Metabolic Rates in Pressurized Pressure Suits

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Four subjects wearing a full pressure space suit were tested in a high altitude chamber at sea level pressure and at simulated 34,000 feet with a suit pressurized to 3.5 psig. The subjects were exercised on a treadmill, and their metabolic rates were measured and compared with the heat removal rates from the suit by ventilating oxygen gas at 15 cubic feet per minute flow, 40°F dew-point temperature, and 70° and 80°F dry-bulb temperature. Avenues of heat loss other than by suit ventilation gas flow were minimized, so a heat balance was achieved between the subjects' metabolic heats, the heats removed by the ventilation system, heats stored by the subjects, and useful work ("efficiency") accomplished by the subjects. It was found that the gas flow was marginal for cooling at light work rates (at 180 kcal/m²/hr) and inadequate for heavier work, in which case the subjects apparently stored the excess heat. The metabolic rates observed with the pressurized suits were quite high, and represented approximately twice the rates observed in experimentation with unpressurized suits.

THE GENERAL OBJECTIVES of this program were to ascertain the metabolic rates of personnel wearing a full pressure suit*, and to effect a "heat balance" of the subjects' metabolic heat with the heat removed by the environmental control system.

These experiments were conducted in the AiResearch high-altitude chamber. The simulated altitude runs were conducted at 34,000 feet altitude equivalent pressure, with the suit pressurized to 3.5 psi above chamber pressure. The suit was covered by a reflective outer garment, and radiant heat transfer was further minimized by heating the chamber walls. The ventilation gas inlet conditions, as measured at the suit inlet connector, were 100 per cent oxygen (excluding water) at 15 cubic feet per minute, 70°F dry-bulb temperature, and 40°F dew-point temperature. Four subjects walked on a horizontal treadmill at various speeds to produce the desired elevated metabolic rates.

In addition to the experiments carried out at altitude, four tests were conducted at sea level in order to ascertain the validity of extrapolating sea level test results and data to altitude conditions. The only change in inlet conditions for the sea level experiments was an increase in the inlet dry-bulb temperature from 70 to 80°F. The sea level tests were unsuccessful in duplicating the results of the tests at 34,000 feet.

The general conclusions are (1) that a high rate of energy expenditure is required for walking in the pressurized pressure suit, this rate being at least twice that required for walking in an unpressurized pressure suit, and (2) that the ventilation gas inlet characteristics are marginal for removing metabolic heat even at moderate work loads.

*Supplied by International Latex Company.

From the AiResearch Manufacturing Company.

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SUBJECTS

Prior to the selection of subjects, the potential test subjects were screened by a FAA Class I medical examination to ensure physical competence and conformity with experimental requirements, an altitude-chamber indoctrination program that included lectures on the physical, physiological, and psychological effects of low pressure, and a low-pressure exposure (6.3 psia) in the altitude chamber. After selection, the four remaining test subjects were familiarized with the test apparatus and the experimental design, and were trained to walk on the treadmill. The physical characteristics of the subjects selected to participate in this experiment are listed in Table I.

TABLE I. BASIC DATA ON TEST SUBJECTS

Subject	Age (yrs)	Weight (kgm)	Height (cm)	BSA (m²)
JP	25	73.71	170.18	1.85
WH	23	74.27	174.62	1.88
RV	21	68.60	170.81	1.79
RG	34	68.60	177.80	1.85

APPARATUS

The altitude chamber used in this work had an internal volume of 750 ft.^{3}, and was equipped with a 250 ft.^{3} airlock and with windows for visual observation of the test subject and observer. The mechanism used to induce the elevated metabolic rates on the test subjects was a variable-speed, level treadmill. The altitude chamber wall and ambient temperatures were maintained at 96°F by electric blankets wrapped around the chamber. Two of these blankets formed a door-like partition inside the chamber to prevent heat leaks from the airlock-door area. Thermocouples were placed at various locations on the internal wall of the chamber and in the ambient chamber air to permit monitoring and regulation of wall and ambient temperatures.

The environmental control system used for this experimentation was designed specifically to maintain the selected suit flow rate, temperature, pressure, and relative humidity. This system is diagrammed schematically in Figure 1.

Suit-inlet and -outlet dew-point temperatures were measured within ±0.5°F by two AiResearch-built instruments which function by observation of condensa-

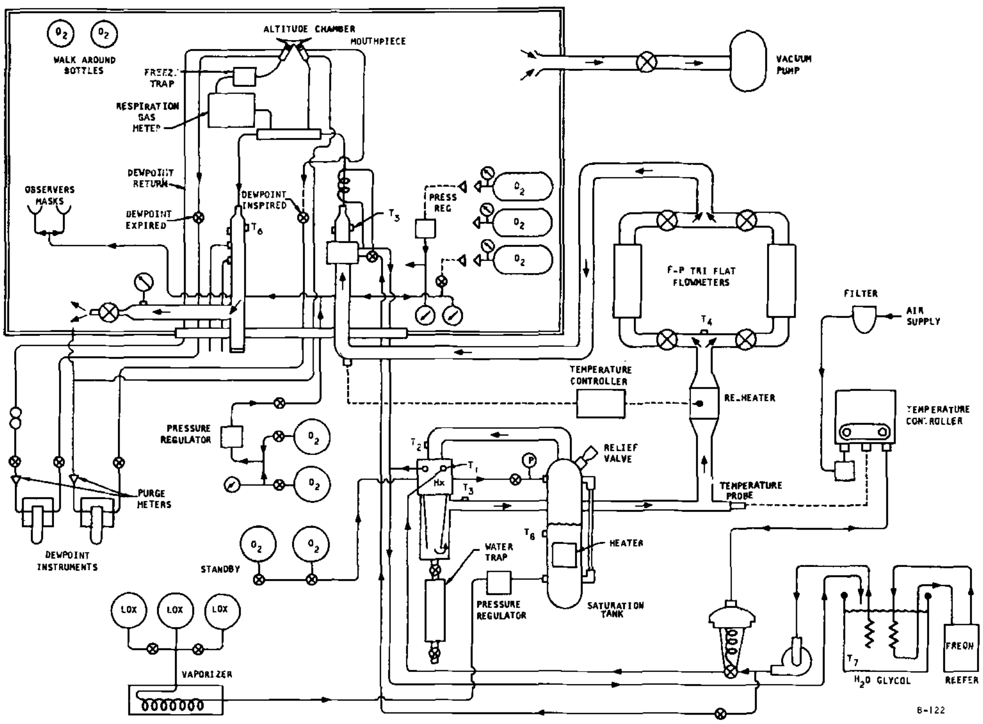

Fig. 1. Schematic diagram of environmental control system used in this experiment.

tion on thermally controlled mirrors. Samples were collected at the suit-inlet and -outlet quick-disconnect fittings and were ducted through heated stainless steel lines to the instruments. The gas sample leaving the heated dew-point cell then passed through a variable-area purgemeter and into a diaphragm pump for return to the altitude chamber. Trained personnel can operate the dew-point instruments reliably with a reproducibility of 0.25°F.

The expired and inspired gases were analyzed for carbon dioxide content with a Beckman IR15-A infrared analyzer; a Beckman F-3 oxygen analyzer was employed to determine oxygen partial pressures. From these analyzers the gas sample was returned through a sample return line to the appropriate flow section so that the sampling system was kept a closed loop.

PROCEDURE

Upon arrival at the test facility, each subject was medically examined in order to ensure his physiological and psychological ability to carry out the experimental regimen successfully. The nude weight of each subject was measured and recorded at this time as well as at the end of the test day. The dietary intake on the day of the experiment was also noted; it was found, however, that all test subjects were in the post-absorptive state by the time the first metabolic rate was measured.

The various bioinstrumentation sensors were then affixed to the subject's body. An exploring electrocardiogram electrode was placed in a modified V-4 position close to the apex of the heart. Skin temperature thermocouples were placed in the subject's axilla and on the inner surface of his groin. A rectal temperature thermistor probe was inserted so that the base of the probe was situated beyond the anal sphincter; in no case was this probe ejected. A short-time-constant thermistor was placed on the microphone boom to indicate respiration rate and to detect nasal breathing during the metabolic rate determinations.

When the bioinstrumentation sensors were applied and secured to a supporting harness; a two-piece cotton underwear garment was donned by the subject, and the bioharness again adjusted and secured. The subject then donned the pressure suit. The bioinstrumentation wires were connected and the electrical continuity of the sensors was checked before the suit torso zipper was closed. The gloves and boots were put on and the suit restraint harnesses adjusted to ensure proper fit and maximum mobility. Before the helmet was donned, the faceplate and the mouthpiece for the respiration system were positioned. The helmet was then put over the subject's head; the respiration thermistor was connected to the bioharness prior to inserting the base of the helmet into the neck ring. A reflective garment consisting of six layers of reflective mylar was then donned to help minimize radiant-heat transfer from the suit. The subject was then connected to the chamber environmental control system.

During the donning procedure, the test subject and the test observer were required to breathe 100 per cent oxygen to ensure blood denitrogenation. This period of denitrogenation lasted for a minimum of one hour.

After all equipment was checked for proper function, the first mode of experimentation was started. In this mode, the subject remained at sea level in the resting condition until the selected criteria for thermal and physiological equilibrium were satisfied. The criteria for equilibrium were steady outlet dew-point and dry-bulb temperatures from the suit, and a stable pulse rate and rectal temperature from the subject.

When this steady state was observed, the subject's metabolic rate was determined. The subject placed the mouthpiece in his mouth and began breathing suit gas that was ducted through the two respirometers as illustrated schematically in Figure 2. The subject breathed on the mouthpiece until his respiration was regular and steady; he continued breathing through the mouthpiece until the gas analyses for oxygen and carbon dioxide were completed. During these analyses, two determinations of ventilated volume were made, each for a six-minute period. Oxygen consumption and carbon dioxide production, and hence metabolic rate, could then be calculated from the change in the partial pressures of these gases in a known quantity of ventilated gas. Because of the restricted volume inside the helmet, a nose clip was not employed; however, nasal breathing, as detected by the thermistor just below the subject's nose, was not permitted during metabolic rate determinations. Upon completion of the metabolic rate determination, the subject removed the mouthpiece from his mouth and resumed normal oral-nasal breathing.

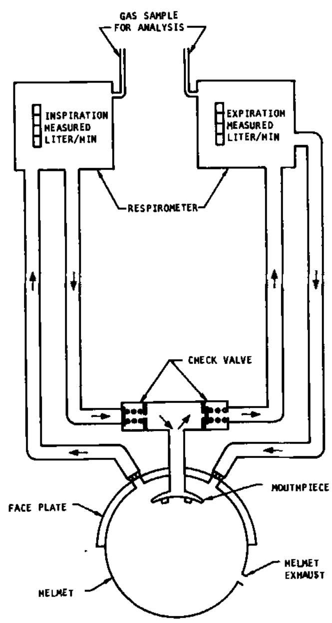

Fig. 2. Schematic diagram of respiratory circuit.

When sufficient data had been collected for the steady-state resting condition at sea level, the chamber was evacuated to the test simulated altitude (34,000 feet) and stabilized. The subject remained at rest while the suit was pressurized to 3.5 psig above the chamber pressure. When the suit-outlet environmental parameters (dew-point temperature, dry-bulb temperature, and gas flow rate) were observed to be stable at this pressurized resting condition, a measurement of metabolic rate was made in the manner described above. When these data had been recorded, the subject again stopped breathing on the mouthpiece and was prepared for the next test condition.

The subject then stood on the treadmill while the various instrumentation and ventilation lines were secured so that they would not interfere with the treadmill or obstruct the subject as he walked. After a preparatory count, the subject began walking as the treadmill was started at its minimum speed of 0.4 mph. The subject continued walking until the suit outlet gas conditions and the physiological measurements were stable, at which time he began breathing through the mouthpiece. A determination of the subject's metabolic rate was then made at this steady state while he walked at 0.4 mph.

Upon completion of this test condition, the treadmill was stopped and the subject was seated for the subsequent resting condition. The suit was depressurized and the subject made as comfortable as possible. The subject remained at rest until the environmental and physiological measurements again indicated that a stable state had been achieved, at which time another metabolic-rate determination was made in the unpressurized resting condition. Because of the normal suit-to-cabin pressure differential from the suit and the outlet ducting, the subject was at a slightly higher pressure than chamber ambient in this "unpressurized" state.

When the subject was sufficiently rested to continue walking, he was placed on the treadmill in the same manner as before, the suit pressurized to 3.5 psig, the treadmill started, and the treadmill speed adjusted to 1.2 mph. When the various measurements were stable, the metabolic rate was determined by partial pressure spirometry as before. Following this 1.2-mph condition, the subject was allowed a rest period (with the suit unpressurized) before starting further exercise periods.

Physiological and environmental measurements were recorded throughout the entire experimental sequence, although the results reported are for the conditions of stability described above. The sea-level experiments were conducted in exactly the same fashion as described above for the altitude experiments, save that the chamber remained at ambient barometric pressure, and the inlet dry-bulb temperature was increased to 80°F to simulate the reduced sensible heat capacity of the low-pressure ventilating gas at altitude.

During the initial experiments, attempts were made to achieve a preselected metabolic rate of 930 Btu/hr.; it was found, however, that the treadmill's minimum speed (0.4 mph) induced a metabolic rate higher than this value. Subsequent experiments included deliberate attempts to achieve a 1600-Btu/hr. metabolic rate by adjusting the treadmill speed on the basis of metabolic rates observed at the treadmill speed of 1.2 mph. These attempts were carried out in the same manner as those previously discussed; these tests continued until the desired rates were obtained or until lack of time prevented further experimentation.

The raw environmental and thermodynamic data were reduced by an IBM 7074 computer, which computed the latent, sensible, and total heat removed from the suit by the ventilating gas stream. An IBM 7074 computer was also programmed to compute an analysis of variance when given a multicell matrix with a varying number of entries per cell. The two matrices which were statistically evaluated using the computer are shown in Table II. Matrix 1 has a single row which represents the resting activity condition, and four columns which represent the two levels of pressurization and the two simulated altitudes. Matrix 2 contains

TABLE II. MATRIX 1 — MATRIX OF INDEPENDENT VARIABLES FOR ANALYSIS OF VARIANCE

Column 1 Sea Level Unpressurized	Column 2 Sea Level Pressurized	Column 3 Altitude Unpressurized	Column 4 Altitude Pressurized

MATRIX 2 — MATRIX OF INDEPENDENT VARIABLES FOR ANALYSIS OF VARIANCE

	Column 1 Sea Level, Pressurized	Column 2 Altitude, Pressurized
Row 1 Resting		
Row 2 Treadmill at 0.4 mph		
Row 3 Treadmill at 1.2 mph		

three rows representing resting, walking at 0.4 mph, and 1.2 mph; the columns represent the condition of the suit pressurized at sea level and at altitude.

The raw and computed data for the various dependent variables were entered in the appropriate cells of these two matrices. These variables were pulse rate, rectal temperature, axillary skin temperature, respiration rate, metabolic rate, sensible heat removal rate, latent heat removal rate, and total heat removal rate. The computer performed an analysis of variance for each of these completed matrices (e.g., Pulse Rate, Matrix 1; Pulse Rate, Matrix 2; etc.). For every significant F-ratio which was obtained, the computer computed the appropriate "t" scores. The cell means and the general matrix means were also printed out by the computer. A probability of less than 0.5 that the differences were a result of chance was accepted as significant.

RESULTS AND DISCUSSION

The primary results of this experimentation are graphed in Figures 3 and 4, which show the metabolic rates of the subjects plotted against the concomitant heat removal rates from the suit by ventilation. Figure 3 depicts the results for the altitude tests (simulated 34,000 feet), and Figure 4 depicts those for the sea level tests. It is apparent from these figures that the metabolic rates observed during this experimentation were quite high. Further, these metabolic rates are considered conservative because of the occurrence of oxygen debt at high exercise rates, and the voluntary control of nasal breathing (it is not thought that any appreciable degree of nasal breathing occurred; however, any which did occur would result in diminished oxygen consumption through the mouthpiece circuit). Comparison of these metabolic rates with metabolic rates observed in our laboratory for subjects walking in unpressurized suits indicates that suit pressurization entails a large metabolic cost for similar rates of walking.[1] In general, it appears that metabolic rates for subjects exercising in pressurized suits are approximately 100 per cent greater than the corresponding rates in unpressurized suits.

In setting up a heat balance, the heat removed from the suit must be compared with the metabolic heat generated by the subject. In this experiment, precautions were taken to minimize radiant and convective heat loss from the outside of the suit, so the only routes of heat removal were by latent and sensible transfer by the ventilating gas stream. Under these conditions, the difference between the ventilation heat removal and the metabolic rate represents the sum of body heat storage and the energy expended by the subject in moving the suit and walking on the treadmill. The energy expended in walking and moving the suit is usually described in terms of efficiency, which is the percentage of heat expended as useful work; recall that this strictly physical measure of efficiency is not the same as the "efficiency" with which an individual walks.[2,3]

With reference to Figure 3, it can be seen that a considerable discrepancy exists between the heat removed from the suit by ventilation and the subject's metabolic heat. For the experiments conducted at simulated altitude (34,000 feet), there is approximately a 335-Btu/hr.

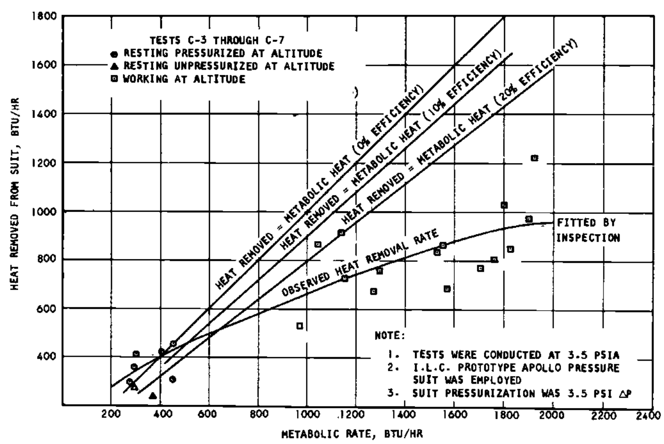

Fig. 3. Metabolic rates of subjects plotted against suit ventilation heat removal rates, for tests conducted at simulated altitude.

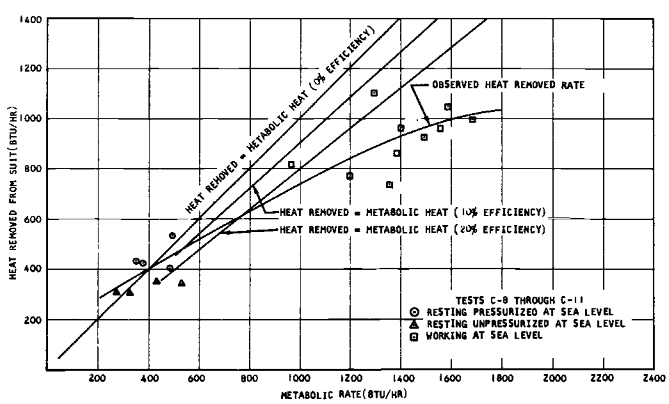

Fig. 4. Metabolic rates of subjects plotted against suit ventilation heat removal rates, for tests conducted at sea level.

difference between the heat removed from the suit and the metabolic heat at a metabolic rate of 1000 Btu/hr., assuming zero efficiency. Assumptions of 10 per cent and 20 per cent efficiency reduce this discrepancy to 235 Btu/hr. and 135 Btu/hr., respectively. At a metabolic rate of 1600 Btu/hr., these differences are approximately 780 Btu/hr. assuming zero efficiency, 560 Btu/hr. at 10 per cent efficiency, and 390 Btu/hr. at 20 per cent efficiency. At a metabolic rate of 2000 Btu/hr., these differences approach 1040 Btu/hr. and 840 Btu/hr. and 620 Btu/hr. for zero, 10 per cent and 20 per cent efficiencies respectively. This discrepancy between metabolic rate and heat removed from the suit (latent and sensible) by the oxygen flow must be accounted for in terms of the efficiency of walking in the pressurized suit, by storage of body heat, by radiant heat loss, and by sources of experimental error. The metabolic rate determinations, as discussed above, are considered conservative. Radiant heat loss was unlikely, because reflective coveralls were used and tank wall and air temperatures were maintained at or above skin temperature. Since other sources of experimental error may be considered random, and consequently tending to cancel each other out rather than reinforcing error in either direction, it would appear that the discrepancies between metabolic rate and heat removed from the suit at zero efficiency are conservative (or minimal) estimates of the combined values of body heat storage and energy expended as work. Since human work is rarely more than 20 per cent efficient, it may be assumed for the purpose of discussion that the true value of the body's heat production lies somewhere between the Heat Removed = Metabolic Heat 10 per cent and 20 per cent efficiency lines. This assumption leads to the conclusion that under these experimental conditions, 135 Btu/hr., 390 Btu/hr., and 620 Btu/hr. were stored in the body at energy expenditures of 1000 Btu/hr., 1600 Btu/hr., and 2000 Btu/hr., respectively.

Inspection of the sea level data indicates that under the sea level conditions, with the inlet temperature elevated to 80°F, and with an assumed efficiency of 20 per cent, heat was stored at rates of 60 Btu/hr. and 270 Btu/hr. for energy expenditures of 1000 Btu/hr. and 1600 Btu/hr., respectively. Consequently, the sea level experimentation cannot be considered representative of conditions at altitude. This conclusion is further substantiated by the analysis of variance conducted on the dependent variables.

Of particular interest, primarily for its unvarying nature, is the suit-outlet dry-bulb temperature observed in these tests. The stability of the outlet temperature, which was average 90°F with a standard deviation of only $\sigma = 1.04°F$, is consistent with data obtained in 78 tests conducted by the experimenters prior to this experiment.

The analysis of variance conducted for the various dependent variables for each of the resting modes (Matrix 1) indicated a significant effect of the experimental conditions only on pulse rate and on sensible heat removal. Subsequent analysis by the method of Student's "t" revealed that the effects of the independent variables were exhibited by the differences in pulse rate between the sea level unpressurizd and the sea level pressurized conditions, and by the differences in pulse rate between the sea level unpressurized and the altitude pressurized conditions only. The effect of the experimental conditions on sensible heat removal was exhibited by significant values of "t" for all conditions except between the sea level unpressurized and sea level pressurized conditions. The means of these resting data are presented in Table III.

TABLE III. MATRIX 1 — CELL MEANS FOR PARAMETERS EXHIBITING SIGNIFICANT CHANGES

Parameter	Column 1	Column 2	Column 3	Column 4	General Mean
Pulse Rate, Beats/min.	73.600	84.500	78.000	90.714	80.840
Sensible Heat, Btu/hr.	275.966	199.170	97.715	169.719	205.409

The only other parameter on which these conditions produced an effect of nearly statistical significance was metabolic rate. Here, it is felt, the variance within each subject and between subjects was sufficiently large to mask the effects of the independent variables with this small number of subjects and test samples.

The analysis of variance conducted in the two-way classification table for the joint effects of work rate and altitude on the dependent variables (Matrix 2) indicated that work rate (resting, 0.4 mph, and 1.2 mph) had a significant effect on pulse rate, latent heat production, total heat removal, and metabolic rate. This analysis also indicated that the independent variable "altitude" had a significant effect only on the sensible heat removal rate from the suit. The means of these parameters are tabulated in Table IV. It is of special interest that work rate and altitude did not exhibit significant interaction effects upon the dependent variables measured. This would support the tentative hypothesis (unconfirmed by this experiment) that altitude conditions might adequately be simulated at sea level by manipulation of the rate of sensible heat removal.

Comparison of results by the method of Student's "t"

TABLE IV. MATRIX 2 — CELL MEANS FOR PARAMETERS EXHIBITING SIGNIFICANT CHANGES

Parameter	Row	Column 1	Column 2	General Mean
Pulse Rate,	1	84.500	90.714	
Beats/min.	2	98.500	121.833	107.704
	3	138.000	133.500	
Metabolic Rate,	1	429.250	387.097	
Btu/hr.	2	1241.275	1010.650	970.215
	3	1570.000	1754.250	
Sensible Heat,	1	199.170	169.719	
Btu/hr.	2	198.873	188.482	182.266
	3	200.285	152.380	
Latent Heat,	1	250.300	245.420	
Btu/hr.	2	612.493	592.001	496.794
	3	816.711	764.722	
Total Heat,	1	449.470	415.139	
Btu/hr.	2	811.366	780.482	679.060
	3	1016.996	917.102	

for cells within matrices of dependent variables exhibiting significant F-ratios provided the following conclusions. Sea level pulse rate at rest did not differ significantly from the altitude pulse rate at rest or from the 0.4-mph pulse rate at sea level, but did differ significantly from pulse rates at all other conditions. Metabolic rates were not significantly different between the 0.4 mph and the 1.2 mph conditions at sea level only; there were significant differences in metabolic rate from the other work rate conditions. Comparison of all other combinations of conditions indicated that for a given work rate there was no significant effect of altitude on metabolic rate.

Comparison among all combinations of conditions indicated that sensible heat removal was significantly different only between sea level and altitude conditions at rest and between sea level and altitude conditions at the 1.2 mph work rate. Latent heat removal was significantly different for all comparisons of conditions with the exception of differences between sea level and altitude conditions for rest, 0.4 mph, and 1.2 mph. Also, no significant difference was exhibited between 0.4 mph and 1.2 mph at altitude, although significance was approached. Analysis of the data with respect to the total heat removed from the suit (latent plus sensible heat) indicates exactly the same results as noted for latent heat removal.

Other conclusions of a general nature which may be drawn from these results are: (1) that walking in the pressurized pressure suit required a metabolic energy expenditure of at least 100 per cent greater than that required for the unpressurized suit as measured in previous experimentation, and (2) that the cooling capability of the suit ventilation oxygen flow at these test conditions was marginal for light work (180 kcal per sq. meter per hr.) and inadequate for heavier work.

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