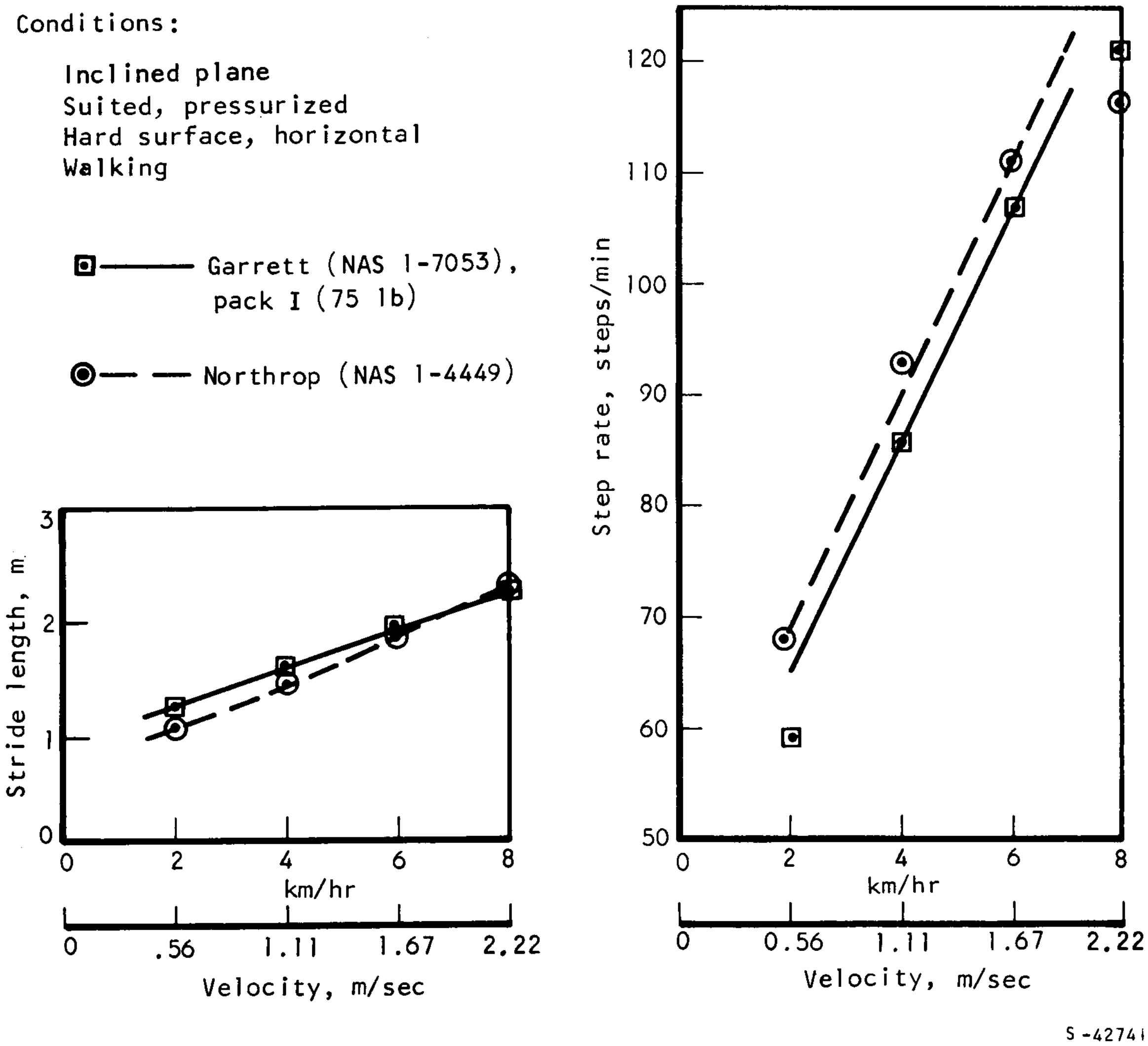

Figure 38. Comparison of Stride Length and Step Rate Between Programs, with Pressurized Suits

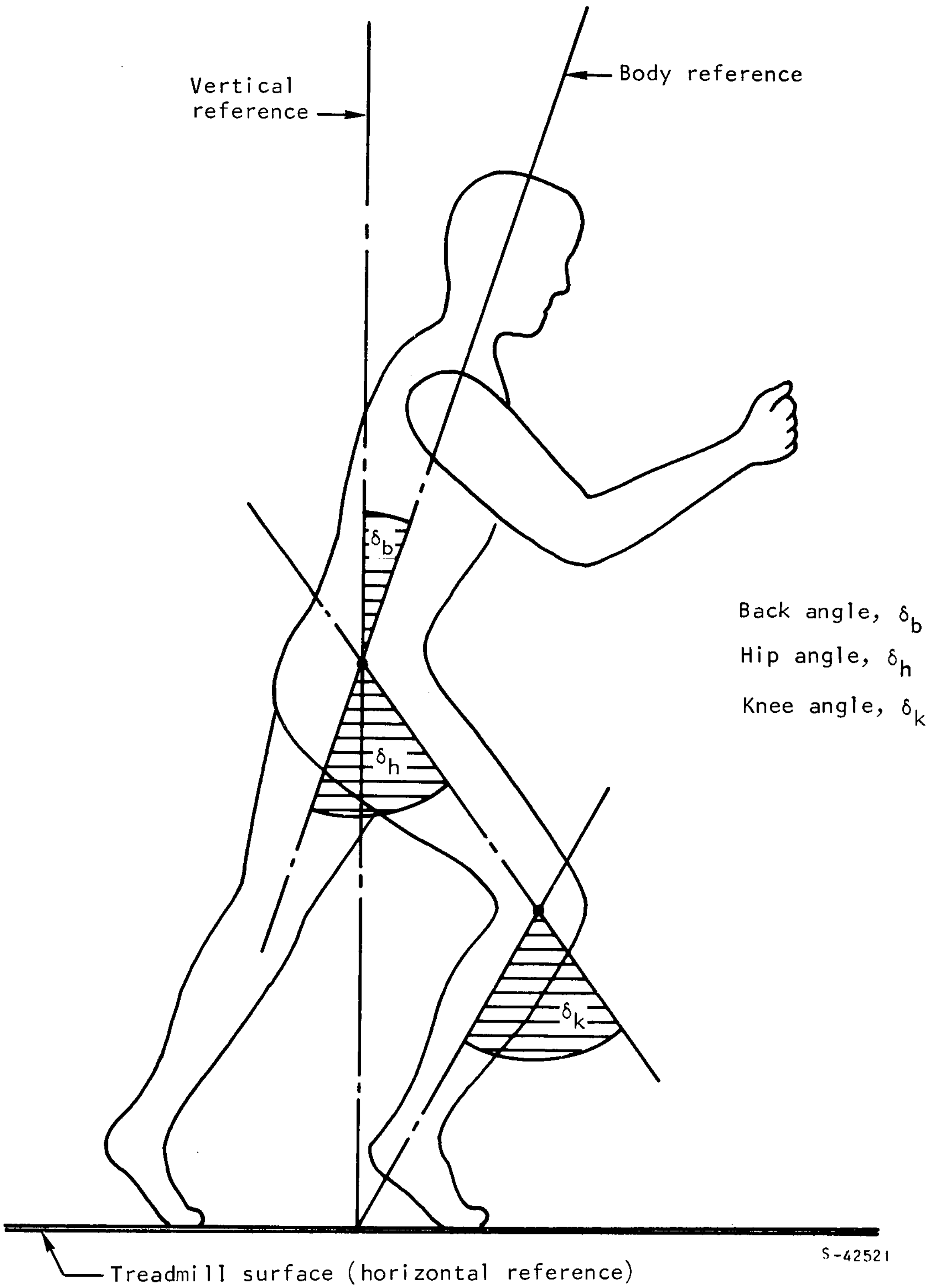

Figure 39. Definition of Body Angles

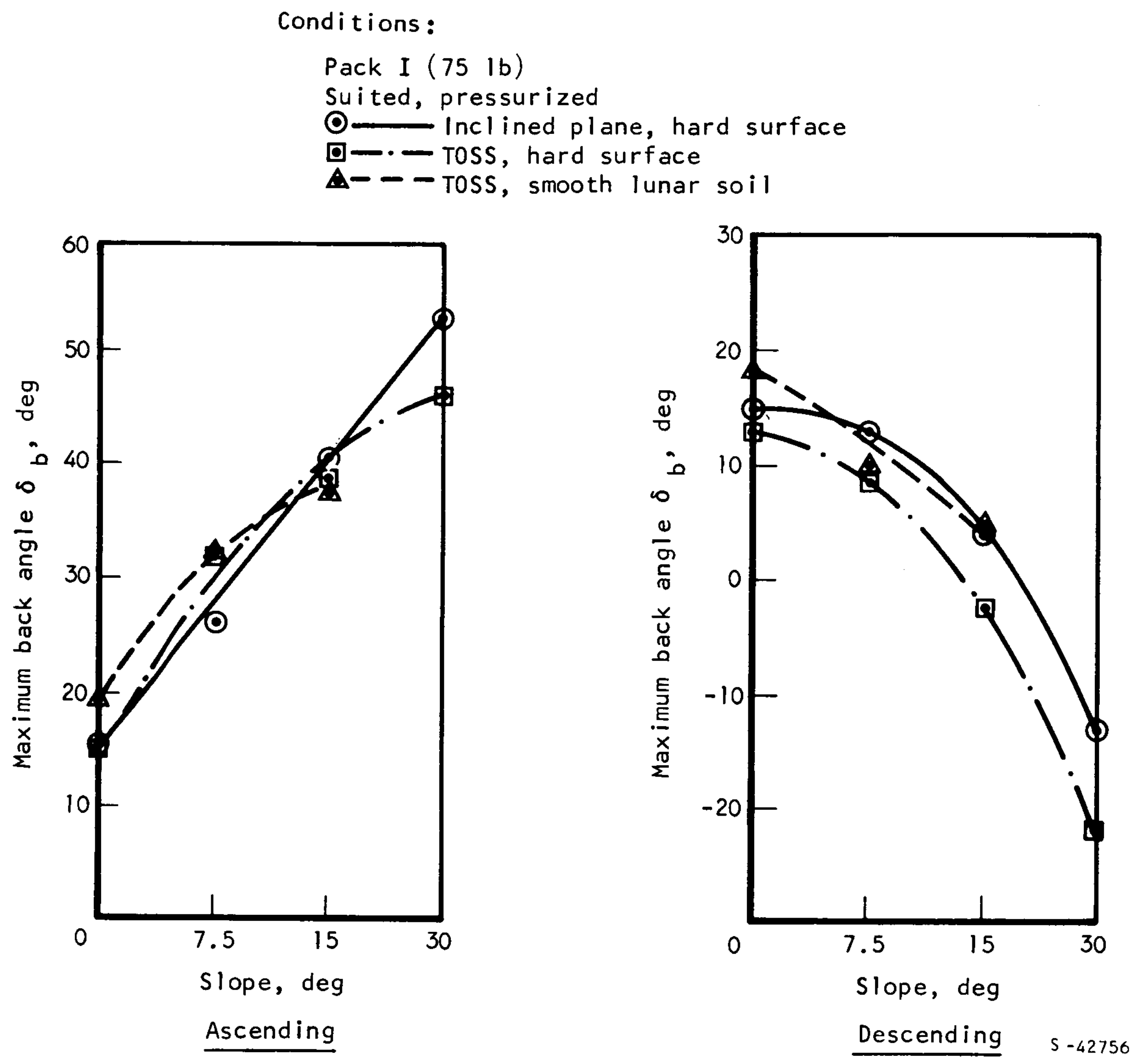

Figure 40. Maximum Back Angle vs Slope, Comparison of Simulators and Surface Conditions, Traversing with Pack I

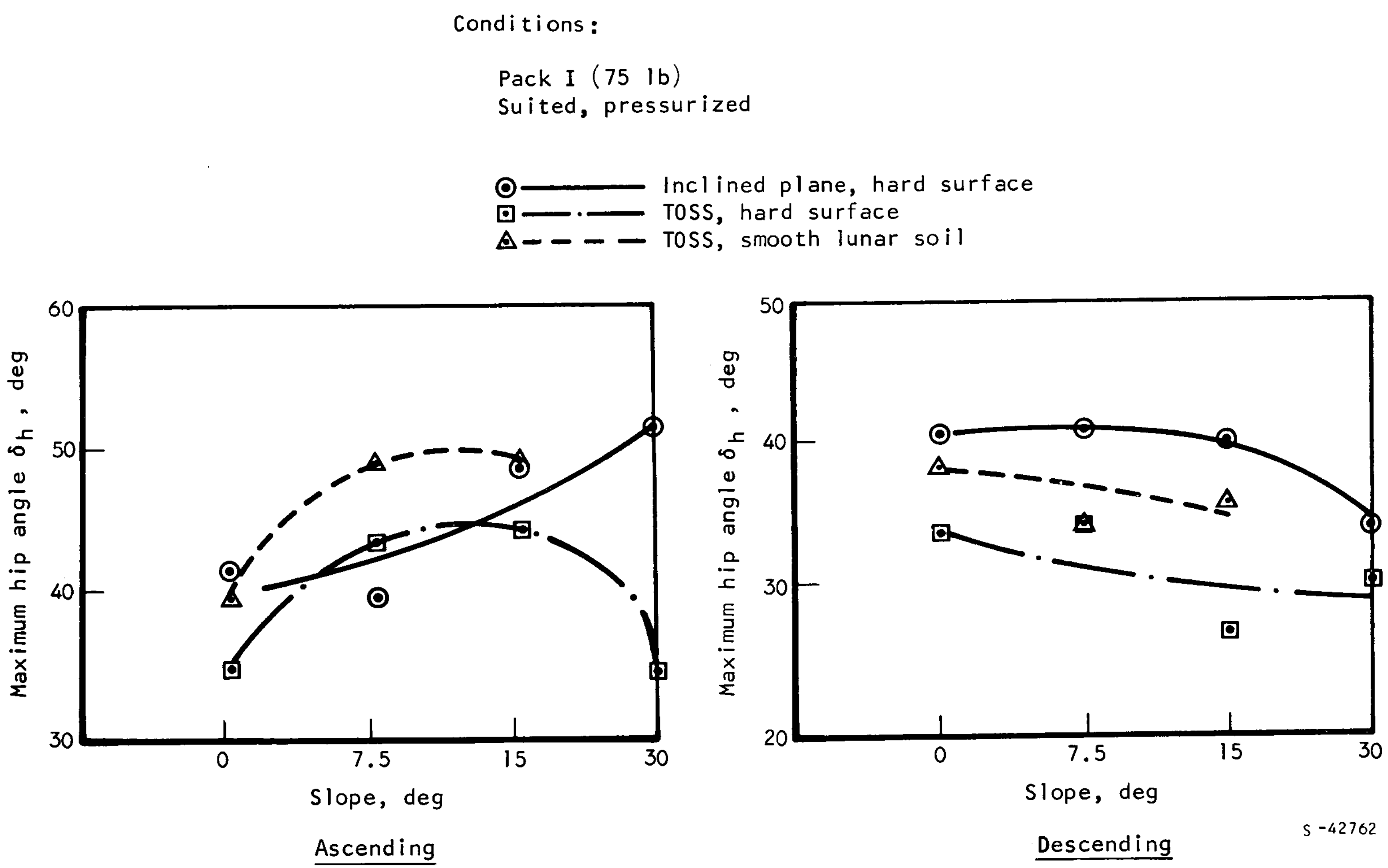

Figure 41. . Maximum Hip Angle vs Slope, Comparison of Simulators and Surface Conditions, Traversing with Pack I

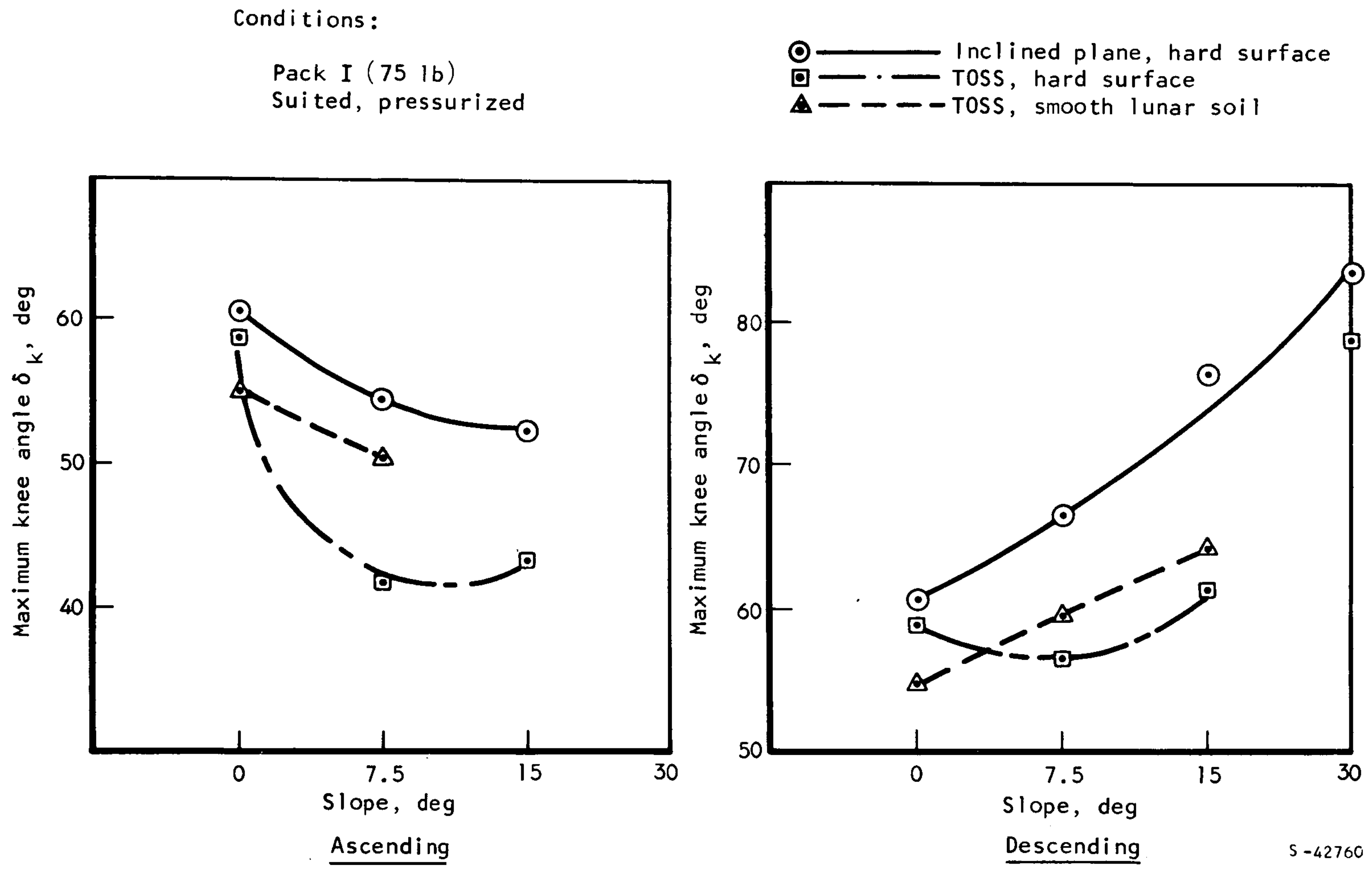

Figure 42. Maximum Knee Angle vs Slope, Comparison of Simulators and Surface Conditions, Traversing with Pack I

4. Back angle increases for simulated lunar soil conditions as compared to the hard surface with the horizontal TOSS simulator. There is no difference in back angle between the two types of simulated lunar surfaces. Whether ascending or descending a 7.5-deg slope in the TOSS simulator, no differences occurred in back angle for either the hard surface or the simulated smooth lunar surface. For a 15-deg slope, a significantly lower back angle was observed on the hard surface than on the simulated smooth lunar surface. The data on 15-deg ascending are insufficient for comparisons between hard surface and simulated lunar soil conditions.

5. The only difference in back angle between the inclined-plane and the TOSS simulators on a horizontal hard surface occurs during the run gait, where back angle is lower in the TOSS simulator. For 7.5-deg ascent, however, a lower back angle is exhibited on the inclined-plane simulator than with the TOSS simulator. For a 15-deg slope, there is no difference between simulators while ascending. There is insufficient data for 30-deg ascending TOSS simulator to allow comparisons. Back angle is significantly higher on the inclined-plane simulator than with the TOSS simulator for descending 7.5- , 15- , and 30-deg slopes, because the subjects leaned farther back from vertical in the TOSS simulator than in the inclined plane.

6. Back angle is higher for all conditions when ascending than when descending.

7. Hip angle δ_h is not greatly influenced by velocity during horizontal locomotion. Ascending slopes, however, increase hip angle as velocity increases, but descending slopes do not affect it.

8. Using the inclined-plane simulator, the only influence of gait on hip angle was seen with the heavier packs, especially in the run and lope modes where the hip angle was higher than with the 75-lb pack. With the TOSS simulator and a hard surface, the lope gait produced a higher hip angle than did the run gait.

9. With the TOSS simulator and lunar soil conditions, an increase in hip angle was seen as velocity increased. There was no difference between the lunar surfaces and the hard surface or between the two types of lunar surfaces.

10. During ascent at 7.5 deg, the inclined-plane simulator produced a lower hip angle than did the TOSS simulator. There was no difference between the simulators during ascent at 15 and 30 deg. The effects were reversed during descent, and the inclined-plane data showed higher hip angles at all slopes than did the TOSS data.

11. Knee angle is unaffected by velocity during runs on the horizontal hard surface with either simulator. During ascent at 7.5 and 15 deg, however, knee angle increased with velocity, and the inclined-plane simulator showed greater values of knee angle during the descending slope tests than did the TOSS simulator; but neither system tended to show changes in knee angle with changes in velocity during descent.

12. On a horizontal hard surface with the TOSS simulator, there is no change in knee angle associated with gait. On the inclined-plane simulator, there is a significant increase in knee angle with the lope, run, and walk gaits.

13. Each heavier pack produced a lower knee angle.

14. With the two lunar surfaces, a velocity effect is noted on knee angle, but there is no difference between the two types of soil conditions.

15. The inclined-plane simulator produces higher knee angles at all velocities than does the TOSS simulator with a hard surface or smooth lunar soil.

16. Increased slope increases knee angle during descent and decreases knee angle during ascent.

RANGE PROJECTIONS

The prediction of range capabilities for men walking on the lunar surface has been thoroughly treated by D. E. Hewes in NASA TN D-3934, Analysis of Self-Locomotive Performance of Lunar Explorers Based on Experimental Reduced Gravity Studies, May 1967 (Reference 3). Hewes developed the concept of range factor as equal to $V/\dot{Q} \times 1000$ where V = velocity and $\dot{Q}$ = metabolic rate. Computation of range factors for the Gemini suit at Earth gravity and at lunar gravity with a simulated lunar soil is illustrated in Figure 43. The substantial increase in distance achieved on the lunar surface per unit energy expenditure over that observed under Earth gravity conditions is readily apparent.

If the results of the current program are extrapolated to hypothetical operational situations, some interesting observations can be made. To do this, however, it is necessary to look at the constraints for locomotion on the lunar surface imposed by a portable environmental control system (ECS). Approximate values for total metabolic capacity (total oxygen supply and total heat rejection capability) for two candidate systems are 1200 kcal (4750 Btu) and 2000 kcal (7900 Btu). In addition, the current practical maximum rate of heat removal from a space suit is approximately 500 kcal/hr (1999 Btu/hr). The assumed values for these constraints can be applied to the experimental data to ascertain both the range limit for self-locomotion and the duration "in the field" as a function of the velocity of locomotion. Figure 44 illustrates the ranges that can be achieved with these two assumed ECS pack capacities as a function of velocity. It can be seen from Figure 44 that beyond 4 km/hr, range is only slightly affected as velocity increases through 8 km/hr. At 8 km/hr, a range of 15 km could be achieved with the 1200-kcal pack, and 24 km could be achieved with the 2000-kcal pack. If, however, the heat dissipation from the suit was limited to 500 kcal and little or no heat storage by the astronaut was allowed, the range would become substantially limited.

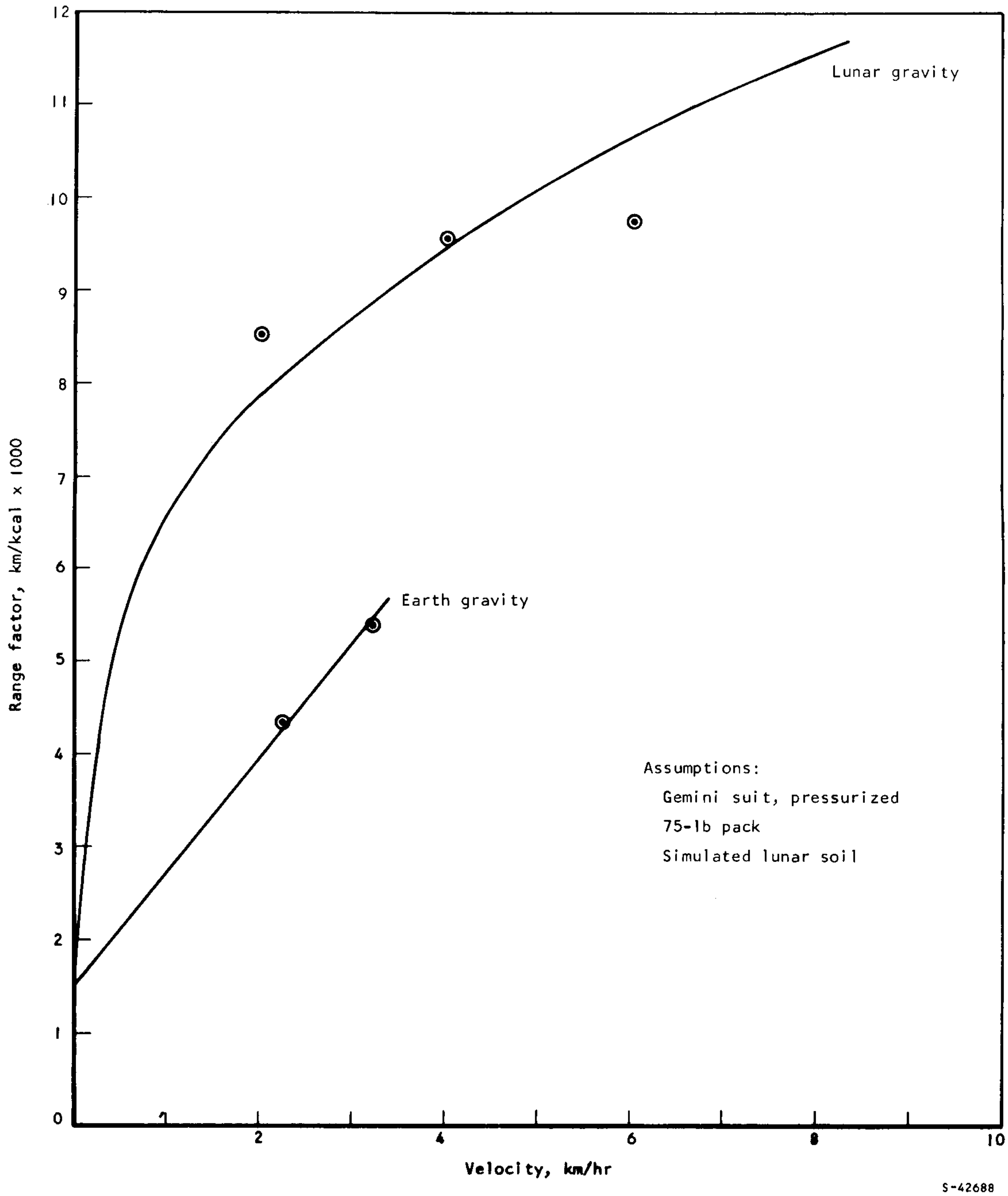

Figure 43. Range Factors at Earth Gravity and at Lunar Gravity, with Simulated Lunar Soil and Gemini Suit

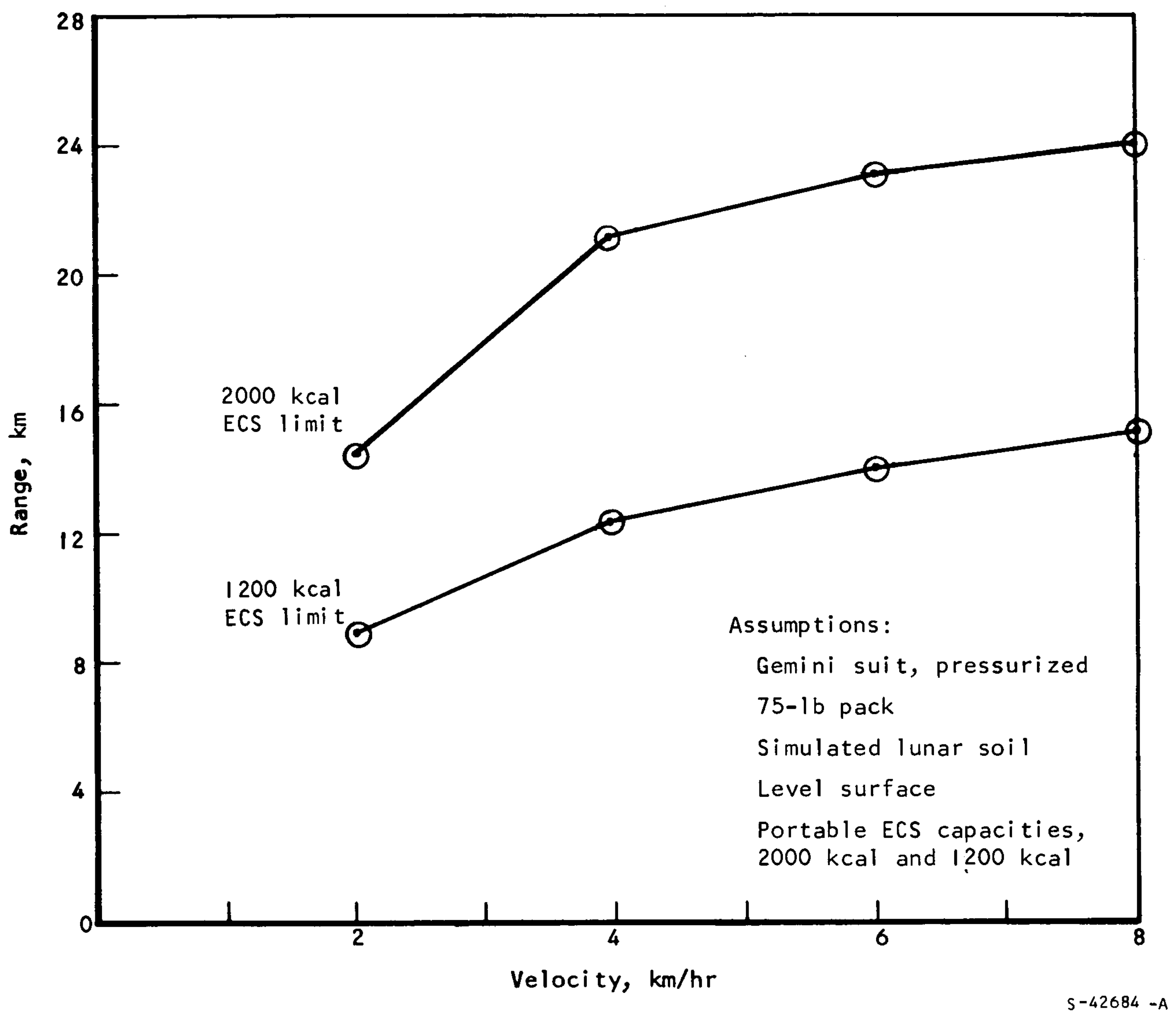

Figure 44. Range Limit as a Function of Velocity, Assuming Two Portable ECS Capacities

The ranges achievable for the two assumed pack capacities are accomplished in durations that decrease with increasing velocity as shown in Figure 45 which plots the maximum duration for walking on the lunar surface as a function of velocity.

In reviewing these comments, it is emphasized that these data assume the use of a Gemini suit, that the surface is horizontal (zero grade), and that the characteristics of the lunar surface are quite similar to the simulated lunar soil used in this program.

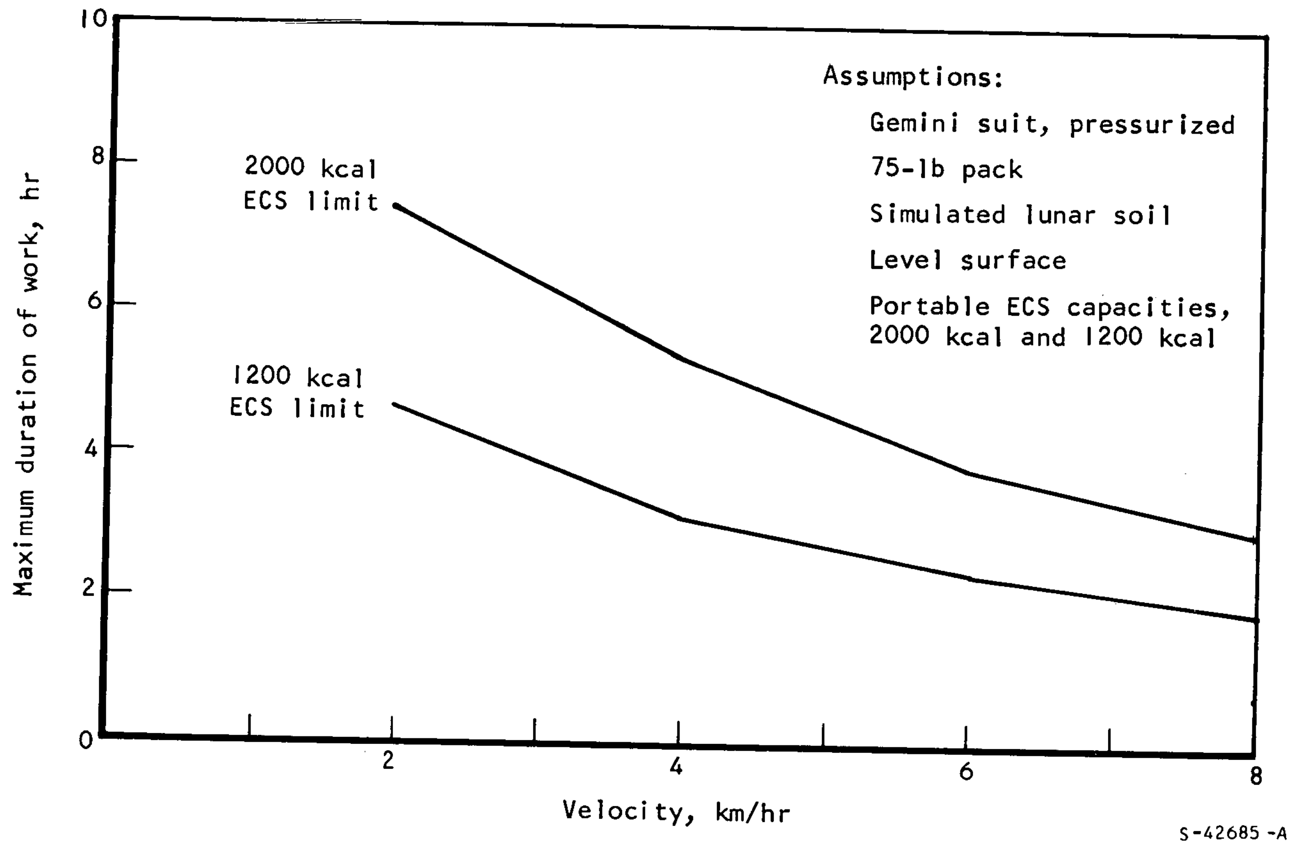

Figure 45. Duration of Lunar Walk as a Function of Velocity, Assuming Two Protable ECS Capacities

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SECTION 5

CONCLUSIONS

1. Metabolic rates are lower during locomotion in simulated lunar gravity than at 1 g. The decrease is approximately 30.5 percent at 2 km/hr and 64.6 percent at 8 km/hr in mufti, and 51.1 percent at 2 km/hr and 37.9 percent at 3 km/hr in the Gemini space suit.

2. Energy cost for a loping gait is higher than for either walking or running. This observation is consistent for subjects either with or without space suits.

3. The metabolic rate for walking in a Gemini space suit on a level surface at any given gait and velocity with a 75-lb pack is unchanged by substitution of 240- or 400-lb pack weights.

4. For self-locomotion on level grades with a simulated lunar surface, energy expenditures range from 4.35 kcal/min at a 2-km/hr velocity to 12.28 kcal/min at 8 km/hr.

5. Metabolic costs for locomotion on a horizontal lunar surface increase sharply for ascending slopes: 36 percent greater for 7.5-deg slopes and 88 percent for 15-deg slopes. Metabolic costs for descending these grades, over horizontal locomotion, decrease by 29.1 percent (7.5 deg) and 41.3 percent (15 deg). On ascending or descending slopes, the metabolic cost for carrying a 240-lb pack increases over that for a 75-lb pack.

6. Locomotion on simulated lunar soil increases energy cost over that required on a hard surface (i.e., normal treadmill surface) for horizontal walking, as well as for ascending or descending slopes.

7. In the walking or running gaits, there are no differences in energy costs between the 3-deg-of-freedom simulator and the 6-deg-of-freedom simulator. For the lope gait, higher levels of energy expenditure occur with the 6-deg-of-freedom simulator.

8. The ratio of oxygen repayment to total oxygen cost is relatively constant, regardless of test conditions or level of energy expenditure.

9. The average energy expenditure rate is essentially identical to the instantaneous rate of energy expenditure at the end of any given test.

10. Heart rate and metabolic rate are correlated $R = 0.80$; however, the standard error about the regression line is ± 1.07 kcal/min ($\sim$514 Btu/hr). Consequently, the 95-percent confidence interval is ± 2.09 kcal/min ($\sim \pm 875$ Btu/hr or 1750 Btu/hr) for predicting energy expenditure from heart rate.

11. In general, the values of step rate, stride length, and locomotive index (η) increase as velocity increases.

12. When heavy packs are carried, the variance in kinematic parameters is reduced.

13. Treadmill and walkway kinematic data are quite similar for the inclined-plane technique of simulation.

14. Kinematic data are similar for both the 3-deg-of-freedom and the 6-deg-of-freedom simulations at velocities under 6 km/hr.

15. Values of locomotive index (η), step rate, and stride length are essentially identical for either shirt-sleeve or pressurized suit conditions.

16. There is no significant change in back angle (δ_b) with velocity changes for horizontal locomotion on either simulator.

17. The type of gait does influence back angle (δ_b). Back angle increases between walk and run and between walk and lope on the 3-deg-of-freedom simulator. Back angle differs for all gaits on the 6-deg-of-freedom simulator.

18. When the 240-lb pack is substituted for the 75-lb pack, back angle (δ_b) does not change while walking on the inclined-plane simulator, but does increase for the lope and run gaits. Back angle increases for all gaits when the 400-lb pack is substituted for the 75-lb pack.

19. Back angle (δ_b) for horizontal locomotion is greater for lunar soil conditions than for hard surfaces and back angle (δ_b) is greater for ascending than for descending slopes under all conditions.

20. Hip angle (δ_h) is not greatly influenced by velocity on a horizontal surface. For ascending slopes, hip angle increases as velocity increases. Hip angle is not affected on descending slopes. Hip angle (δ_h) does not differ between the lunar surfaces and the hard surface or between the two types of lunar surfaces.

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