Technical Report

OBSERVATIONS ON LUNAR GRAVITY SIMULATION

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FOREWORD

This report was prepared by the Department of Life Sciences, AiResearch Manufacturing Company, a division of The Garrett Corporation, Los Angeles, California. It presents a description, results, and conclusions of experiments performed for the NASA Manned Spacecraft Center, Houston, Texas, under Contract NAS 9-6481.

The technical assistance of A. K. Walther, N. J. Belton, G. Harding, G. Raynes, and L. J. Miller, and the outstanding effort and cooperation of the six text subjects are gratefully acknoledged.

ABSTRACT

Experiments were conducted to evaluate and compare the metabolic costs of performing upper- and lower-torso work in a G-2C pressure suit and to evaluate 1/6-g six-degree-of-freedom simulators based on the metabolic costs of the exercise. Tests were performed at 1 g and at 1/6 g using a counterbalance vertical suspension simulator. Metabolic rates and other physiologic costs of self-locomotion were evaluated at 1/6 g using six subjects wearing pressurized Gemini pressure suits. The physiologic costs of upper-torso work were evaluated in both a 1 g and 1/6-g environment.

Results show that metabolic rates measured at 1/6 g are significantly increased with velocity. Energy costs for carrying a 75-lb earth-equivalent-weight pack at 1/6 g increased when compared to costs obtained without additional weight; this increase approached significance. When data were normalized for the subject's lunar weight, it appeared that the subject did not perform as efficiently in simulated lunar gravity as in a 1 g environment. No significant differences were observed between metabolic cost of performing at 1 g and at 1/6 g or between different modes of accomplishing the tasks. The energy costs imposed by the use of the Gemini pressure suit obviates comparing differences between decreased gravity simulators.

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SECTION I

INTRODUCTION

The experiments of this study were designed to evaluate and compare the metabolic costs of performing upper- and lower-torso work in a G-2C pressure suit and to compare the data with those obtained in other pressure suits at 1 g and at 1/6 g with different types of simulators. The major effort under this contract, performed for the NASA Manned Spacecraft Center under Contract NAS 9-6481, was an evaluation of 1/6-g environment, six-degree-of-freedom simulators, using a Gemini series pressure suit.

Six subjects wearing pressurized G-2C suit performed locomotive tasks at 1/6 g in a special counterbalance simulator. In addition, upper-torso testing was accomplished at both 1/6 g and 1 g. Metabolic rates and other physiologic data were collected during each test and used to evaluate the physiologic cost of the various tasks.

This report describes the experimental design, the methods and procedures used in the experimentation, and the results and conclusions of the experiments.

SECTION 2

METHODS AND MATERIALS

SUBJECTS

Six healthy males were selected from the AiResearch test subject panel on the basis of their medical history, physical condition, pressure-suit training, decreased-gravity-simulation experience, and emotional stability. The subjects' anthropomorphic data are shown in Table 1. Each subject participated in all test modes.

EXPERIMENTAL DESIGN

The experimental design for the walking and the upper-torso tests is shown in Figure 1. Each cell in the matrices represents a different test condition. All tests were performed in a pressurized Gemini series pressure suit.

The experimental design for the walking experiments (Design A) shows the six experimental conditions studied with the subjects in a 1/6-g environment simulated in a vertical-counterbalance, six-degree-of-freedom simulator. The independent variables were velocity and load. The subjects performed each of the three velocities while carrying either no added weight or a 75-lb earth-equivalent-weight load.

Design B depicts the 4-cell orthogonal design used for upper-torso work. Tests were performed at 1 g and 1/6 g with two types of upper-torso exercise. One type was a simultaneous pull with both hands at a work rate of 10 ft-lb/ 2 sec (5 pounds per hand raised 1 foot). The second type of exercise was accomplished by alternating the hands to raise the weights, i.e., 5-ft-lb/sec per hand or a total work rate of 10 ft-lb/2 sec.

The primary dependent variable was metabolic rate, which was determined continuously by open-circuit spirometry. Other dependent variables were heart rate, oxygen consumption, carbon dioxide production, and minute ventilation.

The data variants for each of the independent variables were analyzed; they are reported in Section 5. The metabolic rates obtained for the walking experiments were tested for statistical significance by a two-way analysis of variance arranged as Design A of the experimental design shown in Figure 1. Statistical analysis of the data for upper-torso tests was performed using the Student's "t" test.

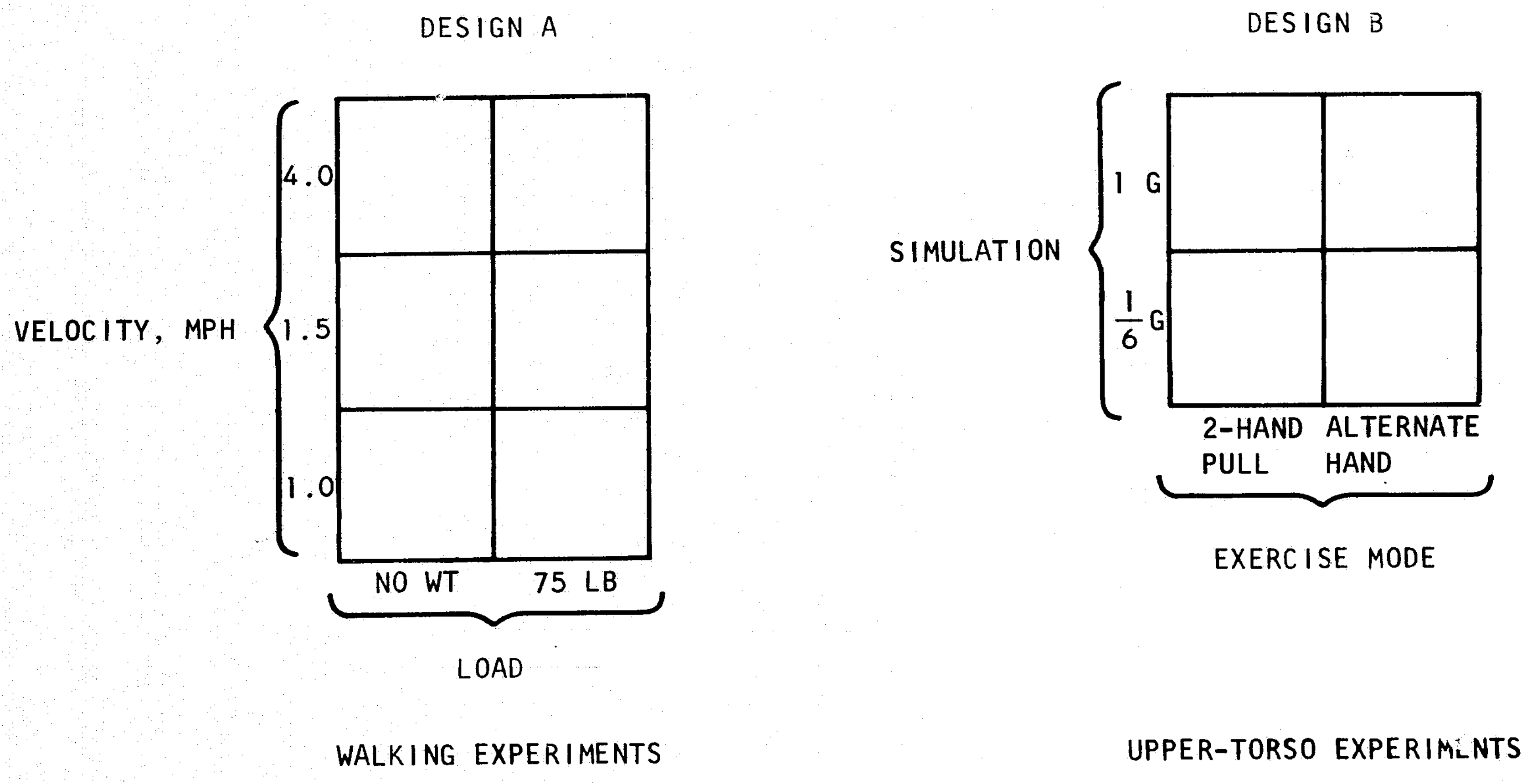

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Figure 1. Experimental Design

TABLE 1

ANTHROPOMORPHIC CHARACTERISTICS OF TEST SUBJECTS

Subject	Age, Years	Height		Weight		Body Surface Area, M^2
		in.	cm	lb	kg	
C. B.	22	69.75	177.2	156	70.8	1.88
D. B.	24	68	172.7	149	67.7	1.81
V. C.	42	68.75	174.6	175	79.4	1.94
M. G.	24	68.75	174.6	147	66.8	1.82
L. P.	31	70.5	179.1	148	67.3	1.85
R. W.	32	70.5	179.1	163.5	74.2	1.94
Mean	29.2	69.4	176.2	156.4	71.0	1.87

APPARATUS

General

All tests were performed in the AiResearch outdoor decreased-gravity simulator. A six-degree-of-freedom counterbalance suspension simulator was used in conjunction with a treadmill for the walking exercise tests. This simulator and a 1-g test configuration were used with a weight-pulley system described previously for the upper-torso exercise tests.

Six-Degree-of-Freedom Counterbalance Suspension Simulator

Lunar gravity simulation was accomplished in a simulator with the vertical suspension provided by a counterweight. The basic system, illustrated schematically in Figure 2, consists of a C-brace gimbal, a swivel, a yoke with air pad bearing, a cable and pulleys, a lightweight beam, and a counterweight. The system provides the six degrees of freedom desired for reduced-gravity simulation. Degrees-of-freedom sources are listed in Table 2.

This simulator differs from that used under Contract NAS 9-6494 (Reference 1). The two translation degrees-of-freedom were provided by air bearings rather than roller trucks, and the C-brace was much smaller and lighter. This simulator, therefore, tended to impose lower frictional forces than were observed in the simulator used in the contract noted above.

The six-degree-of-freedom suspension simulator was used in conjunction with a treadmill that had a walking surface of 5 ft by 16 ft. The belt speed was variable from 0 to 12 mph through a hydraulic drive system and could be adjusted continuously during operation. The neoprene treadmill belt had a rough surface.

Lunar gravity simulation was achieved by counterbalancing the entire weight of the C-brace, cabling, hoses, clamps, and metabolic rate measuring system components plus 5/6 of the subject's suited weight. Weighting was achieved with a load cell mounted in the vertical suspension cable. Using this technique, only 1/6 of the subject's suited weight was applied at the boot/treadmill interface.

For tests where the subject was to carry the equivalent of a 75-lb earth load, the subject was weighted with an additional 12.5 lb to his lunar weight.

One-G Test Configuration

The full-gravity test configuration conforms to the description above. The subject was weighted, however, so that the force at the boot/treadmill interface was equal to the total weight of the suited subject.

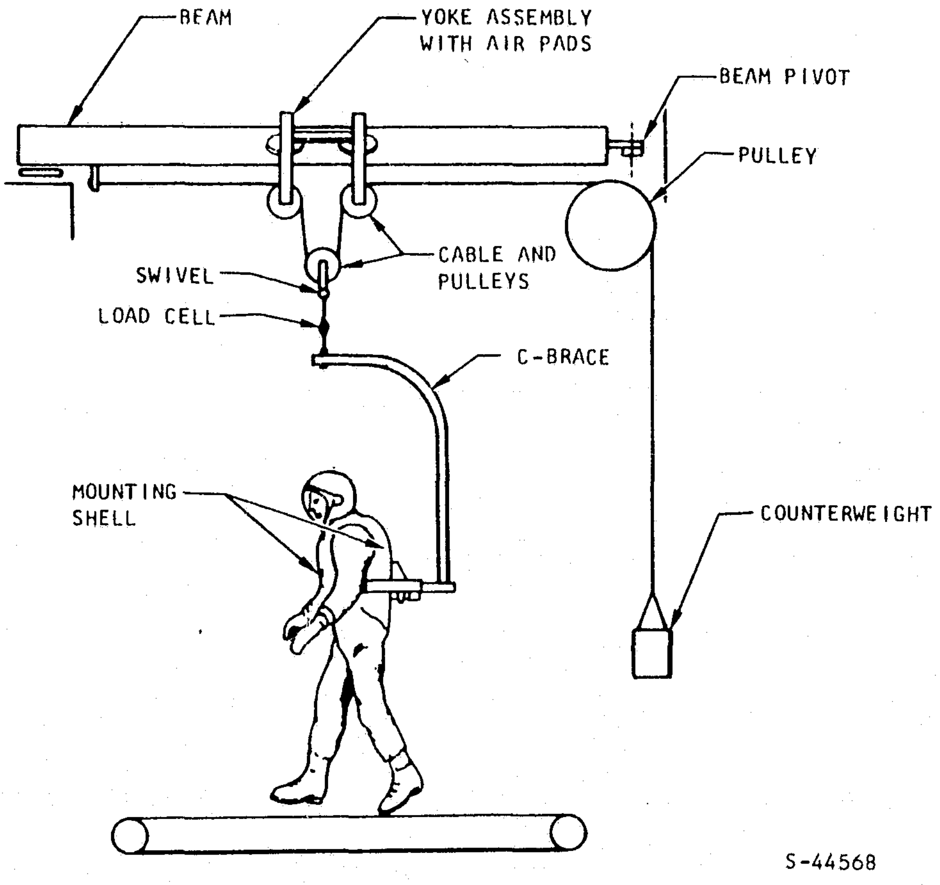

Figure 2. Counterbalance Suspension System

TABLE 2

TOSS DEGREES OF FREEDOM

Component	Degrees of Freedom
C-Brace Gimbal, pitch and roll	2
Swivel, yaw	1
Counterweight vertical	1
Yoke (with air pads), fore and aft	1
Beam (pivot and air pads), lateral	1
Total degrees of freedom	6

Apparatus for Upper-Torso Exercise

The weight-pulley system and upper-torso techniques developed for NAS 9-6494 for use with the six-degree-of-freedom simulator (Reference 1) were used for this test series. The mounting board for the pulley system was positioned at the end of the treadmill, so that all tests could be performed in the same simulator setting.

Instrumentation and Control Systems

The suit environmental control system and instrumentation used in this program were identical with those used for the Contract NAS 9-6494 investigation. There were minor differences, however, in the orientation of the equipment and in data acquisition. The major difference was the positioning of the housing containing the Franz-Mueller respirometer on the back half of the subject's mounting shell. This respirometer was modified with a magnetic switch of the reed type. The signal generated was fed into a ramping circuit that produces a cumulative breath volume signal. In addition, the expired gas lines were slightly longer and thus yielded a minor increase in the time constant for gas analysis.

SECTION 3

TEST PROCEDURES

PREPARATION

On arriving at the test facility, the subject was weighed. He then completed his nutritional questionnaire, the appropriate bioinstrumentation was attached, and his general state of health was noted. After donning a waffle-weave undergarment and the pressure suit, he entered the test area, the bioinstrumentation was connected to the dynagraph, and tracings were recorded. If the data readout was clear, the suit was closed. A nose clip was placed on the subject's nose, the gloves were donned, and the subject was positioned in the simulator used for that particular test. The suit inlet and outlet hoses were then connnected, the helmet closed, the suit ventilation inlet flow rates adjusted to 12 cfm, and the suit pressure regulated to the required pressure level. The subject was then lifted with the counterbalance system until his feet left the treadmill; weights were then added to the C-brace to correct any imbalance to the subject's center of gravity. The subject was then lowered onto the treadmill surface and weighted appropriately for the g field for that test.

When the test conductor was satisfied that the subject and all systems were ready, the first test count was started. Resting metabolic rates were measured for 4 min in 2-min blocks before each exercise event. The exercise event was then started and lasted for 14 min with continuous recording of physiologic and systems data. The data required for metabolic rates were measured every 2 min over the tests. The data recorded during the last 4 min of each event were used as steady-state data. Each exercise period was followed by a rest period, during which the heart rate was monitored to preexercise levels. This sequence was repeated over the test period.

The subjects first performed the walking (Figure 3) and upper torso (Figure 4) tasks in the six-degree-of-freedom counterbalance simulator without any additional load. The tests were presented randomly; the only restriction was that the two upper-torso tasks would not be performed consecutively. When this test series was complete, the subjects performed the walking tasks with the added weight. The 1-g upper-torso tasks were done in conjunction with these tasks, one test being performed before the 1/6-g testing and one after the walking modes were complete. The sequence was randomized during this second series of tests.

DATA COLLECTION

All data were recorded continuously in analog form. This permitted a constant check of the data as they were generated, as well as the physiologic status of the subject being tested. In addition to the analog data collection system, an analog-to-digital conversion system was used with automatic recording of all the digital data on punched paper tape. The format of this tape was programmed to match a computer link located within the test facility. This computer link is used in conjunction with an SDS 940 computer located at Tymshare, Incorporated. The computer program used for data reduction was based on the equations presented in Reference 1.

Figure 3. Pressure-Suited Subject Subject Walking at 1/6 G in the Counterbalance Simulator

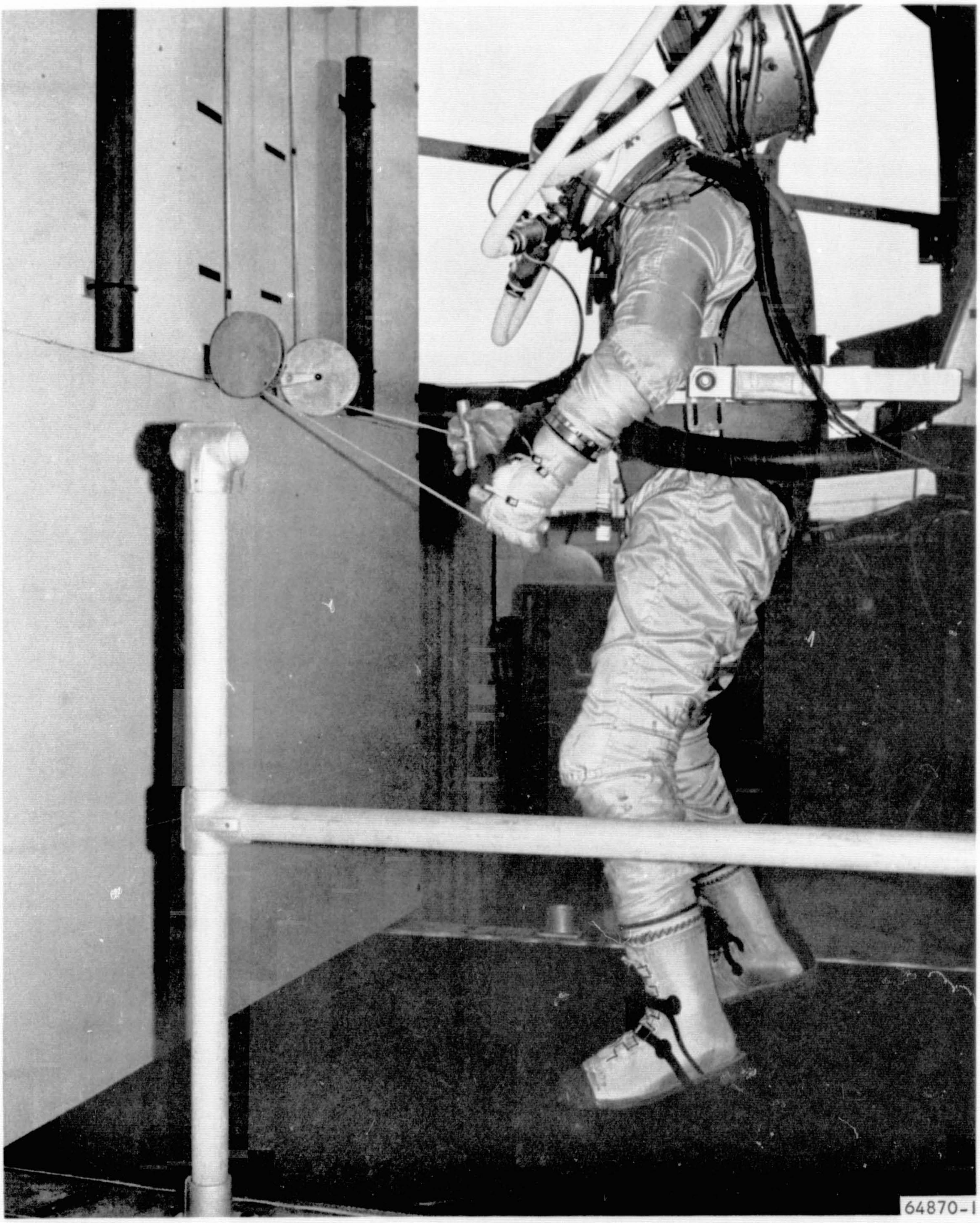

Figure 4. Pressure-Suited Subject Performing Alternate-Hand Upper-Torso Task at 1/6 G in the Counterbalance Simulator

SECTION 4

RESULTS

INTERNAL PRESSURE-SUIT CONDITIONS

The ranges of observed values for both monitored and controlled suit conditions are shown in Table 3. The suit gas flow, pressure, and inlet temperatures were controlled parameters. Suit gas flow and pressure were consistent. Inlet temperatures varied as the subject requested more or less cooling. Suit outlet temperatures again reached similar levels, regardless of exercise mode, as reported previously (Reference 1 and 2). Since cryogenic air was used as the gas source for ventilating the suits, the inlet dew point was always zero. The outlet dew points were relatively low in most walking tests at 1.0 and 1.5 mph. All subjects exhibited sweating at the 4 mph velocity. Sweating was very apparent in most of the subjects during the 1-g upper-torso tasks.

All tests were performed outdoors over a 10-day period. The ambient temperature during the test periods ranged from 63° to 71°F, with a mean temperature of 66.6°F. The barometric pressure ranged from 756.4 to 762.1 mm Hg, with a mean pressure of 758.9 mm Hg.

WALKING EXPERIMENTS

The physiologic costs of self-locomotion at 1/6 g in a pressurized Gemini series pressure suit while carrying two different loads are shown in Table 4. Metabolic rates increased significantly with velocity ($p < .01$) for each load-carrying condition. The differences between the metabolic rates obtained while carrying no load or carrying the added 12.5 lb lunar weight approached but did not reach statistical significance at the 0.05 level ($p < .07$).

The increased metabolic costs of carrying the additional weight was expected, and this increase would have been statistical if (1) the sample variance was less or (2) a larger sample had been studied.

A summary of metabolic rates is presented in Table 5. Row 1 presents the data as shown in Table 4; row 2, these data normalized for body surface area; row 3, the data normalized for the subject's nude weight as measured at 1g; and in row 4, the data from row 1, normalized for the subject's lunar weight equivalent. The equivalent lunar weight was derived from the subject's nude weight, plus the weight of the pressure suit assembly divided by 6. For the tests in which added weight was carried, this weight was added to the subject's nude weight and pressure suit assembly weight and divided by 6.

The data in Table 5 reflect a decrease in metabolic rate in simulated lunar gravity. Normalization of these data on a lunar-weight basis demonstrates a decrease in the efficiency of locomotion per kilogram of weight moved. It should also be noted that the subjects were more efficient when carrying the added weight, indicating an advantage in weight-carrying in simulated lunar gravity.

TABLE 3

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

Simulator	Gas Flow, cfm	Pressure, psi	Inlet Temperature, °F	Outlet Temperature, °F	Inlet Dew Point, °F	Outlet Dew Point °F
1/6-G 6-DOF	12 to 13	3.5	50 to 68	75 to 82	0	4 to 28
1-G	12 to 13	3.5	56 to 66	75.5 to 80	0	9 to 52

TABLE 4

PHYSIOLOGIC COSTS OF SELF-LOCOMOTION IN A PRESSURIZED GEMINI PRESSURE SUIT AT SIMULATED LUNAR GRAVITY

		Counterbalance without Added Weight			Counterbalance with 12.5 lb Lunar Weight		
		1 mph	1.5 mph	4 mph	1 mph	1.5 mph	4 mph
Metabolic Rate,	$\bar{x}$	2.50	3.00	6.37	2.88	3.28	7.32
kcal/min	±σ	±0.26	±0.92	±1.16	±0.28	±0.50	±1.19
$\dot{V}_{CO_2}$ STPD	$\bar{x}$	0.396	0.485	1.068	0.463	0.554	1.238
2/min	±σ	±0.038	±0.152	±0.207	±0.049	±0.084	±0.220
$\dot{V}_{CO_2}$ STPD	$\bar{x}$	0.483	0.591	1.302	0.560	0.677	1.426
2/min	±σ	±0.046	0.183	±0.262	±0.061	±0.096	±0.301
$\dot{V}_E$ BTPS	$\bar{x}$	15.027	17.909	33.235	16.292	18.677	36.106
2/min	±σ	±0.790	±5.282	±5.937	±1.627	±2.582	±6.935
Heart Rate,	$\bar{x}$	66.2	73.2	105.8	81	83.2	121.8
beats/min	±σ	±14.6	±14.2	±9.7	±16.1	±13.3	±11.0

TABLE 5

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

	Without Added Weight			With 12.5 lb Lunar Weight		
	1 mph	1.5 mph	4 mph	1 mph	1.5 mph	4 mph
Kcal/min	2.50	3.00	6.37	2.88	3.28	7.32
Kcal/min/M^2	1.34	1.60	3.41	1.54	1.75	3.91
Kcal/min/kg Earth weight	0.035	0.042	0.090	0.041	0.046	0.103
Kcal/min/kg Lunar weight	0.175	0.211	0.447	0.145	0.165	0.367

UPPER-TORSO EXERCISES

A summary of the physiologic costs of two upper-torso tasks at both 1/6 g and 1 g, performed while wearing a pressurized Gemini pressure suit, is given in Table 6 and shown graphically in Figure 5.

No statistical differences were noted between exercise modes either within g fields or between g fields. Thus, there was no difference between performing the upper-torso tasks with both hands simultaneously or with alternating hands. The average metabolic rates for the 1-g tasks were lower than for those performed at 1/6 g; however, they were not significantly different. Such differences have been demonstrated to be highly significant when performed in shirt sleeves (Reference 3). The lack of difference between the gravity fields while wearing the pressurized Gemini suit would indicate that the metabolic costs imposed by the suit masks the more subtle differences between g fields.

Table 7 presents the average metabolic rates for the upper-torso tasks, normalized as described for the walking tests. An apparent decrease in efficiency is noted when the data are normalized for the subject's lunar weight. However, at 1 g the subject at every 2 sec raised a weight that was approximately 6 percent of his nude weight, while at simulated 1/6 g he raised a weight that was approximately 30 percent of his lunar weight equivalent. This fivefold difference in proportional weights equates very closely with the magnitude of increase in metabolic rates. Thus, if these data were further corrected for work performed proportional to the subject's weight, there would be no difference in efficiency. It is probable that the subject would be unable to raise a weight proportionate to his earth weight at 1 g.

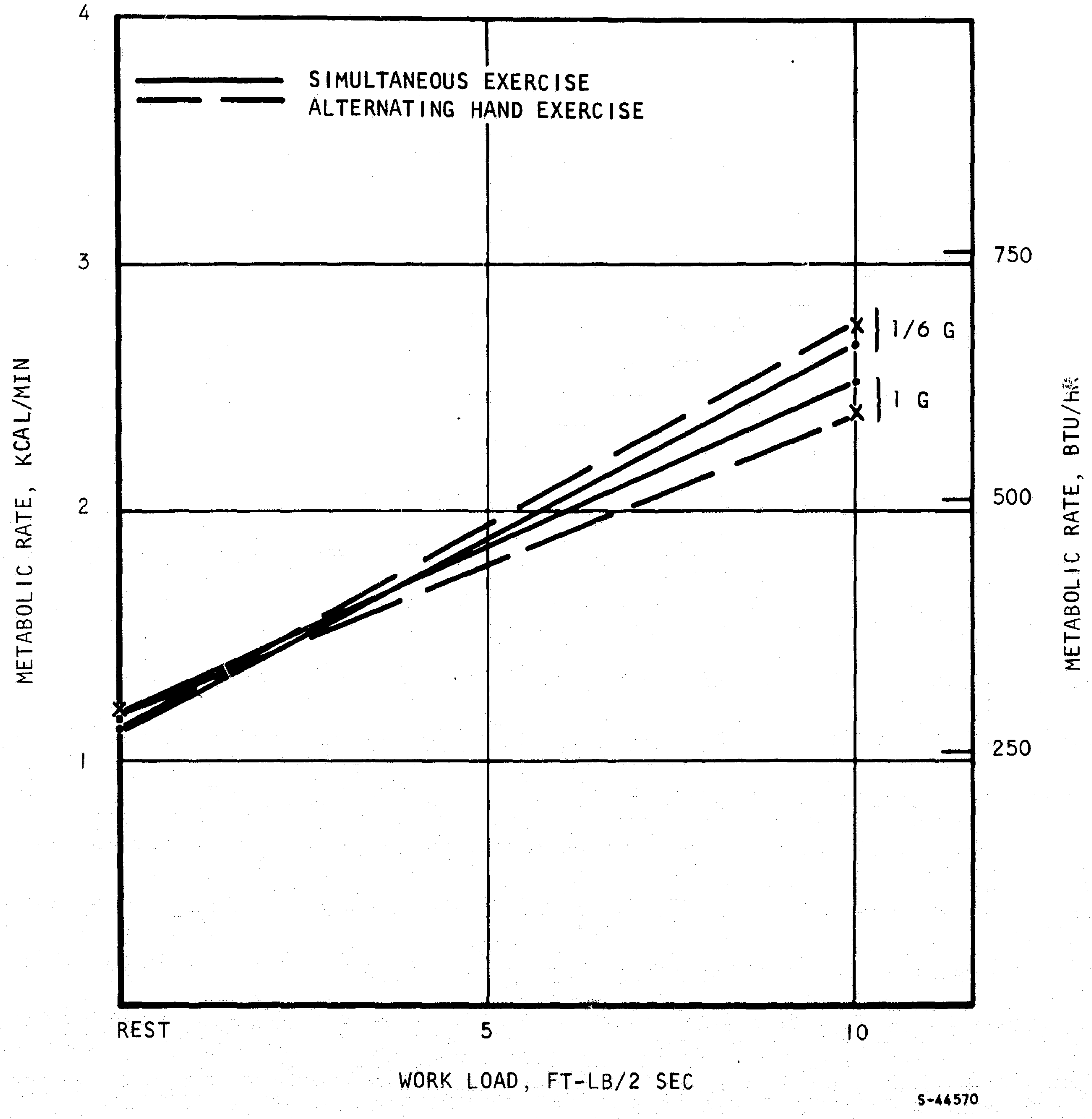

Figure 5. Metabolic Rate for Upper-Torso Exercise in Pressurized Gemini Suits at 1/6 G and 1 G

TABLE 6

PHYSIOLOGIC COST OF UPPER-TORSO TASKS PERFORMED IN A PRESSURIZED GEMINI PRESSURE SUIT

		1/6 g		1 g	
		Simultaneous	Alternate	Simultaneous	Alternate
Metabolic Rate,	$\bar{x}$	2.71	2.77	2.52	2.44
kcal/min	$\pm\sigma$	±0.32	±0.48	±0.43	±0.31
$\dot{V}_{CO_2}$ STPD,	$\bar{x}$	0.502	0.584	0.460	0.423
l/min	$\pm\sigma$	±0.108	±0.192	±0.061	±0.061
$\dot{V}_{O_2}$ STPD,	$\bar{x}$	0.611	0.636	0.550	0.510
l/min	$\pm\sigma$	±0.132	±0.191	±0.090	±0.073
$\dot{V}_E$ BTPS,	$\bar{x}$	19.931	19.790	18.019	17.512
l/min	$\pm\sigma$	±3.243	±4.571	±2.042	±1.871
Heart Rate,	$\bar{x}$	86.2	81	90.8	86.8
beats/min	$\pm\sigma$	±14.3	±23.3	±16.3	±18.8

$\bar{x}$ = mean
$\pm\sigma$ = ±1 standard deviation

TABLE 7

AVERAGE METABOLIC RATES FOR UPPER-TORSO WORK IN A PRESSURIZED GEMINI PRESSURE SUIT

	1/6 g		1 g	
	Simultaneous	Alternate	Simultaneous	Alternate
Kcal/min	2.71	2.77	2.52	2.44
Kcal/min/M^2	1.45	1.48	1.35	1.30
Kcal/min/kg Earth Weight	0.038	0.039	0.035	0.034
Kcal/min/kg Lunar Weight	0.190	0.194	--	--

SECTION 5

DISCUSSION

The results of the current self-locomotion tests support the previously demonstrated thesis (References 1, 2, 4, and 5) that the energy requirements for locomotion under simulated lunar gravity are less than in a 1-g environment. This decrease in metabolic rates results from having to provide the energy necessary to move only 1/6 of the weight of the individual and his suit.

Figure 6 presents a summary of the metabolic rates measured during locomotion in pressurized Gemini suits. All of these data were obtained in the AiResearch laboratories (References 2 and 4). The data obtained at 1 g are much higher than those obtained during any lunar gravity simulation. The curves generated from the data from this study with a counterbalance simulator are marked CW (counterbalance with no load) and CW + WT (counterbalance with 75-lb earth-weight load). Comparison of these data with the data from the the turbine-operated suspension simulator (TOSS) and inclined plane tests indicate no difference between the data when a 75-lb earth-weight load is carried in a counterbalance simulator at 1/6 g. Since carrying the additional weight yielded metabolic rates that approached statistical significance when compared to not carrying a load in the same simulator, it is probable that the data for at least the TOSS may be different from those obtained without additional weight in the counterbalance.

In general, it can be stated that similar tests performed in a pressurized Gemini pressure suit will not show a difference between simulators when metabolic rates are used as the criteria. It is apparent that this pressure suit is a relatively rigid suit that restricts the motions of the subjects, and the suit alone imposes a metabolic cost that masks any effects that might be due to the difference between the simulators themselves. To discriminate between these simulators, tests must be performed in shirtsleeves or in highly mobile suits that do not restrict the motions of the wearer.

Figure 7 presents a comparison of the data obtained from this study with the Gemini pressure suit and the more mobile state-of-the-art pressure suits now under development (Reference 1). The data for tests in the inclined plane (Reference 1) did not reveal any statistical difference between metabolic rates while locomoting the RX-2 and A5-L pressure suits. Since the metabolic data for tests with the Gemini suit on the counterbalance simulator without a load lie within the data for the RX-2 and A5-L suits on the inclined plane, it can be inferred that the G2-C data are not different from the RX-2 and A5-L data. The metabolic rates for carrying the 75-lb load in the Gemini suit on the counterbalance cannot be compared as easily with the previous RX-2 and A5-L data. Since the metabolic data for locomotion in the mobile suits were statistically lower in the counterbalance simulator when compared to the data for the inclined plane simulator, a similar relationship would be expected to hold for the G2-C metabolic rates obtained in this study. This, however, is not the case.

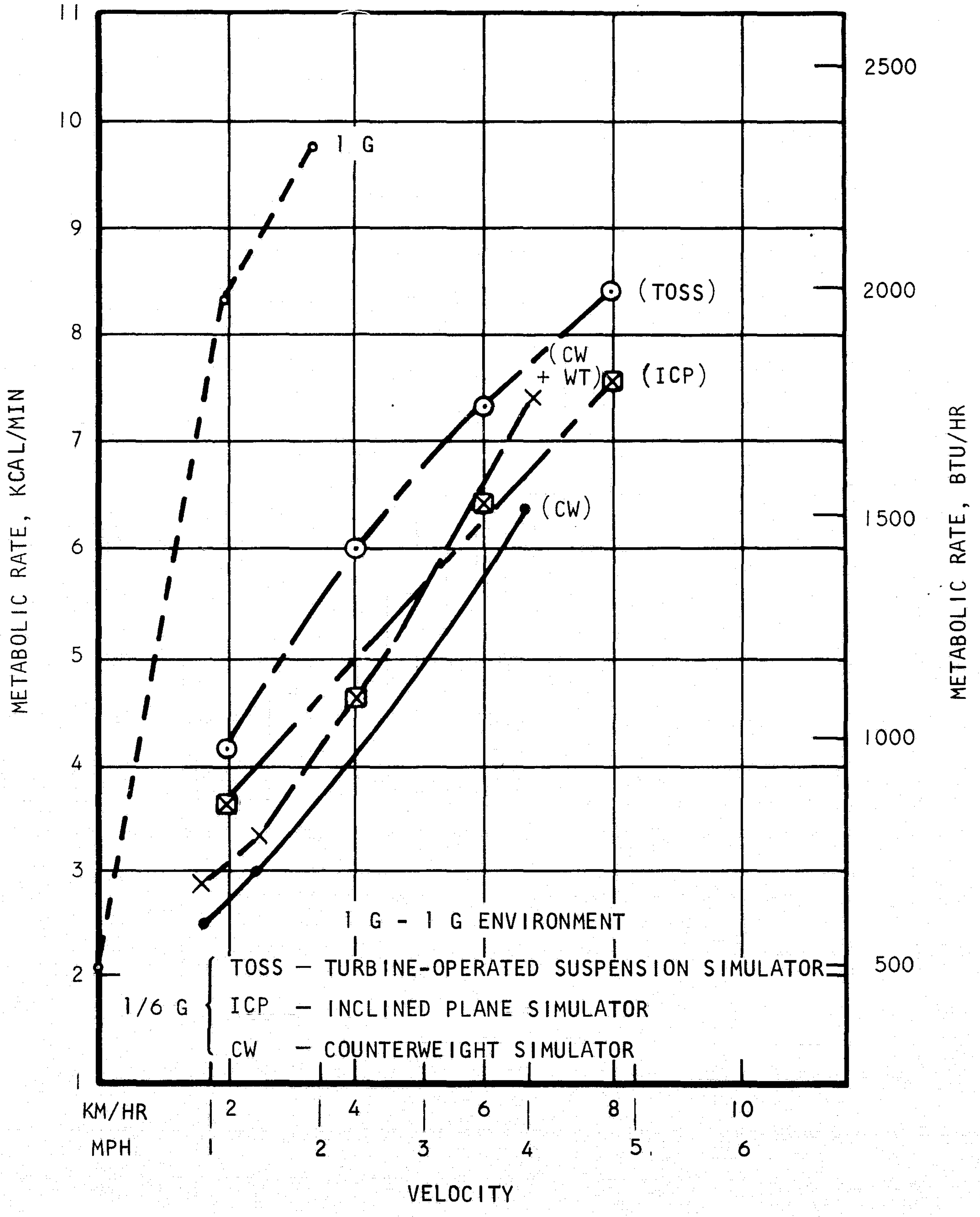

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Figure 6. Summary of Metabolic Rates for Locomotion in Pressurized G-2C Pressure Suits from Current Study and from Published Data (References 2 and 4)

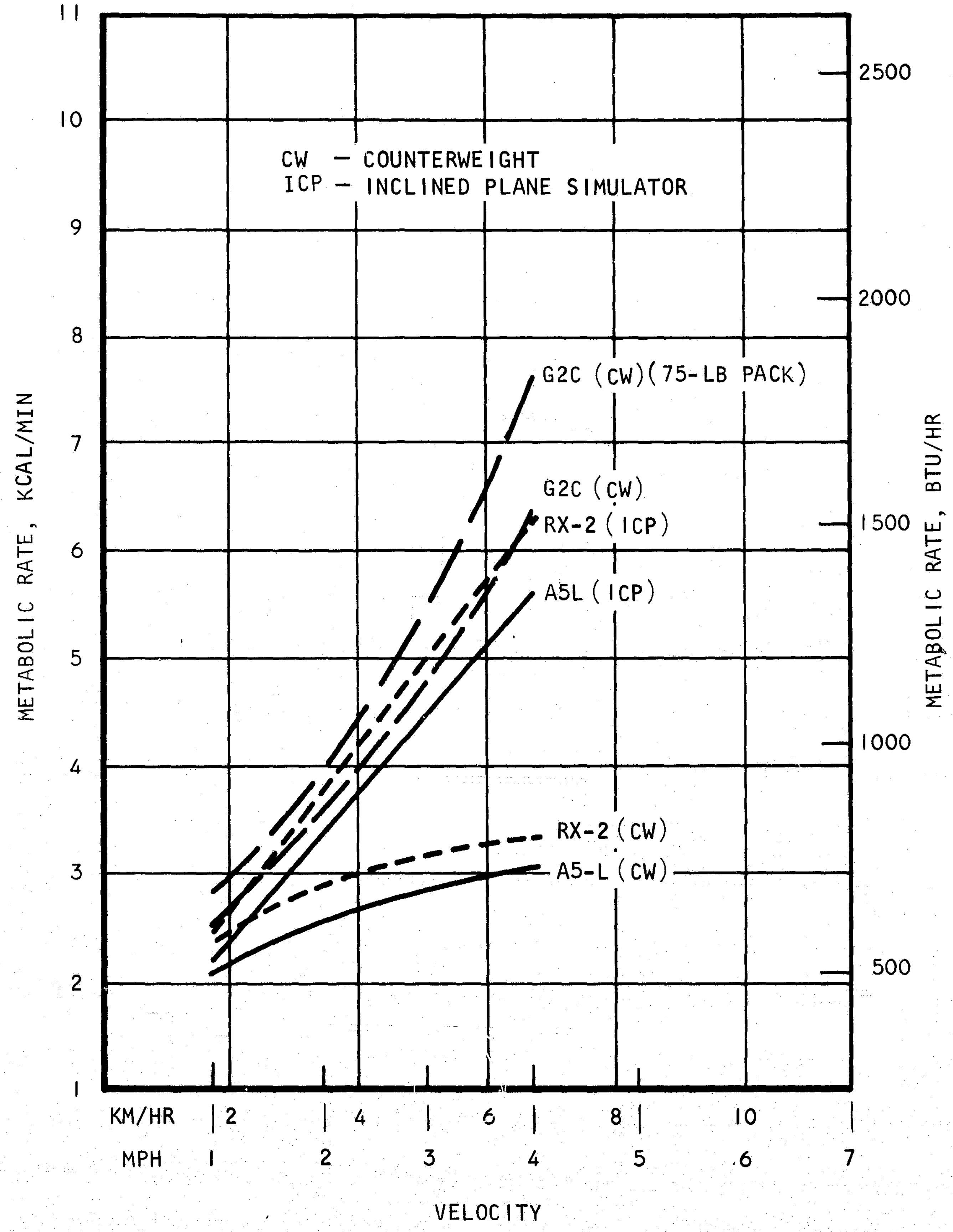

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Figure 7. Comparison of the Metabolic Cost of Self-Locomotion in Simulated Lunar Gravity with Three Different Pressure Suits

Based on the data shown in Figures 6 and 7, and the preceding comments on the comparison of these data, it is apparent that problems exist in deriving meaningful comparisons between the various simulation techniques. However, the following must be considered as potential effects based on these data: (1) it is readily apparent that simulator comparisons cannot be derived from tests performed with the Gemini pressure suit, and (2) if, in fact, the difference between the Gemini suit and the more mobile pressure suits at lunar gravity, as indicated with use of the counterbalance simulator, is real, and no difference exists between the G2-C data and the mobile suits in the inclined plane simulator, then the simulation techniques must be suspect as adequate techniques for simulating decreased gravity fields for this type of testing. However, such a conclusion is not completely warranted, since the data were derived at different times and with only two of the subjects participating in both programs. Further testing is necessary to determine whether this effect is real and, if it is real, the exact reason for such differences.

The physiologic data generated during the upper-torso tasks have provided little information to clarify the factors affecting upper-torso work in decreased gravity fields. The lack of significance between the metabolic rates measured at 1 g and 1/6 g in a pressurized Gemini suit indicates that the suit masks this previously reported potential effect (Reference 3).

The 1/6-g data for the Gemini suit tests are compared to the metabolic data obtained for upper-torso exercise with the RX-2 and A5-L pressure suits in Figure 8. There are no discernible differences between any of these data. The reason for this lack of difference is obscure.

One possible explanation is that all three suits provide approximately the same mobility in the arms and shoulders for this exercise vector. Another possible reason is that during testing the arms are operated in a 1-g field, even though the individual's torso is suspended at 1/6 g. The metabolic costs of the upper-torso activity are complicated by these factors. A systematic research program is necessary to understand the factors affecting upper-torso work in a decreased-gravity environment.

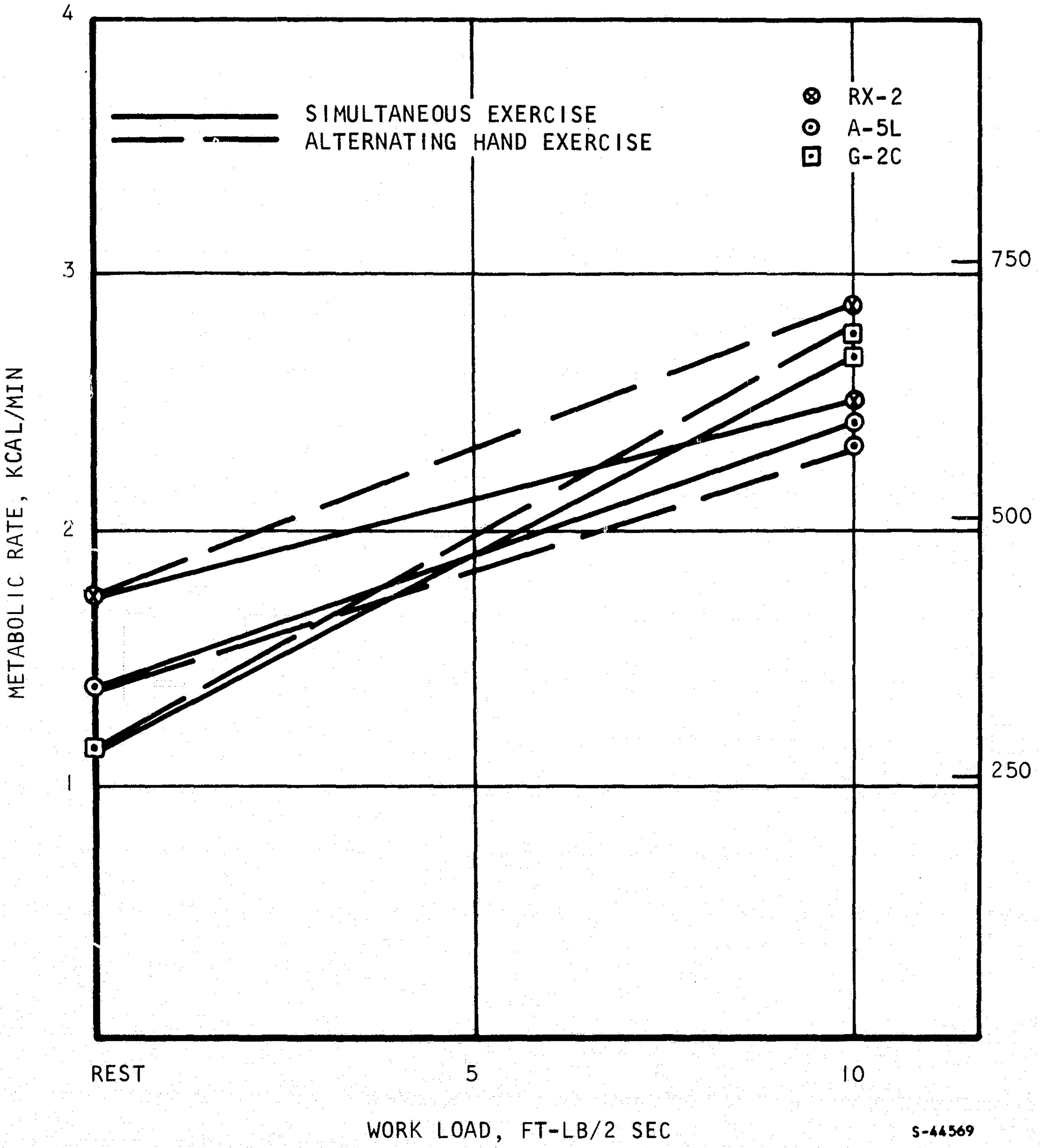

Figure 8. Metabolic Cost of Upper-Torso Exercise in Pressurized Suits at 1/6 G in Six-Degree-of-Freedom Simulators

SECTION 6

CONCLUSIONS

Results of the experiments led to the following conclusions:

(a) Metabolic rates (kcal/min) for walking are lower in the 1/6-g environment than in the 1-g environment

(b) Metabolic rates normalized for equivalent lunar weight (kcal/min/kg) show an increase in cost per kilogram at 1/6-g as compared to that at 1 g. This implies a decrease in efficiency with locomotion in lunar gravity.

(c) Metabolic rates were significantly increased with increases in velocity for locomotion in the G2-C pressure suit.

(d) Differences in the metabolic rates between carrying a 75-lb earth-weight pack at 1/6 g and carrying no additional weight approached significance.

(e) Due to the metabolic cost of using the Gemini pressure suit, potential differences between simulators could not be discerned. The Gemini series pressure suits should not be used in experiments designed to evaluate decreased gravity simulators.

(f) Metabolic rates were not different for performing upper-torso tasks at 1-g and 1/6 g in the Gemini pressure suit.

(g) Upper-torso work performed with both arms simultaneously or by alternating the arms was not significantly different in either g environment.

(h) Further testing is required to adequately evaluate simulator differences and to understand upper-torso work at decreased gravity.

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