10. OXYGEN-CO_2-ENERGY

Prepared by

E. M. Roth, M. D., Lovelace Foundation

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10. OXYGEN-CO_2-ENERGY

The factors determining oxygen consumption and CO_2 production of men during various tasks on Earth is covered in the first part of this Compendium, followed by data for zero gravity and subgravity environments. The second part covers the effects of the oxygen and carbon dioxide partial pressure environments on human physiology and performance in space operations.

ENERGY-OXYGEN RELATIONSHIPS

Oxygen consumption and heat production data are important in determining how much oxygen must be supplied a man for specific space missions, in designing respiratory equipment which will allow him to do heavy work, and in arranging cooling equipment which will remove the heat his body produces.

The expenditure of human energy can be monitored: (1) by direct measurement of work output; (2) by direct measurement of heat output; (3) by measuring total caloric intake and subtracting the stored amount; (4) by measuring the turnover of fuels in the body; (5) by measuring carbon dioxide production, an index of fuel oxidation; and (6) by measuring oxygen consumption (122, 181).

Direct calorimetry measures heat output as heat and requires elaborate apparatus. Indirect calorimetry depends on the calculation of heat production from the gaseous products involved in the combustion of food. (See Nutrition, No. 14.) The two methods used in indirect calorimetry are called "closed" and "open." In the "closed" method pure oxygen is breathed in a loop circuit with a spirometer wherein CO_2 is absorbed chemically and O_2 consumption is measured from the reduction in mean volume of the system. In the "open" system, breathing air, both O_2 consumption and CO_2 production are calculated from the volume and composition of expired air. This permits one to establish the ratio of CO_2 produced to O_2 consumed (Respiratory Quotient, RQ). The latter varies according to the proportion of carbohydrates, proteins, and fats participating in the metabolic process and determines the caloric equivalent per liter of O_2 consumed. For instance, at moderate activities (RQ = 0.96), energy expenditure (Q kcal/min) is calculated from O_2 consumption ($\dot{V}$ liters/min) as:

$$Q = 5 \dot{V}_{O_2} \tag{1}$$

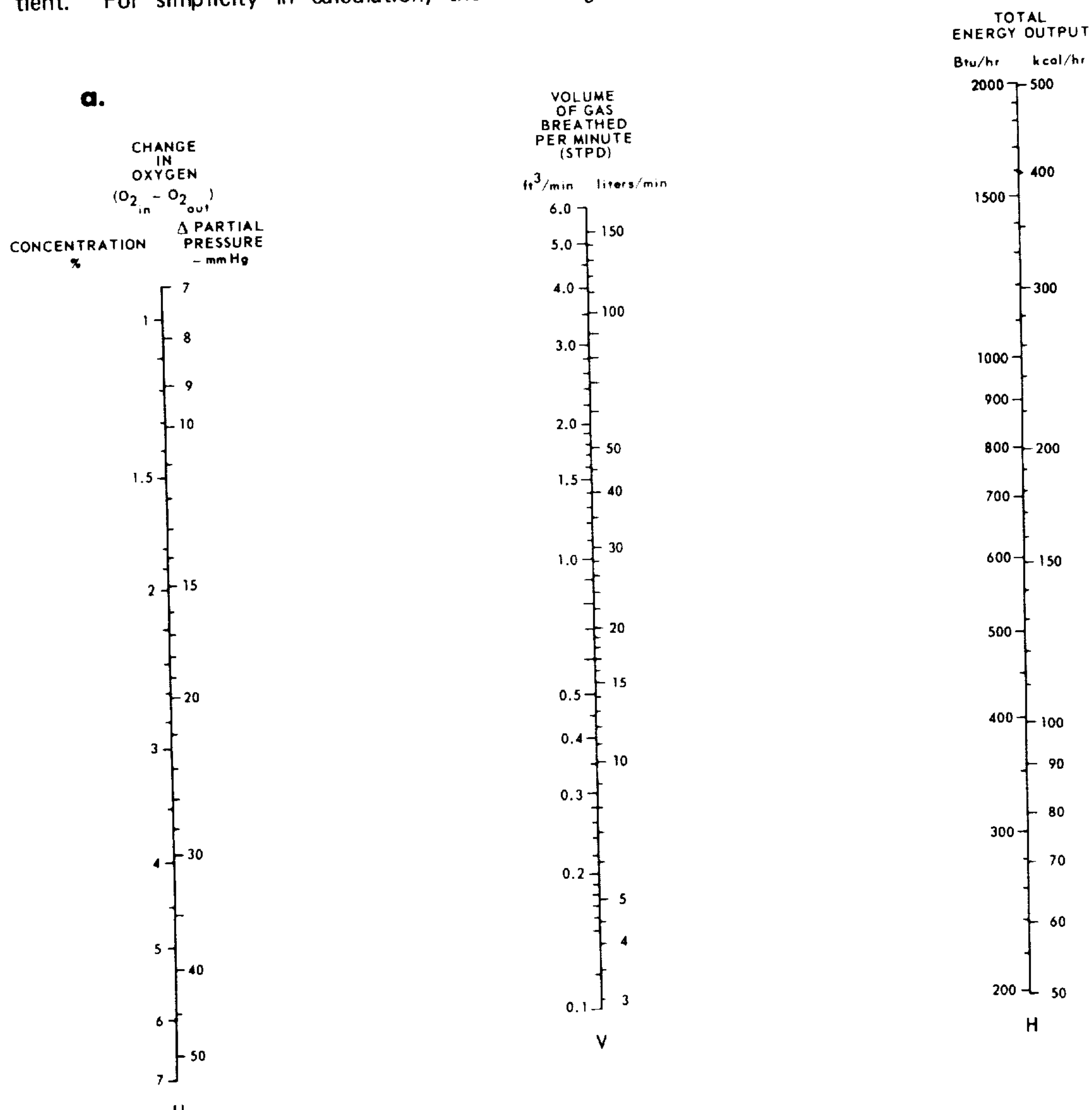
In order to perform this conversion on a molar basis, it is necessary to correct measured gas volumes to physical standards of $0^{\circ}C$, 760 mmHg and dry gas, expressed by the abbreviation STPD (standard temperature and pressure, dry). Figures 10-1 and 10-2 are nomograms and equations which can be used to determine interrelated metabolic data from respiratory data.

Figure 10-1

Oxygen Costs - Nomograms

(After Fletcher[85])

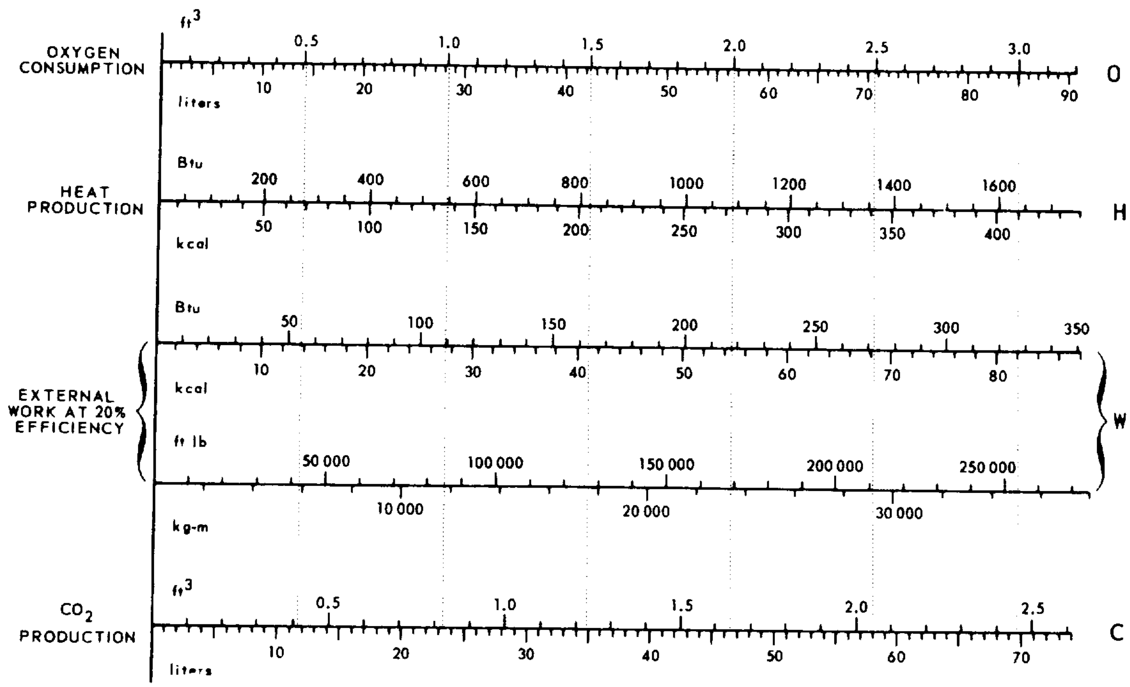
Heat output is determined from respiratory data in the following way. First, the oxygen consumption is calculated from the respiratory ventilation volume of the subject and the difference in oxygen concentration between the inspired and expired air. Second, the volume is corrected to $0^{o}C$, 760 mm Hg, dry (STPD); this is particularly important at reduced atmospheric pressures. Third, the heat output corresponding to each unit volume of oxygen is selected, either by approximation or from a knowledge of the subject's diet or from his measured respiratory quotient. For simplicity in calculation, the following two nomograms have been constructed.



Nomogram a uses the standard values: RQ = 1.00 and 1 liter of oxygen is equivalent to 5.0 kcal. It permits direction calculation of heat output (H) in Btu/hr from oxygen uptake (U) and ventilation rate (V). Alternatively, U can be calculated from H and V, or V from U and H.

Figure 10-1 (continued)

b.



Nomogram b uses the standard values: RQ = 0.82 and 1 liter of oxygen is equivalent to 4.825 kcal. This nomogram allows one to interrelate, by drawing straight vertical lines, the values for oxygen consumption (O), heat output (H), external work output (W), and carbon dioxide production (C), at typical conversion rates. Note that H may be as much as 3% lower or 5% higher than the quoted value at any specific oxygen consumption, depending on the RQ, which equals 0.7 for a pure fat diet and 1.00 for a pure carbohydrate diet. Values given in the third and fourth lines have to be modified if the efficiency changes. Typical ranges are 5 to 25%, average 20%, so that the listed work output may increase by three-quarters if the task is one that can be performed at high efficiency (e.g., bicycling). Conversely, the true value may be reduced by three-quarters if the function is inefficiently performed, e.g., high speed walking.

Figure 10-2

Oxygen Costs - Equations

(After Fletcher[85])

a. Formulas for calculating the energy equivalent of any given oxygen consumption:

For any gas mixture, $K = \theta \times O_{cons}$

where K — is the energy expenditure,
θ — is the energy equivalent per unit volume of oxygen consumed, and
O_{cons} — is the volume of oxygen consumed, STPD (0°C, 760 mm Hg, dry).

If breathing gas mixtures, $K = \theta \times (O_{in} - O_{out})$

where O_{in} — is the volume of oxygen (STPD) supplied to the mask, suit, or cabin, and
O_{out} — is the volume of oxygen (STPD) leaving the mask, suit, or cabin.

If breathing air, $O_{in} = 20.93\%$ and $K = V(20.93 - O_{exp\%})$ with error less than 1%

where V — is the volume of air (STPD) exhaled, and
$O_{exp\%}$ — is the percentage of oxygen in the expired air.

Values for θ:		
	Pure fat diet; during prolonged exhaustion:	θ = 525.3 Btu/ft^3, 4.686 kcal/liter
	Mixed diet:	θ = 545.0 Btu/ft^3, 4.825 kcal/liter
	Pure carbohydrate diet; heavy exertion:	θ = 565.8 Btu/ft^3, 5.047 kcal/liter

b. Formulas for calculating gross and net oxygen costs and efficiencies:

Gross values

--below maximum aerobic capacity*

$$C_{gross} = \frac{O_{work}}{T_{work}} \qquad E_{gross} = \frac{W \times 100}{C_{gross}}$$

--above maximum aerobic capacity

$$C'_{gross} = \frac{O_{work} + O_{debt}}{T_{work}} \qquad E'_{gross} = \frac{W \times 100}{C'_{gross}}$$

Net values

--below maximum aerobic capacity

$$C_{net} = \frac{O_{work} - O_{rest}}{T_{work}} \qquad E_{net} = \frac{W \times 100}{C_{net}}$$

--above maximum aerobic capacity

$$C'_{net} = \frac{O_{work} + O_{debt} - O_{rest}}{T_{work}} \qquad E'_{net} = \frac{W \times 100}{C'_{net}}$$

Oxygen debt

$$O_{debt} = O_{recovery} - O_{rest}$$

(measured over the same time interval, which must be adequate for the oxygen consumption to return to normal)

where C_{gross}, C'_{gross}, C_{net}, and C'_{net} are rates of oxygen consumption,
O_{work}, O_{rest}, O_{debt}, and $O_{recovery}$ are quantities of oxygen consumed,
E_{gross}, E'_{gross}, E_{net}, and E'_{net} are efficiencies (in percentage units),
W is the quantity of external work produced, and
T_{work} is the time during which work is performed.

* The maximum aerobic capacity is a characteristic measurement for each individual; it is influenced by the individual's state of training, his age (Fig. 10), and other factors.

Figure 10-2 (continued)

C. Formulas for calculating energy cost and variance of walking on a level with load

For speeds between 2.0 and 4.5 mph, the following equations give predictions for the energy cost of marching and its variance:

$$E = K + Y$$

$$K = 0.0083\ (10 + W + L)\ e^{v/50}$$

$$Y = 0.56 \pm 0.0091\ W$$

$$\sigma^2 = 0.017\ e^{v/25}$$

where E = total energy expenditure in kilocalories per minute,

K = energy expenditure in kilocalories per minute above resting expenditure,

Y = resting energy expenditure in kilocalories per minute,

σ^2 = variance in K,

W = body weight in kilograms,

L = load carried in kilograms,

v = marching velocity in meters/min, and

e = exponential constant.

Conversion factors to other units of energy are:

1 kcal = 3.96 BTU
= 427 kgm
= 309 ft lb
= 0.00156 hp hr

Basal metabolic rate, measured at absolute rest in the fasting state, is commonly expressed in percent of a predicted value based on body surface area, sex, and age. The medical profession applies a time-honored "within 15%" rule to clinical evaluation of basal metabolic rates. This rule is supported by a reliability study which established a 99% probability that an individual's true basal metabolic rate will not deviate from the mean of his norm group by more than 15% (107). The Dubois (68) expression for body surface is: (Figure 10-3)

$$A = W^{0.425} \times H^{0.725} \times 0.007184 \qquad (2)$$

where A = surface area (m^2)

W = weight (kg)

H = height (cm)

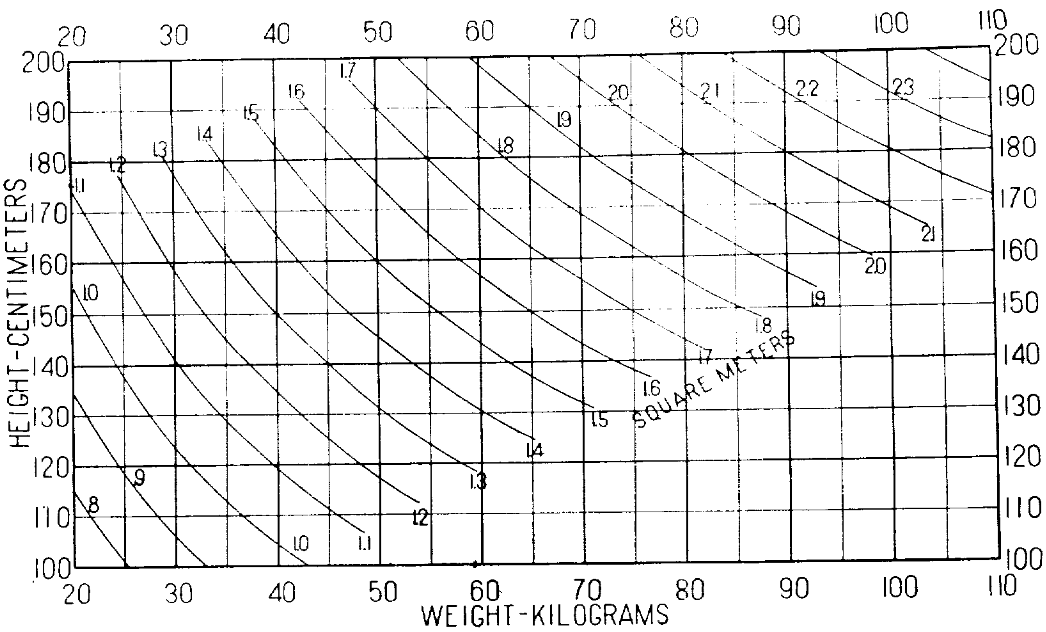


Chart for determining surface area of man in square meters from weight in kilograms and height in centimeters.

Figure 10-3

Body Surface Area Determination

(After Dubois[68])

For men age 35, the basal metabolic rate is given as 39.19 kcal/m^2/hr. Multiplying this value by the Dubois area will give a good first approximation of the BMR for a particular Astronaut.

For estimating the energy cost of various activities it is acceptable to use simplified calculations without CO_2 determinations, as presented in Figure 10-2a, with an error of less than 1%.

Energy Cost of Work

The average daily oxygen consumption on Earth for different heat outputs, body size, and diets is seen in Figure 10-4. The data for energy and nutritional requirements in orbital flight are presented in Nutrition, (No. 14). The total daily energy requirement for different operational exercise routines on Earth is presented in Figure 10-5. These are of value in estimating survival requirements in remote places on Earth.

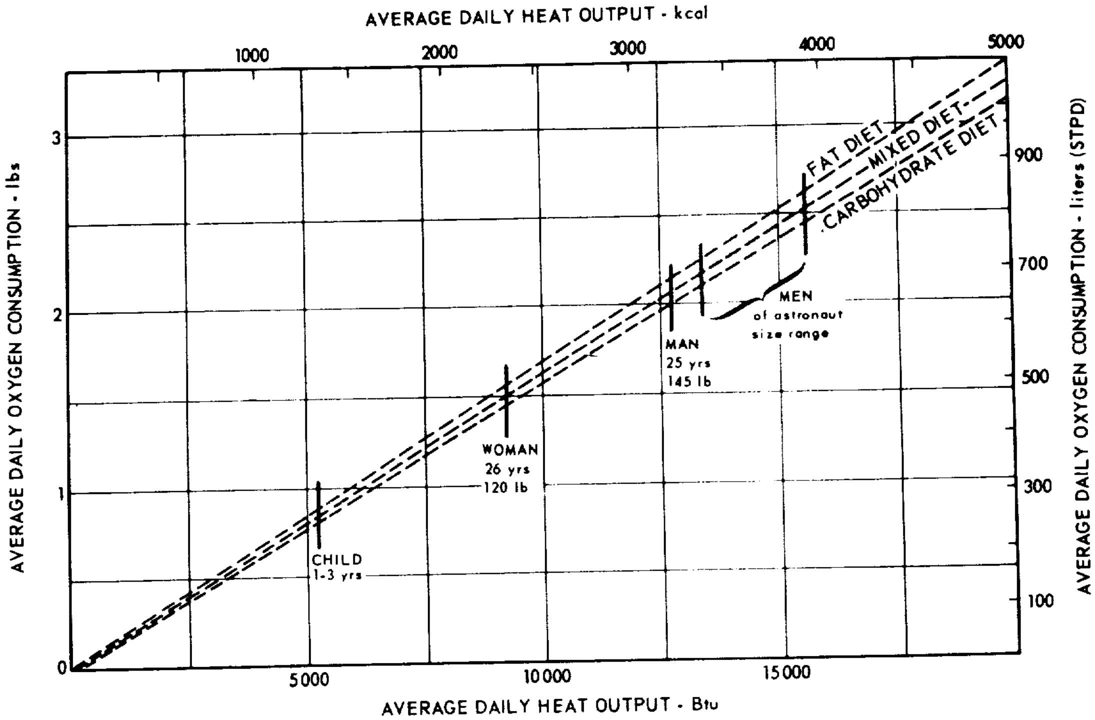
Physical work can be generally classified as to its severity as in Table 10-6. The severity of several tasks on Earth has been classified in the same way. Table 10-7 represents the energy cost of special activities which parallel the energy costs of activity in survival situations on Earth or in driving vehicles or aircraft. Because of the modifying factors of inflated suits and subgravity states, these energy costs should not be used directly for extravehicular operations without the approximate correction factors to be discussed below (211). Since large men consume more oxygen than small men, it is suggested that as a rough approximation for survival studies on the Earth, the values given be increased by 7.5% for large astronauts and reduced by 6% for small astronauts, based upon the size range of the men in current NASA programs. Important subject-to-subject differences exist even in men of the same size. These commonly give rise to variations as high as 60% when different men are performing the same task, as high as 30% when adjustments for body size are made, and as high as 10-15% when repeated measurements are taken on the same man.

The problem of the efficiency of energy conversion to external work is of interest (211). Factors which must be considered in appraisal of overall efficiency of performance include the rate of work, the load, the duration and quality of work, rhythmicity, and the speed of recovery in intermittent tasks. It is, of course, quite difficult to assess all these variables independently for any given task. Efficiency is expressed by the formulas in Figure 10-2b. The individual variation in mechanical efficiency for any given task is relatively small. In a review of the literature it has been suggested that during work on the bicycle ergometer the standard variation in mechanical efficiency was only ±8% of the found values for athletes, normal healthy people, and people with heart and respiratory troubles, provided the work level was adapted to the capacity of the individual (11).

The efficiency with which external work is produced also varies widely. It is lowest in the work of respiration (less than 5%); is 10-20% for common tasks, and highest at high work loads in bicycling and walking on the inclined treadmill (up to 26%) in trained men. When non-steady-state values for oxygen consumption are used, values up to 35 or 40% have been reported (211). Variations of these magnitudes must be allowed for in using the tables. To obtain closer estimates, measurements must be made on each astronaut in tasks closely simulating the actual task to be performed.

There are several terrestrial categories of locomotor tasks whose variables are pertinent to survival and lunar operations. These are presented in Tables 10-8 and 10-9. The effect of slope and speed which are seen in Tables 10-7, 10-8, and 10-9 are dissected in Figures 10-10 and 10-11. These data indicate the rather severe progression in energy requirement as treadmill slopes up to 25% are negotiated. The 25% slope requirement of up to 15.8 kcal/min approaches the 20.2 kcal/min for walking on the level in soft snow with a 20 kg load. From Table 10-8 it can also be seen that the negotiation of downhill slopes of 25% takes considerably more energy at 2.6 mph than does level treadmill walking at the same speed.

Oxygen cost referred to in Figure 10-10 includes the oxygen debt which is inevitably incurred in short sprints at high speed and is paid off after the event. The highest actual O_2 consumption ever reported for man is 6.17 L/min (218). More recent investigations have shown that the oxygen costs increase linearly with running speeds in the range from 150 to 360 m/min (13). The oxygen debt capacity has been found to be only slightly higher than the maximum aerobic minute value. The oxygen requirements for running a 4-min.



Body size is the most important determinant of average daily oxygen cost. This chart shows representative values for a child of 1-3 years, a woman of 25 years weighing 120 lb, and a man of 25 years weighing 145 lb. The values were calculated according to the method of the UN Food and Agriculture Organization, and assume that all three live at a mean annual temperature of 50° F and are neither sedentary nor very active. For comparison, the requirements of men of the size and age of the average of the Mercury astronauts are also given.

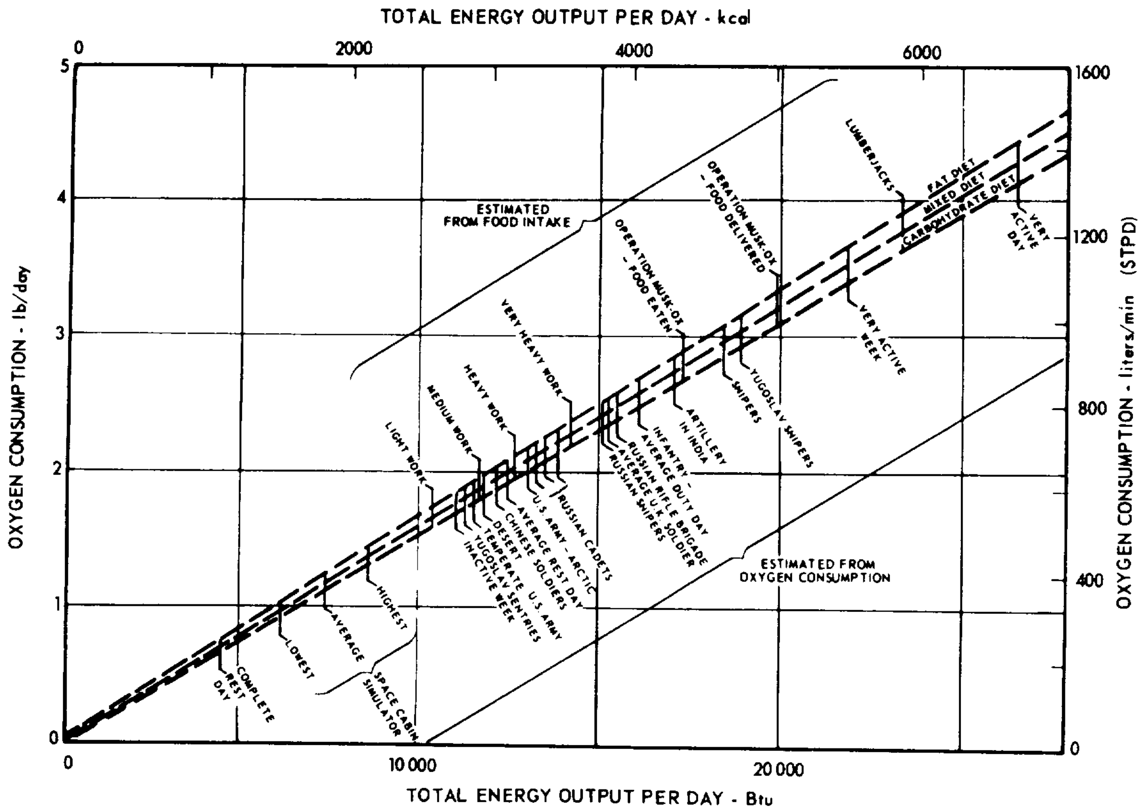
Modifications to the calculated values must be made for differences in environmental temperature. At 70° F the comparable daily expenditures, averaged over a year, would be reduced by 5%.

The three dashed lines show the values for oxygen consumption for different dietary mixtures.

Figure 10-4

Daily Oxygen Costs and Body Sizes

(After United Nations Food and Agriculture Organization[247])



This chart contains data on the total daily energy exchanges of adults. Vertical axes give total oxygen consumption. Horizontal axes give total energy output.

There are two methods of calculating daily energy exchange. The preferred method is by indirect calorimetry, in which oxygen consumptions are measured and a complete time-activity study is made. Representative figures for soldiers, derived by using this technique, are given on the lower half of the diagram as an indication of the wide day-to-day and week-to-week variation within a uniform group, and of occupation-to-occupation variations.

The alternative method is by precise estimation of food intake and body weight change. Since not all food is absorbed, and since changes in body weight are not all due to energy storage or liberation, this is a difficult technique to use accurately. Representative figures obtained from food intake are given in the upper half of the diagram as an indication of light, medium, heavy and very heavy work in industry on a year-round basis. Also given are the approximate food-supply and food-eaten figures for Operation Musk-Ox, which was a 4-month, 3400-mile motorized journey across Northern Canada in winter. Long distance journeys across the moon will require special planning for food and oxygen supplies. Values obtained in space cabin simulator trials have been added as a guide to in-flight requirements. Highest values regularly recorded are for lumberjacks, whose food intake contains much fat

Figure 10-5

Oxygen Costs of Daily Routine

(After Fletcher[85], adapted from many sources)

Table 10-6

Classification of Physical Work by Its Severity

(After Fletcher (85), adapted from Christensen (51))

	lb O_2/hr	kcal/min	Btu/hr
Very light work	below 0.10	below 2.5	below 595
Light work	0.10 - 0.19	2.5 - 5.0	595 - 1190
Moderate work	0.19 - 0.28	5.0 - 7.5	1190 - 1785
Heavy work	0.28 - 0.38	7.5 - 10.0	1785 - 2380
Very heavy work	0.38 - 0.47	10.0 - 12.5	2380 - 2975
Unduly heavy work	over 0.47	over 12.5	over 2975

Table 10-7

Oxygen Costs of Special Activities

(After Fletcher(85) from many sources)

SPECIAL ACTIVITIES

		Typical values for		
		lb O_2/hr	kcal/min	Btu/hr
Engineering tasks				
Medium assembly work		0.11	2.9	680
Welding		0.12	3.0	720
Sheet metal work		0.12	3.1	760
Machining		0.13	3.3	800
Punching		0.14	3.5	840
Machine fitting		0.17	4.5	1060
Heavy assembly work--noncontinuous		0.20	5.1	1210
Driving vehicles and piloting aircraft				
Driving a car in light traffic		0.05	1.3	300
Night flying--DC-3		0.06	1.6	380
Piloting DC-3 in level flight		0.07	1.7	400
Instrument landing--DC-4		0.10	2.5	590
Piloting light aircraft in rough air		0.11	2.7	640
Taxi-ing--DC-3		0.11	2.9	680
Piloting bomber aircraft in combat		0.12	2.9	700
Driving car in heavy traffic		0.12	3.2	760
Driving truck		0.13	3.3	790
Driving motorcycle		0.14	3.5	840
Moving over rough terrain on foot				
Flat firm road	2.5 mph	0.11-0.19	2.8-4.9	660-1140
Grass path	2.5	0.12-0.20	3.2-5.1	760-1240
Stubble field	2.5	0.16-0.23	4.0-6.1	960-1440
Deeply plowed field	2.0	0.19-0.27	4.9-6.9	1160-1640
Steep 45° slope	1.5	0.19-0.27	4.9-6.9	1160-1640
Plowed field	3.3	0.30	7.8	1850
Soft snow, with 44 lb load	2.5	0.79	21.0	4850

Table 10-7 (continued)

SPECIAL ACTIVITIES (continued)

		Typical values for lb O_2/hr	kcal/min	Btu/hr
Load carrying				
Walking on level with 58 lb load, trained men	2.1 mph	0.07	1.9	450
	2.7	0.11	2.9	690
	3.4	0.18	4.6	1100
	4.1	0.32	8.3	1980
Walking on level with 67 lb load, trained men	2.1	0.09	2.3	550
	2.7	0.11	2.9	690
	3.4	0.20	5.1	1210
	4.1	0.33	8.4	2000
Walking on level with 75 lb load, trained men	2.1	0.10	2.5	600
	2.7	0.13	3.4	810
	3.4	0.20	5.2	1240
	4.1	0.34	8.6	2100
Walking up 36% grade with 43 lb load, sedentary men	0.5	0.26	6.7	1590
	1.0	0.47	12.3	2910
	1.5	0.62	16.0	3800
Swimming on surface				
Breast stroke	1 mph	0.27	7.0	1650
	2	1.13	29.0	6900
	3	3.78	97.0	23100
Crawl	1	0.35	9.0	2150
	2	0.70	18.0	4200
	3	1.87	48.0	11400
Butterfly	1	0.47	12.0	2900
	2	1.13	29.0	6900
	3	2.92	75.0	17850
Walking under water				
Walking in tank	minimal rate	0.11	2.9	700
Walking on muddy bottom	minimal rate	0.21	5.5	1300
Walking in tank	maximal rate	0.28	7.2	1700
Walking on muddy bottom	maximal rate	0.33	8.4	2000
Movement in snow				
Skiing in loose snow	2.6 mph	0.32	8.1	1930
Sled pulling--low drag, hard snow	2.2	0.34	8.6	2020
Snowshoeing--bearpaw type	2.5	0.34	8.7	2070
Skiing on level	3.0	0.35	9.0	2140
Sled pulling--low drag, medium snow	2.0	0.38	9.7	2310
Snowshoeing--trail type	2.5	0.40	10.3	2460
Walking, 12-18"snow, breakable crust	2.5	0.50	12.7	3010
Skiing on loose snow	5.2	0.52	14.6	3800
Snowshoeing--trail type	3.5	0.59	14.8	4200
Skiing on loose snow	8.1	0.80	20.6	4900
Measured work at different altitudes				
Bicycle ergometer 430 kg-m/min	720 mm Hg	0.20	5.1	1230
430	620	0.19	4.9	1170
430	520	0.21	5.4	1290
Mountain climbing 880-1037 kg-m/min	610 mm Hg	0.36-0.43	9.2-11.0	2200-2640
566- 786	425	0.30-0.37	7.7- 9.5	1840-2260
393- 580	370	0.25-0.41	6.4-10.5	1530-2520

Table 10-8

Energy Cost of Progression for Adult Males

(After Roth[211], adapted from Dittmer and Grebe[62])

Activity		Subjects: No.	Subjects: Wt, kg (a)	Subjects: Remarks	Speed: mi/hr	Speed: km/hr	Energy expenditure: kcal/min	Energy expenditure: Btu/min	O_2 requirement, liters/min (b)
Walking, level, on:					3.5	5.5	5.6	22.4	1.13
Hard-surface road		2	68-69	Carrying 9 kg clothing and apparatus	3.5	5.6	6.3	25.2	1.28
Grass-covered road					3.4	5.4	7.0	28.0	1.43
Furrow in field					3.3	5.2	6.9	27.6	1.41
Harvested field					3.3	5.3	7.7	30.8	1.57
Plowed field					3.2	5.1	10.0	40.0	2.05
Harrowed field					3.8	6.0	11.9	47.6	2.29
Hard snow		1	83		5.7	9.1	15.8	63.2	3.22
Soft snow		1	83	Carrying 20-kg load	2.5	4.0	20.2	80.4	4.13
Walking, grade, uphill	2.7%	2	70	Soldiers	3.5	5.6	6.1	24.4	(1.23)
	5.0%	1	70	Trained individual	2.0	3.2	4.1	16.4	(0.83)
	5.0%	1	70	Trained individual	2.5	4.0	4.8	19.2	(0.97)
	5.5%	1	70	Soldier	3.5	5.6	7.5	30.0	(1.50)
	6.2%	2	70	Soldiers	3.5	5.6	7.8	31.2	(1.56)
	7.3%	2	70	Laboratory workers	3.5	5.6	8.6	34.4	(1.73)
	8.3%	1	70	Soldier	3.5	5.6	9.3	37.2	(1.87)
	8.6%	2	70	Laboratory workers	2.4	3.8	7.2	28.8	(1.43)
	8.6%	64	70	1 marathon runner, 23 sharecroppers, 40 trained individuals	3.5	5.6	9.3	37.2	(1.87)
	9.0%	2	70	Soldiers	3.5	5.6	9.3	37.2	(1.87)
	10.0%	7	70	Civilian public service workers	3.5	5.6	9.7	38.8	(1.93)
	11.8%	2	70	Soldiers	3.5	5.6	11.0	44.0	(2.20)
	14.4%	2	70	Soldiers	3.5	5.6	12.3	49.2	(2.47)
Walking, grade, treadmill, uphill	0%	2	70-79		2.6	4.2	3.9-4.4	15.6-17.6	0.80-0.90
	5.0%						5.4-5.9	21.6-23.6	1.10-1.20
	10.0%						7.4-7.8	29.6-31.2	1.51-1.60
	15.0%						9.7-10.3	38.8-41.2	1.98-2.10
	20.0%						12.2-13.0	48.8-52.0	2.48-2.65
	25.0%						14.7-15.8	58.8-63.2	3.00-3.23
Walking, grade, treadmill, downhill	0%	2	70-79		2.6	4.2	3.9-4.4	15.6-17.6	0.80-0.90
	5.0%						3.4-3.7	13.6-14.8	0.70-0.76
	10.0%						3.3-3.6	13.2-14.4	0.68-0.73
	15.0%						3.7-3.8	14.8-15.2	0.75-0.77
	20.0%						4.2-4.3	16.8-17.2	0.85-0.88
	25.0%						4.8-4.9	19.2-19.6	0.97-1.00

[a] Values for all subjects listed as weighing 70 kg are proportional calculations from values for subjects of other weights.

[b] Values in parentheses are calculations assuming 1 liter of oxygen is equivalent to 5 kcal. The oxygen requirement per minute for a given rate of energy expenditure may exceed the oxygen uptake during any given minute if an oxygen debt is being accumulated, resulting in very high values for level running and swimming.

Table 10-9

Energy Expenditure in the Antarctic (Three Subjects)

(After Milan[176])

Age	Wt. kg	Surface area	Activity	kcal/hr/m²	kcal/min
33	70	1.78 m²	Walking, moderate pace, hard snow surface	147.5	4.4
			Walking, moderate pace, 6 in. new snow	192.7	5.7
			Walking up 10% grade, hard snow, moderate pace	165.0	4.9
			Walking down 10% grade, hard snow, moderate pace	163.8	4.8
33	75	1.94 m²	Standing in cold	87.4	2.8
				85.8	2.8
			Walking slowly, hard packed snow	150.9	4.9
			Walking, brisk pace, up 10% grade	213.2	6.3
				244.9	7.9
19	73.6	1.92 m²	Walking, level terrain, hard packed snow, stopping occasionally	129.7	4.1
				119.8	3.8
				93.8	3.0
				110.7	3.5
				153.7	4.9
			Walking, slow pace, subject warm	130.3	4.2
				130.2	4.2
			Walking up 10% grade, brisk pace	192.0	6.1
				218.2	7.0

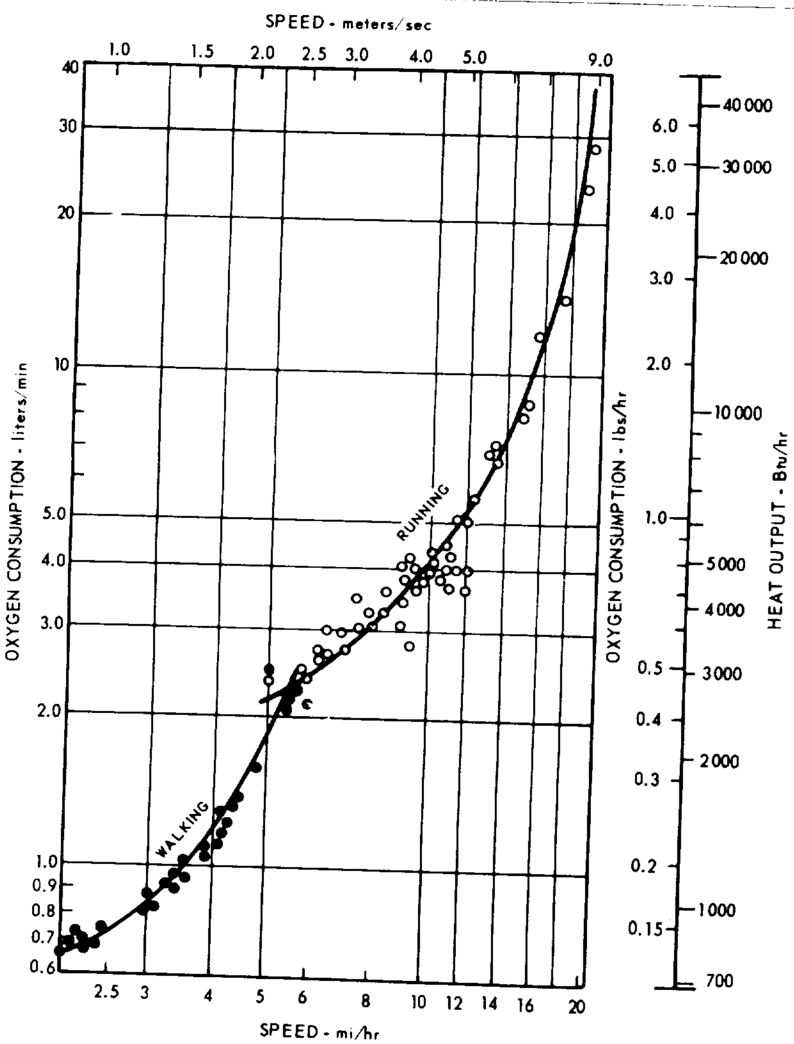
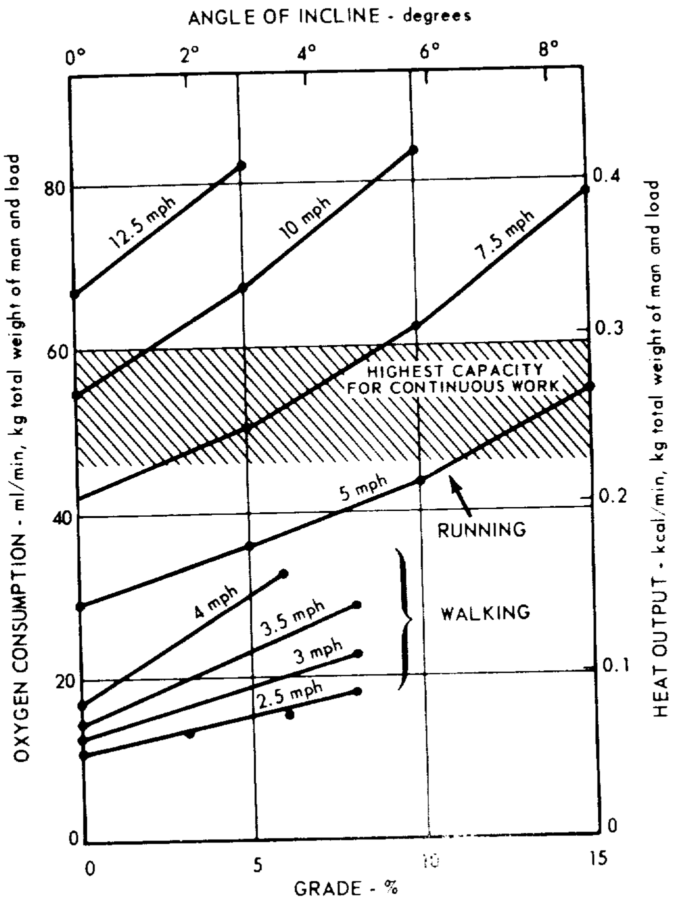


Figure 10-10

Energy Cost of Walking and Running

This chart gives the rate of oxygen cost or requirement and of total heat output as functions of speed, for men walking and running on the level, without load. Data were collected on a large number of subjects by eight authors. Heat outputs are calculated from the oxygen consumption on the basis that 1 liter/min is equivalent to 1158 Btu/hr at a respiratory quotient of 0.85. At 5 mph, the oxygen cost of walking rises above that of running at the same speed. For walking and running uphill, see Figure 10-11. Oxygen cost referred to on this figure includes the oxygen debt which is inevitably incurred in short sprints at high speed and paid off after the event.

(After Fletcher[85], from Dittmer and Grebe (eds.)[62])



This chart presents data for use when planning experiments on the inclined treadmill. (For level walking and running, see Figure 10-10). It permits estimates to be made of the oxygen consumption of men wearing heavy equipment, providing their capability is known in terms of speed, slope, endurance, and load carriage. Only well-trained men are capable of sustained climbing so that few men will be capable of reproducing the severer combinations.

The chart is based on extensive experiments in few subjects: in the upper segment, two middle-distance runners; in the lower segment, ten healthy male volunteer walkers. The hatched area indicates a range of values of the so-called "maximum aerobic capacity," which is approximately equal to the highest oxygen consumption that can be maintained continuously. Its value depends primarily on the body build and degree of training of the subject. The hatched area should be considered valid only for superior athletes. (See discussion of Figure 10-15.) Considerable variation must be expected, from subject to subject and from experiment to experiment.

Calculations based on the results of Åstrand (10) show that 95% of oxgyen costs fall within the range of "mean ± 8%" at values between 30 and 50 ml of oxygen per kg.

For oxygen costs of walking and running uphill, estimate per cent grade from the height of rise in 100 feet, or estimate the angle of incline from the tangent, derived from the vertical rise and the horizontal distance. Note that above the hatched area, work is exhausting, and the greater the oxygen consumption the shorter the maximal running time. Appropriate training increases both maximal oxygen consumption and the endurance time at submaximal levels, which is why long-distance cyclists, oarsmen, runners, skiers, and swimmers have outstandingly high values for both.

Equations for calculating the energy cost of load carrying and the predicted variance are given in Figure 10-2c.

Figure 10-11

Energy Cost of Walking and Running Uphill at Different Speeds and Slopes

(After Fletcher(85), adapted from Åstrand(10), Goldman and Iampietro(98), and Margaria et al(163)) mile (15 mph) are 79 - 81 ml/Kg per min. The 4-min. mile is run by individuals having a maximum $\dot{V}O_2$ of 68 ml/Kg per min. The debt, therefore, amounts to 4 x 12 = 48 ml/Kg + 20 to 25 ml/Kg additional deficit incurred during the first two minutes of the run. Thus, the total amounts to approximately 68 - 73 ml/Kg, or for a 70 Kg runner to an oxygen debt capacity of 4.8 - 5.1 liters.

The effect of body weight on the energy for walking on the level is:

$$C = 0.47\,W + 1.02 \tag{3}$$

where C = kcal/km

W = gross weight in kilograms

Formulas for calculation of the energy cost and variance of walking on the level with external loads at speeds of 2.0 to 4.5 mph are seen in Figure 10-2c. The general effect of speed on the energy of walking over the range of about 3 to 6.5 km/hr or 2-4 mph is given by the equation:

$$C = 0.8V + 0.5 \tag{4}$$

where C = kcal/min

V = speed in km/hr

As a rough estimation, it is well to know that walking on a hard level surface at 2 mph requires 2 Mets (2 times basal metabolic rate); 3 mph, 3 Mets; and 4 mph, 4 Mets + (13).

For grade walking over the range studied, the energy cost per unit weight is essentially the same whether the weight is of the body or the load (98). The pooled data from this study and the open literature were treated statistically and the following curve-fitted formula was evolved relating energy cost E for a 70 kg subject in kcal/min to progression rate V, load L, and grade G over the ranges V = 1.5 to 4.5 mph, L = 0 to 30 kg, and G = 0 to 9%.

$$\begin{aligned} E = {} & 4.3+(1.1V-0.22V^2)+(-6.3G+8.2GV-0.5GV^2+3.6G^2V^2) \\ & +(4.06LG-1.77\,LGV-0.003LV^2+0.24LGV^2-0.06LG^2V^2) \end{aligned} \tag{5}$$

Length of stride is also a variable to be considered. Figure 10-12 represents the caloric consumption as a function of stride and cadence for level walking.

The metabolic cost of climbing on hard or sandy surfaces is especially pertinent to the lunar surface. It should be cautioned that even the relative increase in energy cost above level walking to be seen in Figures 10-10 and 10-11 and Table 10-13 will probably not be found in suited individuals operating in 1/6th g (211). The strain of climbing sand dunes with a 40 lb pack during the heat of summer in Yuma, Arizona, as seen in Table 10-13, represents the limit of capacity at 2.5 mph for periods of 1/2 hr.

Table 10-14 indicates the energy required for going up and down stairs and ladders with variable loads.

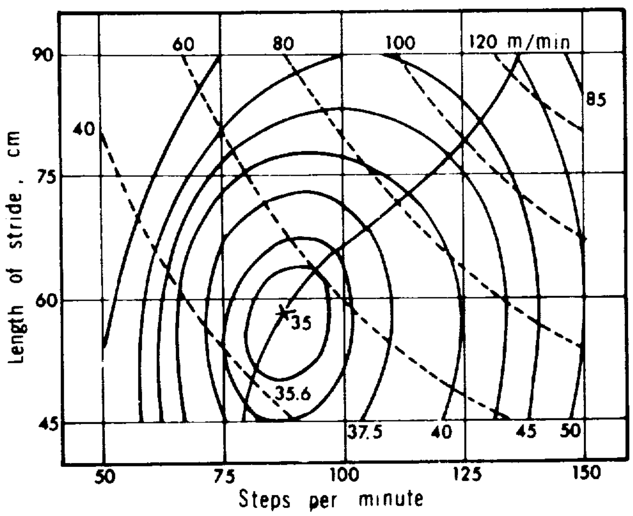


Figure 10-12

Caloric Consumption as a Function of Length of Stride and Cadence

Dashed lines represent speeds in m/min; thin solid lines (contour lines), caloric consumption; heavy solid line, optimal combinations of cadence and length of stride for various speeds

(After Brunnstrom[37], redrawn from Atzler and Herbst[12])

Table 10-13

Energy Cost and Strain of Walking with Loads on Sand Dunes (1G)

(Adapted from Winsmann and Daniels[264])

Activity	Mean kcal/m²/hr for —			
	No load	25 lb	30 lb	40 lb
Treadmill	131	144	–	150
Level sand surface	212.2	242.6	248.5	269.6
Level hard surface	145.2	155.7	161.4	166.2
Up sand-dune slopes (2.0–2.5 mph)	282.9	333.2	320.2	346.1
Down sand-dune slopes	186.2	205.0	216.0	231.5

a. Energy Cost of Walking and Carrying Pack Loads

(Speed = 2.5 mph; figures are average of four trials on each of four subjects.)

Activity	Mean kcal/m²/200 yd for—			
	No load	25 lb	30 lb	40 lb
Level sand	9.13	10.58	10.83	11.34
Up sand dunes (11-12% grade)	13.30	15.74	17.00	16.44

b. Comparative Energy Expenditure While Walking on Level Sand and Climbing Sand Dunes, Carrying Various Packboard Loads

Load	Mean final rectal temp., °F		Mean final pulse rate, beats/min	
	Level sand surface	Level hard surface	Level sand surface	Level hard surface
No load	100.8	100.0	126.9	101.4
25 lb	101.1	100.1	139.2	107.7
30 lb	101.3	100.2	146.3	113.3
40 lb	101.6	100.3	160.4	128.7

c. Strain of Walking on Sand with Various Packloads

Table 10-14

Energy Expenditure Going Up and Down Stairs and Climbing Ladders with Variable Loads (1G)

(After Passmore and Drunin[190])

Ref.	Vertical speed, m/min	kcal/min for subject weighing—							
		59 kg	65 kg	69 kg	75 kg	79 kg	80 kg	83 kg	84 kg
191	14.8	6.0		8.4	9.8	9.7		9.3	
191	17.6	8.5		8.4	10.3	10.4		11.8	
66	Not stated		6.2				8.6		8.0

a. Up and Down Stairs Without Loads; Ht. of Each Stair 15.2 cm.

Ref.	Wt. kg	Height of step, cm	Vertical speed, m/min	Load carried, kg	Energy cost, kcal/min
188	63	15.2	8.2	8	8.0
				23	10.4
				38	14.2
188	77	15.2	8.2	8	9.0
				23	10.7
				38	13.2
126	65	17.2	17.2	10	16.2
				20	19.5
				40	25.2
				60	30.7

b. Carrying Loads Upstairs Only (Three Subjects)

Slope of ladder, deg	Vertical speed, m/min	Load, kg	kcal/min
50	9.1	0	7.7
		20	9.5
		50	14.3
70	11.1	0	9.0
		20	11.3
		50	17.1
90	11.9	0	11.5
		20	14.6
		50	25.4

c. Climbing Ladder[143]; Ht. of Each Step 17 cm.

For purposes of estimating metabolic loads in the arctic conditions, several studies of sled pulling are available (253, 254). Under the most difficult subarctic snow conditions, the energy expenditure rates of over 500 kcal/m^2/hr were recorded. The general relationship found was expressed by the formula (254):

$$E = 12.93 + 0.02D + 0.0119D^2 \tag{6}$$

where D = average drag in pounds

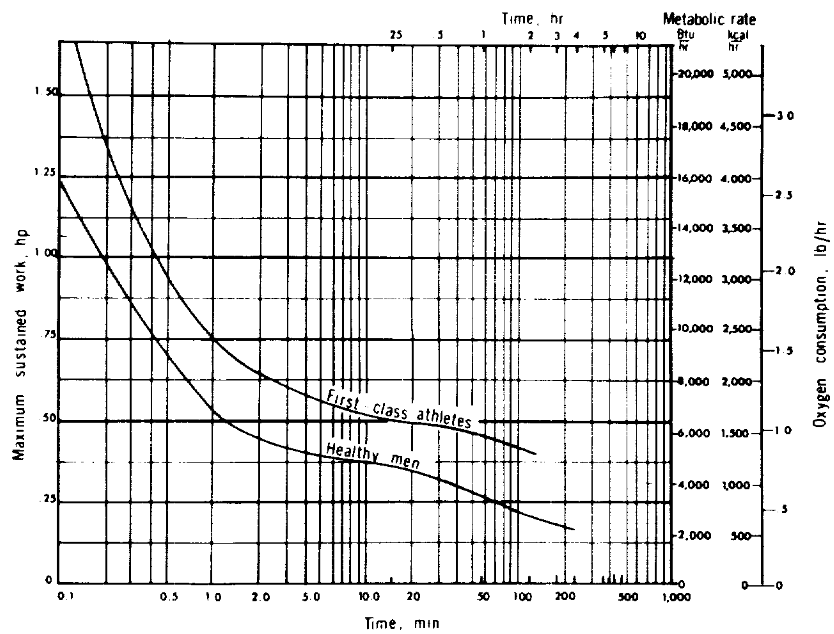
E = kcal/m^2/200 yards

The predicted value for a mean drag of 17.5 pounds is 16.9 kcal/m^2/200 yards. The mean value obtained for a drag of 17.5 pounds in the treadmill study, while wearing arctic ensembles, was found to be 12.16 kcal/m^2/200 yards (253). Simulated sled pulling differs in at least one very important way from real sled pulling. On the treadmill the subjects walk over a smooth, non-skid rubber surface. In the field, such factors as snow depth, breakable crust, skids, and uneven walking surface are certainly responsible for part of the higher metabolic rates.

Maximum Sustained Work Capacity

In emergency situations, the maximum sustained work capacity of men is of importance. Figure 10-15 illustrates that the maximum measurable work which men can sustain until exhausted is greatest for periods of less than 1 minute (85). These are rather special data in that the kind of work is chosen to yield highest power for a given metabolic rate; hence the efficiency is 20%. Running, rowing, cycling, and cranking are the favored methods, with cycling and cranking combined showing the best efficiency. Physical conditioning is of the greatest importance, as is evident from the difference in the two curves, where, incidentally, even the "healthy men" are subjects who are young, physically active, and accustomed to the work used in the tests. Note the near plateau for the period from 5 minutes to 1 hour, showing that a superb athlete can sustain 0.5 horsepower for these times. Data beyond 1 hour are sparse, and the maximum level that can be sustained for 4 to 8 hours is not precisely known. It must be emphasized that these curves represent the very maximum levels for the most select individuals and are far above what even the average astronaut would probably be able to accomplish. The curves should, therefore, be used only as extreme upper limits of endurance.

In general, experimental studies on long-duration exercise have shown that only the well trained individual can work maximally at ~33% of his maximum capacity for that length of time, from day to day (13). For more "normal" people the maximum continuous working rate should not exceed 25%



The curve "First-class athletes" covers superb physical specimens and represents the very maximum attainable. "Healthy men" represents young physically active individuals accustomed to the work performed in the tests. The astronauts probably fall just below the curve for healthy men.

Figure 10-15

Maximum Sustained Work Capacity of Men

(Compiled by Fletcher(85) from several sources) of the aerobic power. The best marathon runners have had oxygen intakes of 65 ml/Kg per minute for a duration of slightly more than two hours, but can not continue at this rate much longer. In "normal" well trained men -- as astronauts are expected to be -- a total energy expenditure of ~1600 kcal in 2-1/2 hours would probably lead to total metabolic exhaustion (13).

When the oxygen demand exceeds the intake of oxygen, an oxygen debt is incurred (160, 164). (See Figure 10-2b.) The older literature states that the maximum oxygen debt that can be incurred for most individuals is approximately 15 liters of oxygen with values to 17 liters having been measured in a few instances (105). As indicated on page 10-7, the maximum debt recently calculated for mile runners is about 68 to 73 ml/kg or 4.8 to 5.0 liters for a 70 kg runner (13). As often done in older studies, one cannot continue recovery oxygen measurements to establish oxygen debt until the normal resting level is attained. Strenuous work aerobically performed for many hours can lead to increased basal metabolic rates for as long as an entire day: thus an increase of only 25 ml/min over the normal resting rate would amount to 36 liters of O_2 in a 24-hour period! One can hardly call this an oxygen debt -- although the excess O_2 was used for some processes which were a consequence of the severe wear and tear during the previous work period. The oxygen expenditures for sustained work above the maximum aerobic capacity of the individual can be summed arithmetically as a function of time. The time for recovery, however, is a geometrical summation and one must consider the elevated body temperature and sweat rates which may persist throughout the recovery period. The problems of determining the efficiency of repayment of this debt have been reviewed (148).

The peak energy output is dependent on age, sex, and other factors (9, 10). These studies indicate that for male subjects, maximum aerobic work capacity decreases from an average of 3.5 to 2.2 liters/min from ages 35 to 63, or by a factor of 26% (21% when calculated per kg body weight). These decrements are of value in predicting the relative work loads that older scientists may be able to undertake in future lunar missions. Individual variations due to training and general health are, of course, major factors determining these maxima. One cannot convert these oxygen consumptions directly to energy requirements since the anaerobic components of these work outputs are not clearly defined. Figure 10-16 represents a summary of the aging data for males, showing the variations expected in the athlete subjects as well as the general population (10, 238). Regular physical training can prevent a major drop of aerobic power with age. There can be no doubt, of course, that continued regular physical activity might become a problem with the increasing incidents of such ills as muscular and arthritic pains, not to mention cardiovascular and respiratory ailments. Thus, relative inactivity is frequently forced upon the aging man, and it is this inactivity which causes the loss of functional resources (13).

Typical maximum oxygen uptakes of the pilot population are reported in the treadmill study of Naval Air Cadets (238). After the usual cadet physical training program, the mean peak was 4.05 liters/min with a standard deviation of 0.39 and a range of 3.22 to 5.17, agreeing with Figure 10-16. The maximum oxygen uptake of the general Air Force population is recorded (15, 18). Figure 10-17 presents these peak oxygen consumptions as found in a treadmill

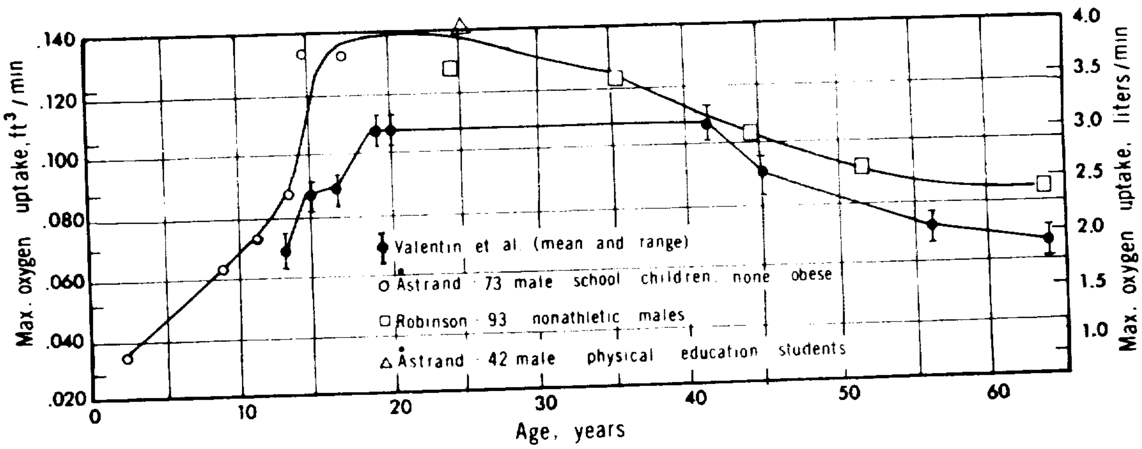


Figure 10-16

Maximum Oxygen Uptake (Aerobic Capacity) of Males

(After Fletcher[85], from the data of Valentin[250] Astrand[10], and Robinson[209])

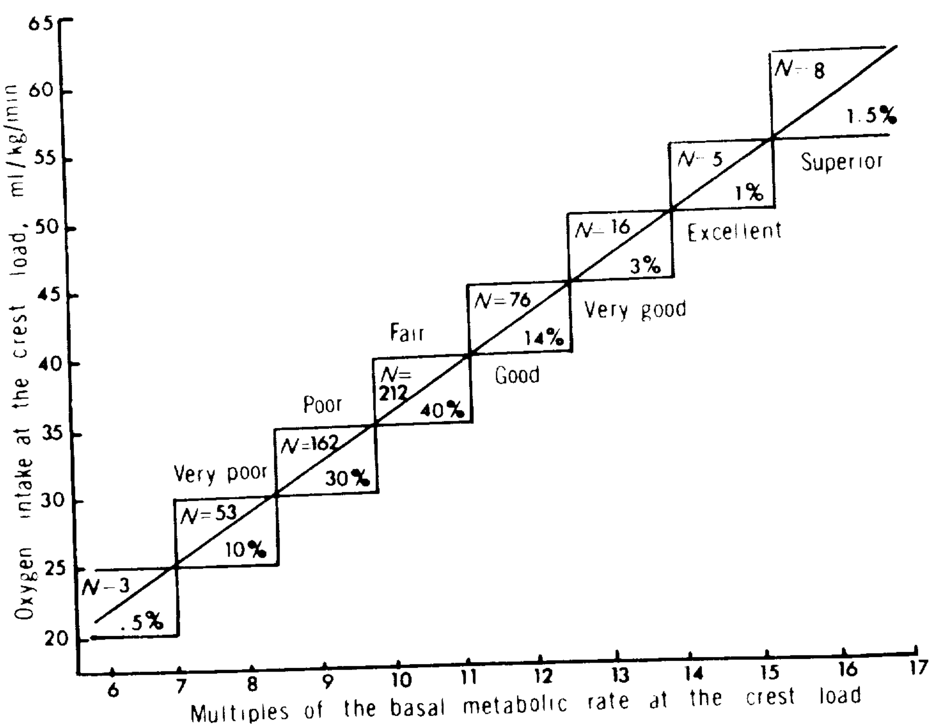


Figure 10-17

The Range of "Physical Fitness" Determined by a Standardized Treadmill Test of 535 Male Adults

(After Balke[15])

Table 10-18

Effect of Acute and Chronic Hypoxia on Aerobic Capacity

a. Maximum Ventilation, Oxygen Intake, and Heart Rate During Ergometer Exercise During Chronic Exposure at Various Altitudes

These men were all well acclimatized to altitude and were able to perform sustained physical exertion at 24,000 ft where an unacclimatized individual would be unconcious in a few minutes.

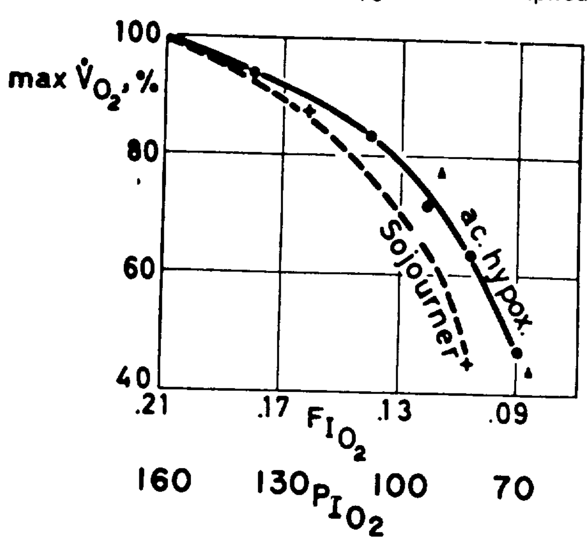
Altitude, ft	Barometric pressure, mm Hg	No. of subjects	Weight, kg	Ventilation, liters/min		Oxygen intake		Heart rate, beats/min	Work rate, kg m/min
				STPD (a)	BTPS (b)	STP, liters/min (c)	ml/kg/min		
Sea level	750	6	72.7	97.9 ± 18.4	119.7 ± 22.6	3.40 ± 0.23	46.8 ± 3.2	192 ± 6	1,500–1,800
15,000	440	5	68	75.0 + 7.3	164.8 ± 15.9	2.58 ± 0.12	37.9 ± 1.8	159 ± 17	1,500
19,000	380	4	65.5	61.4 + 14.3	159.1 ± 37.2	2.14 ± 0.23	32.7 ± 3.5	144 ± 13	900–1,200
21,000	340	4	65.2	56.7 + 8.6	168.8 ± 25.4	1.95 ± 0.11	29.6 ± 1.7	146 ± 11	900–1,050
24,400	300	2	67.5	35.2 ± 2.3	119.8 ± 7.7	1.40 ± 0.09	20.7 + 1.3	135 ± 8	600

a. STPD = Standard temperature and pressure, dry.
b. BTPS = Body temperature and pressure, saturated with water.
c. STP = Standard temperature and pressure.

(After Pugh[203])

b. Reduction of Aerobic Capacity by Hypoxia

Comparison of the maximum O_2 uptake ($\dot{V}_{O_2}$ max), expressed as a percentage of the value observed when breathing air at sea level in acutely and chronically hypoxic individuals as a function of the O_2 fraction or partial pressure of oxygen in the inspired air.



Legend

+ sojourner
• acute hypoxic
▲ natives of high altitude

(After Ceretelli[44], from the data of Margaria[159], Christiansen and Forbes[49], Ceretelli and Margaria[45] and Elsner[74]) test at 3.4 mph with slopes increasing by 1% each minute. The performance rating is arbitrary. Figures 10-16 and 10-17 define upper limits of aerobic capacity to be expected from select and average male populations. With no specific prior training, the mean aerobic capacity of the seven Mercury Astronauts determined on a bicycle ergometer on occasion of the selection procedure before entering the program was 2.60 Liters O_2/min. (145).

Factors Controlling Maximum Work Output

The variations in work capacity brought on by multitudes of situational factors and training have been reviewed (11). Such factors as the decreased basal metabolic rate at rest, slower pulse at rest and during exercise, increased heart volume, increased muscular mass, increased vascularization and glycogen deposition in muscles, slight increase in blood volume and decreased lactic acid level after severe work have been noted as resulting from training. The more intimate day-to-day variations in the work capacity of lumbermen have been described (149).

There are several factors modifying energy cost and maximum levels of exercise which must be considered. The first is the optimum dietary input for varied work loads. For short-term exercise such as 1/4 mile runs or 100-yard swimming sprints, no consistent advantage in efficiency is apparent for diets high in carbohydrates or proteins and fats. For prolonged exercise, however, there is some evidence of the advantage of a high-carbohydrate diet in that a subject could continue strenuous work three times as long on a high-carbohydrate as on a high-fat diet (50). Endurance was actually reduced when athletes were kept on high-fat diets for several days prior to endurance tests. From determination of respiratory quotients it was concluded that while trained athletes can utilize carbohydrate and fat indifferently during rest and light work, they increase the percentage of carbohydrate used when performing heavy work. Neither high-nor low-protein diets given over a period of 2 months affect the energy efficiency of exercise (11). No other dietary factors, given in amounts that exceed the daily minimum requirements, appear to be unequivocally ergogenic in endurance exercise (168).

The question of effect of hypoxia or supplemental oxygen as an aid to exercise tolerance has been a matter of controversy for some time. That a reduction in ambient oxygen pressure reduces work capacity is a well-studied phenomenon. The Himalayan Scientific and Mountaineering Expedition determined the graduated effects of oxygen depletion at different altitudes on men well acclimatized to these altitudes (202, 203). Figure 10-18a presents a summary of these studies. These men were able to perform sustained physical exertion at 24,400 ft whereas an unacclimatized individual would be unconscious in a few minutes! Maximum work, maximum oxygen intake, maximum ventilation STPD, and maximum heart rate declines with increase in altitude. Maximum ventilation BTPS, on the other hand, is higher at altitude than at sea level, except at the highest camp. There was no significant difference in the values obtained at heights between 15,000 and 21,000 ft (4,600 and 6,400 m). One obvious factor affecting ventilation at altitude is the reduced work of breathing air of low density. In spite of this reduction, the ventilation BTPS fell at 24,400 ft. This result may be due to the hypoxia of respiratory muscles or a failure of subjects to exert maximum effort.

It appears that exercise at 20,000 ft (6,090 m) and above is halted by factors other than those operating at sea level. Subjectively, the overwhelming sensation which brings work to a close is breathlessness. Very high ventilation rates of about 200 liters/min BTPS - in fact, values approaching the resting 15-second maximum voluntary ventilation (MVV test) - were sometimes observed just before the breaking point at 21,000 ft (6,400 m). Subjects performing the MVV test complained of respiratory fatigue and could not keep up maximum ventilation much longer than the 15 seconds required by the test. To the conclusion that exercise at great altitude is limited by fatigue of the respiratory muscles and that extreme ventilation is the result of the low arterial oxygen tension (20 to 30 mm Hg at 1,200 kg m/min) secondary to the low alveolar oxygen, must be added that cardiac and generalized tissue hypoxia resulting from the limitation of pulmonary diffusion are probably the ultimate limiting factors at high altitude (14, 101, 102, 121, 195, 260).

For individuals not as well acclimatized, other data are available on the effect of acute hypoxia on work capacity which indicate that at an altitude equivalent of 10,000 feet (110 mm Hg P_{IO_2}) there is a 20 to 25% reduction in maximum work capacity, and at 13,000 feet, (98 mm Hg P_{IO_2}) a 33% reduction (7, 145, 205). Figure 10-18b compares the effect of reducing the fraction of inspired oxygen or P_{O_2} of the inspired gas on the maximum oxygen uptake of acutely hypoxic vs chronically hypoxic individuals (sojourners or natives). The sojourner must be at altitude for at least 5 days before such differences are noted in maximum aerobic capacity (21). The mechanism of physiologic adaptation to exercise at altitude has received much study (120, 147, 158, 258).

A question has arisen regarding the ability of hypoxic individuals to reach the same levels of anaerobic metabolism as individuals at sea level. In many studies, maximum lactate concentrations were the same at the end of exercise at sea level as at an oxygen-equivalent altitude (7, 44, 145). This suggests the same muscle lactate levels may determine the maximum effort at sea level and at altitude. However, maximum lactate levels are still a controversial issue. There are at least as many findings on lower levels of lactate. After maximal work at altitude as reports on "no change," but many of these studies involve gradual or subacute exposure to altitude as in mountain climbing (73, 120). The decrease in buffering capacity of the blood by loss of bicarbonate may affect the levels of lactate in subacute exposures to altitude of several days duration (44).

One must also consider the effect of previous hypoxia on exercise tolerance. Table 10-19 shows the effect of previous hypoxia produced by 3-1/2 hrs at 16,000 ft on the treadmill test of Figure 10-17 with a progressive increase of treadmill slope of 1% per minute at 3.4 mph. There is a distinct, if not statistically significant, evidence of a measurable reduction in work capacity correlated with the subjective symptoms. These changes, however, are not significant enough to suggest routine abortion of high-work-load missions after accidental or emergency exposure to acute hypoxia of this degree. The

Table 10-19

Effect of Previous Hypoxia on Maximum Work Capacity
(After Balke et al[16])

Parameter	Control	Previous hypoxia	Av. diff.	Standard deviation	P value
Av. maximal O_2 intake, ml/min	3,100	2,946	153.08	269	0.033
Optimal work capacity, m kg/min	1,091	1,054	36.92	75.18	0.06
Total test duration, min	32.8	31.0			
Time of maximal oxygen intake, min	32.0	30.5			

effect of concomitant drowsiness, headache, and sense of fatigue must be kept in mind.

The augmentation of exercise tolerance by supplemental oxygen above the sea level equivalent is still not a clear-cut picture. There have been several reports in the literature of the effects of oxygen on respiration and performance during heavy work. During moderately severe exercise, the addition of oxygen to the inspired air resulting in a marked and sudden depression of respiration has been reported (8). However, it has also been reported that no effect could be noted when 100% oxygen was substituted for air for athletic and non-athletic subjects performing moderate and severe exercise on a treadmill (19). Addition of oxygen does tend to increase the time to reach the breaking point caused by severe exercise overloads (19). It is postulated that the respiratory effects of inhaling high concentrations of oxygen were due to the abolition of an arterial anoxemia which was thought to be present when air was breathed during exercise of more than critical intensity. Relief of the anoxemia might exert its effects through the carotid and aortic chemoreceptors, or by improving cardiac function, or both. The actual cause of anoxemia in heavy exercise is still obscure. The rapid flow of blood through pulmonary capillaries may limit the time for diffusion across the pulmonary epithelium, or a pulmonary venous shunt may become effective under these severe exercise conditions. A parodoxical finding that 66% oxygen at sea level pressure will have a positive effect, but 100% oxygen, a negative effect on subjective and objective evaluation of exercise performance still requires adequate explanation (211). More work is required on this subject.

The effects of restraint and weightlessness on maximum energy output must also be considered. After a 14 day flight in Gemini 7, the time to reach the endpoint of 180 beats/min heart rate on a bicycle ergometer test with increasing load was decreased by 19 and 26% in the two pilots. There was also a decrease in oxygen uptake per kilo of body weight during the final minutes of the test (24, 61). Bed rest studies also indicate a decrease in exercise tolerance which can be altered by various exercise regimens (30, 43, 48, 178, 179).

Carbon Dioxide reduces the maximum work capacity by increasing dyspneic response to exercise (35, 42, 83, 103, 117). (See Part B Physiology of the oxygen and carbon dioxide partial pressure environment.)

The effects of acute starvation, chronic semi-starvation in exercise capacity is covered in Nutrition, (No. 14).

The effects of hyperthermia and hypothermia (210) on the $\dot{V}O_2$ max, oxygen debt and blood lactate are found on pages 6-98 and 6-121 of Thermal Environment, (No. 6).

Work and Locomotion in Zero and Subgravity States

Energetics in Zero Gravity

The effect of zero gravity and subgravity on the energy cost of metabolism has received both theoretical and empirical study (3, 112, 114, 138, 140, 161, 206, 211, 241, 245, 266). In both cases the effect of pressurized suits must be considered. (See also sub and zero gravity in Acceleration, No. 7.)

The increase in degrees of freedom of movement in the zero gravity of orbital flight is probably a factor in the difficulty of accomplishing extra-vehicular tasks in the Gemini program (156). (See pages 7-133 to 7-158.) No specific data are available on energy consumption in orbital tasks. Gemini extravehicular bioinstrumentation consisted of only the electrocardiogram and the impedance pneumogram. These parameters had been monitored during a great many physiological and psychological tests and under widely varying conditions. The existing pool of information had reconfirmed the fact that heart rate responds to psychological, physiological, and pathological conditions. There are considerable individual variations in these responses; however, since a quantitative indication of workload actually experienced in flight appeared to be of primary importance, the feasibility of using heart rate as a quantitative indication of workload was investigated. On Gemini IX-A, X, XI, and XII, preflight and postflight exercise tests using the bicycle ergometer were performed on the pilots. During these tests, the subject performed a measured amount of work in increasing increments, while heart rate, blood pressure, and respiration rate were monitored and periodic samples of expired gas were collected for analysis. These data were translated into oxygen utilization curves and BTU plots. An increase of about 0.02 beats per minute for each work increment of 1 BTU/hr was noted for the ranges of 100 to 180 beats/minute and 1000 to 4000 BTU. Rough estimates of EVA work loads were thus attained from heart rate data, but these derived data were considered inaccurate, because changes in heart rate caused by thermal, carbon dioxide or other environmental problems could not be taken into consideration. The psychological effect of a new and different environment also could have increased the heart rates without a corresponding change in metabolic rate. Since any error introduced by these factors would have increased the observed heart rate for a given workload level, this relationship was used for establishing maximum possible levels of work load at any instant. For instance, after evaluation of all data from previous EVA missions, altitude chamber tests, and underwater zero-g simulations, it was concluded that if the Gemini XII pilot's heart rate remained under 140 beats per minute for the majority of the EVA, the probability of successfully completing the EVA without exceeding the ELSS capabilities of 2000 BTU/hr was high. Therefore, the pilot was to be advised to slow down and rest whenever his heart rate exceeded 140 beats per minute. If his heart rate exceeded 160 beats per minute, he would be advised to stop all activities.

Periods of exercise were included in both of the standup EVAs. These exercises consisted of moving the arms away from the neutral position of the pressurized space suit. Both arms were brought from the neutral position to the sides of the helmet once each second for 60 seconds. An attempt was made to correlate heart rate data during these inflight exercise periods with preflight exercise tests. When compared in this manner, no significant difference appeared in the response to exercise performed before and during flight. It must be remembered, however, that only qualitative conclusions can be drawn from these data. Valid quantitative conclusions must await the results of more precise inflight medical experimentation in which controlled conditions and additional data collection are feasible.

Several other factors were significant in the energetics aspects of Gemini EVA. One of these was the art of conserving energy as demonstrated in Gemini XII. The pilot of Gemini XII was able to condition himself to relax completely within the neutral position of the space suit. He reported that he systematically monitored each muscle group. When a group of muscles was found to be tense while performing no useful work, he was able to relax these muscles consciously. All of his movements were slow and deliberate. When a task could be performed by small movement of the fingers, he would use only those muscles necessary for this small movement. This technique of conserving energy contributed to the low indicated work levels in the Gemini XII umbilical EVA.

For the final Gemini XII EVA, the oxygen allotment for umbilical EVA was 25 pounds, with 2.9 pounds scheduled for egress preparation and 22.1 pounds for a projected 2-hour and 10-minute EVA time line. From the experience of the Gemini XI pilot at the Target Docking Adapter (TDA) of the GATV, the use of the medium-plus bypass flow mode was planned for all TDA work. This mode increased dry makeup oxygen flow to the ELSS chestpack and increased the capability of the ventilation gas to remove latent heat and to purge carbon dioxide from the helmet. If work loads exceeded the design limits, medium-plus-bypass flow would provide greater protection against visor fogging than that obtained in the normal high flow mode. The pilot elected to remain in the high flow mode for the entire hatch-open period because of the satisfactory cooling and the absence of visor fogging. The pilot stated that he felt that his work rate had not taxed the capability of the system in the high flow mode and that he could have worked somewhat harder without discomfort. Total ELSS oxygen usage for the 126-minute EVA period was 18.9 pounds, which indicated a usage rate of 8.9 lb/hr, as compared to the measured value of 8.5 lb/hr obtained during preflight testing. The EVA pilot performed several tasks intended to evaluate any forces acting on him from either thrust or pressure forces from the ELSS outflow. He reported that he was unable to detect any forces which might be attributable to the ELSS. There was no noticeable float-out or float-up tendency when he was standing in the cockpit with the hatch open. Study of oxygen consumption in Apollo is planned (171).

As its functional utility in performing work, traction serves as the primary source of the counter force (counteractive or reactive force) during the accomplishment of work (267). If the counteractive force is reduced, then according to Newton's third law, the amount of work that can be accomplished must also be reduced. If, however, the task is constant and the tractive environment is altered to a point such that the normal counteractive force supplied by traction is less than the work to be done, then either the task cannot be accomplished or a supplemental source must be found for the counter force. In reduced gravity environments, supplying a supplemental counter force is achieved by several means. The most common technique for both 1-g and weightless situations is the use of one arm for accomplishing the task while the second arm provides the means of transmission of the reactive force to a load sustaining object, e.g., the spacecraft. Other means of accomplishing this load transmission are by using various tethering systems, wedging the body into an opening, and using the skeletal structure in combination with a tether in the "lineman's position." (269)

The alteration in metabolic rate for the accomplishment of a given task in weightlessness should reflect the additional energy required to supply the reactive force by means of the musculoskeletal system over and above the energy required for the task itself. When aids are not available for the transmission of the necessary counterforce, the work cannot be done. Subjects at simulated lunar gravity conditions could not exert a lateral force of 15 ft-lb while pulling a cable to lift a weight (267). In addition to supplying the necessary reactive force for work at 1 g, traction also allows the storage of torsional forces during some forms of work. These stored torsional forces are important in many types of work because they aid in restoring the body to the pre-work position. As traction is reduced, the availability of this form of energy for restoration of body position decreases. Consequently, the energy required to regain the pre-stroke work position increases as traction decreases.

The energy balance for upper torso work under all tractive conditions may be expressed by the following equations relating energy, Q, and efficiency, E: (267)

$$\Delta Q_m (E) = Q_w \tag{7}$$

or

$$\Delta Q_m = Q_w + Q_{wc} + Q_{wr} + Q_s + Q_n \tag{8}$$

Where ΔQ_m is the metabolic cost of work, Q_w is the amount of energy utilized in performing useful work, Q_{wc} is the energy spent in supplying the counteractive force, Q_{wr} is the energy required to restore the body to the prework position, Q_s is energy stored as body heat, and Q_n is the net heat loss. As traction is reduced for a given task, the muscular energy required to supply the counter force must increase to maintain the mechanical conditions necessary to accomplish the work. In other words, the total energy required to accomplish the same task is increased as traction is reduced. Since the efficiency of work is $E = Q_w/\Delta Q_m$, this is equivalent to saying that the efficiency of work is reduced as traction is reduced.

Ground-based simulation has pointed out the effect of a tractionless environment and freedom of movement on energy costs (71, 72, 199, 241, 245, 267). Figure 10-20a and b represent the increase in horsepower output and energy cost for a reciprocating stroke task when the degrees of freedom are increased on a simulator in a 1 g environment. It is of great practical importance that several groups have recently found that most reciprocating arm tasks on zero gravity simulators with 5-6 degrees of freedom require from 30 to 50% more energy than the equivalent task of 1 g when bracing is limited to one free hand (245, 266). Additional points of bracing eliminate almost entirely the excessive energy requirement for the tasks. In a self-paced operation in zero gravity simulation, there is usually an increase in the time required for a given reciprocating task of about 50%. Table 10-26a summarizes more data on the effect of reduced gravity on energy requirement for different tasks.

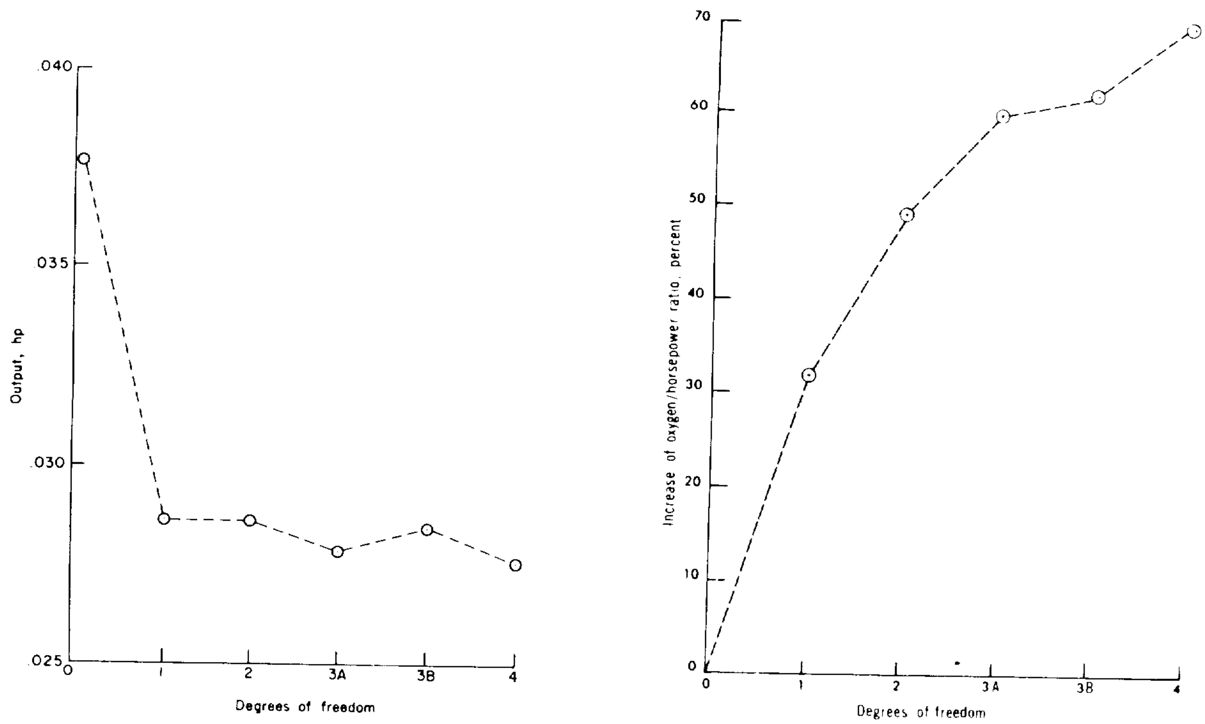
Torque tasks during simulation of zero gravity also point to the requirement for special bracing and traction devices (71, 72, 266, 268). The maximum torque which can be impulsively executed without special bracing is drastically curtailed (244). Because of inertial coupling in the multiple degree of freedom simulators, exact quantification of the torque problem is not available. As was evident in the Gemini series, torque tasks in orbit appear much more difficult than similar tasks in parabolic flight simulation (156). Underwater simulation appears to be a better approach to the problem. (See EVA of the Gemini Program, pages 7-133 to 7-156 in Acceleration, No. 7.)

In a recent study, the metabolic rates on a six-degree-of-freedom, gimballed simulator and underwater simulation were compared (268). Subjects performed typical construction and maintenance tasks discussed on pages 7-173 and 7-176 of Acceleration, (No. 7). The metabolic rates for 2 subjects are compared in Figure 10-20c. It is evident that there is a simulation effect on the data obtained. For example, the resting rate in zero-g is less than one-g, which is less than the neutral buoyancy values. The lower zero-g values are probably the result of the men being completely supported so that the metabolic cost of maintaining balance and posture were not factors in determining the total metabolic rate. The additional metabolic cost in the one-g simulation represents the additional cost of the use of postural muscles and a greater heat load. The twofold increase of resting rates noted with neutral buoyancy results from the subjects' having to exert a reactive force to maintain balance and position during the simulation and the temporal error induced by the long sample lines used in the underwater simulation. Details of techniques used in the simulation are available (268).

The maximum metabolic rates noted during the studies are recorded in the second column of Figure 10-20c. The high peak values of the zero-g simulation result from the high cost of providing the reactive force necessary to accomplish any task. Throughout these work sessions the subjects complained

Figure 10-20

Metabolic Costs of Work During Simulation of Weightlessness



a. Horsepower Output with Various Degrees of Freedom on Reciprocating Task; 15-Pound Load and 22-Inch Stroke

b. Percentage Increase of Oxygen/Horsepower ratio for a Reciprocating Task; 15-Pound Load and 22-Inch Stroke

Effect of degrees of freedom on power output and oxygen efficiency of output in a mechanical weightlessness simulator.

2 df - Subject free to translate horizontally in all directions.

3 dfA - Subject free to translate horizontally in all directions and rotate in a vertical plane.

3 dfB - Subject free to translate horizontally in all directions and rotate in a horizontal plane.

4 df - Subject free to translate horizontally in all directions and to rotate about his own center of gravity in planes parallel and perpendicular to the floor.

(After Streimer et al[245])

c. Comparison of Metabolic Rates During Construction and Maintenance Work (Btu/hr)

Simulation	Rest	Maximum Measured
One-g	697	3243
Neutral buoyancy	1035	2170
Zero-g six-degree-of-freedom	478	3489

(After Wortz et al[268])

of not being able to achieve and maintain a desired position, and had to exert a tremendous effort to accomplish even a simple task. It is interesting to note that the highest metabolic rates were measured during the maintenance tasks and particularly with the removal of a maintenance box. This resulted from problems in positioning to reach the retaining bolts. Filing, drilling, and sawing were also major problems in the zero-g configuration.

The lower peak values seen with the underwater studies are complicated by several factors. It is probable that the thermal loss of the subject is increased and results in lower metabolic rates. There also exists the effect of the drag introduced by the water medium, and also the relative ease with which the subject could bend the suit in the water medium as compared to an air environment. The role of thermal exchange and bending forces in the suit are areas which require clarification in future studies. It should be noted that the greatest portion of the decrease in metabolic rates is probably due to the subjects' being able to take better advantage of their restraint systems during underwater simulations.

In general, metabolic rates remained below 2000 BTU/hr regardless of simulation techniques. Heart rates were never greater than 140 beats per min during underwater tests, and thus compare with those seen on Gemini XII (156). The highest heart rates were noted during zero-g simulation where they reached 155 beats per min during a drilling exercise. Heart rates did not exhibit a linear correlation with metabolic rates in these tests. This indicates that metabolic rates cannot be derived from heart rate for this type of simulation. Sweating was a major problem with all modes of simulation and work tasks. Start of sweating could not be correlated with metabolic rates. This points to the need for body core temperature measurements and study of thermal exchange with the atmosphere to evaluate sweating, metabolic rates, and work during these simulations. Respiratory rates showed no correlation with activity. Tests with a system which isolates the repiratory gases from suit flow are necessary if real-time data are to be obtained which can be correlated with work modes. A mathematical model of the human bio-mechanical function is being developed to be used in conjunction with future metabolic studies of this type (268).

Energetics in Space Suits and Lunar Gravity

Non-locomotor tasks in lunar subgravity conditions must be considered with and without inflation of space suits (199, 236, 267). With only single free-hand fixations, reciprocating tasks require about 20% more oxygen consumption under 1/6th g simulation than under 1 g (211). Figure 10-26a presents data on effect of g-level on the energetics of different tasks. The presence of an inflated space suit adds considerably to the energy requirements for specific tasks as seen in Tables 10-21 and 10-22. Computer programs are being prepared for analysis of space suit and 1/6th g interactions in task analysis (138, 139, 140).

The energetics of locomotion on the lunar surface is a multivariate problem which has still not been adequately solved (67, 112, 114, 140, 161, 204, 206, 211, 267). Simulation appears to be the major difficulty. Several parameters, such as gait, traction, and limb segment velocity are relevant.

Table 10-21

Metabolic Rate in Pressure Suit Operations

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR			Number of Subjects	Vent Flow CFM	Trials
Treadmill	Street		15 Mins	30 Mins	60 Mins			
0.8 mph	Clothes	0.0	510	576	562	5	—	20
0.8 mph	Gemini	0.0	—	811	780	3	11.5	4
	(G-1c-4)	3.7	—	1159	1171	3	11.5	4
1.5 mph	Gemini	0.0	—	953	996	3	11.5	6
	(G-1c-4)	3.7	—	1775	1979	3	11.5	6
0.8 mph	Apollo	0.0	810	804	—	2	13.5	8
	(021)	3.7	1126	1062	—	2	13.5	8
0.8 mph	Apollo	0.0	—	814	826	2	10.5	5
	(024)	3.7	—	926	944	2	10.5	5
Arm Exercise[1]	Apollo	0.0	644	649	—	2	13.5	6
	(021)	3.7	723	730	—	2	13.5	6
Switch Flipping[2]	Gemini	0.0	425	—	—	5	11.5	11
	(G-1c-4)	3.5	625	—	—	5	11.5	11

Task	Suit Type	Suit Pressure PSIG	Heat Production BTU/HR		Number of Subjects	Vent Flow CFM	Trials
Treadmill	Gemini		15 Mins	30 Mins			
1.2 mph	G-1c-4	0.0		824	2	11.5	2
	G-1c-4	3.7		1453	2	11.5	2
2.5 mph	G-1c-4	0.0	1256	1263	1	11.5	1
2.0 mph	G-1c-4	3.7		2079	2	11.5	2
2.0 mph	G-2c-24	0.0	1027		4	11.5	4
2.0 mph	G-2c-24	0.0	1125		4	4.0	4
3.0 mph (6% GD)	G-2c-24	0.0	2309		4	11.5	6
0.8 mph	G-2c-24	3.7	1163		4	11.5	4
0.8 mph	G-2c-24	3.7	1338		2	4.0	2
1.8 mph	G-2c-24	3.7	1929		3	11.5	3

1. The Arm Exercise consisted of lifting an 11.5 lb. weight thru a distance of 18 inches every 5 seconds, alternating between left and right arms.
2. The Switch Flipping task consisted of activating a switch at arms length once every 5 seconds while the subject was sitting in the Gemini mockup couch.

Table 10-22

Caloric Requirements

(After LaChance(141))

Activities	Heat production, Btu/hr
Treadmill walking at 0.8 mph: ª	
Light clothing (normal dress)	520
Space suit, unpressurized	860
Space suit, pressurized 3.5 psi	1520
Space suit, pressurized 5.0 psi	2020
Sitting in mockup activitating switches: ᵇ	
Space suit, unpressurized	420
Space suit, pressurized 3.5 psi	590

ªAt sea level.
ᵇActivating switch once every 5 seconds at sea level.

A simplified view of the problem, however, is to consider the task as being analogous to carrying weights while walking. As gravity is reduced, the weight carried is consequently reduced, and the energy expended for the task is similarly reduced. An effective method of testing this concept is to reduce traction, on a 6-degree-of-freedom simulator, and to add weights to the subjects to return them to their 1-g weight (267). As the simulated level of gravity is reduced, a pronounced decrease in energy expenditure occurs. When weights are added to the subjects to return them to their original (presimulation) weight, only slight increase in metabolic rate occurs, despite the substantial increments in the total weight being transported. This substantiates the concept that weight reduction is a primary mechanism in producing walking metabolic rates that are lower at reduced gravity than at 1 g. Current studies of elastic fabric or foam-sponge counter-pressure suits may lead to considerable reduction in the energy requirement of extravehicular locomotion (110, 257). The effect of inflated space suits is especially significant in this task. Tables 10-21 and 10-22 and Figures 10-23 and 10-24 indicate locomotion in an inflated suit may more than double the energy requirement over that in an uninflated suit in Earth gravity (123). Figures 10-23, 10-24, and 10-25 represent the sensitivity of metabolic rate of progression to gravitation and to suit pressure.

In general, several forms of 1/6th g simulation give remarkably similar results in predicting energy costs of locomotion (140, 199, 266, 267, 269). These are seen in Figure 10-25a and b. Data are available on combined effect of 1/6th g and pressurized suits as seen in Figures 10-24, 25b, and 26b and c. Preliminary studies of horizontal locomotion in 1/6th g with suit pressurized suggest that in the 2-4 mph range, the energy cost may be equal or less than 50% of that required in the unpressurized condition under 1 g (137, 140, 266, 267). Figures 10-26 b and c emphasize the effect of the different simulators and suits. Figure 10-26c illustrates these data in terms of the lunar weight of the subjects; the metabolic rate is plotted in terms of body

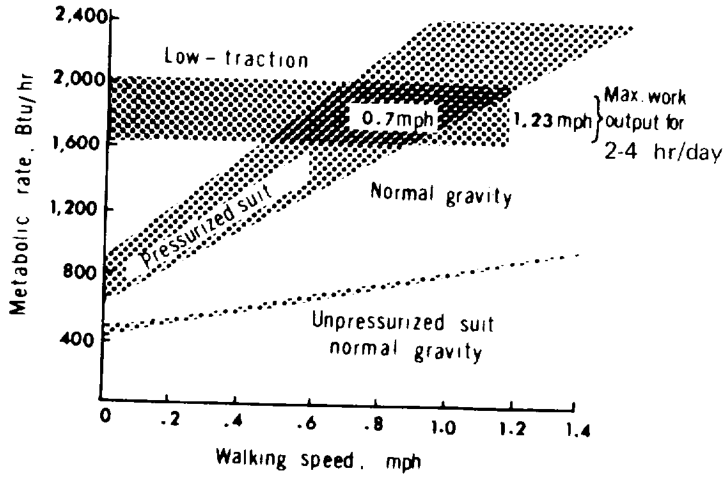


Figure 10-23

Metabolic Cost of Walking in Pressurized Space Suits Under Normal Earth Gravity

(Modified from Garrett Corp.[3])

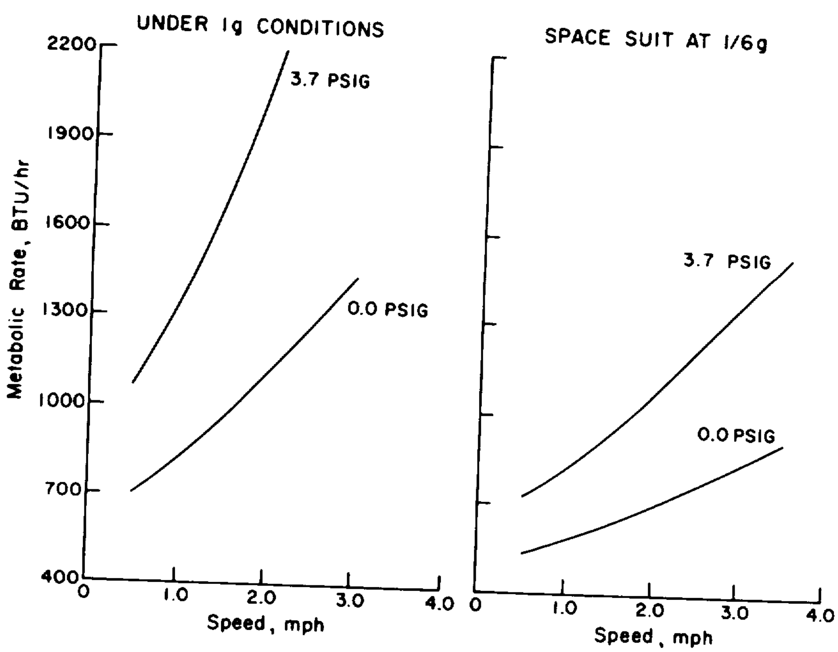


Figure 10-24

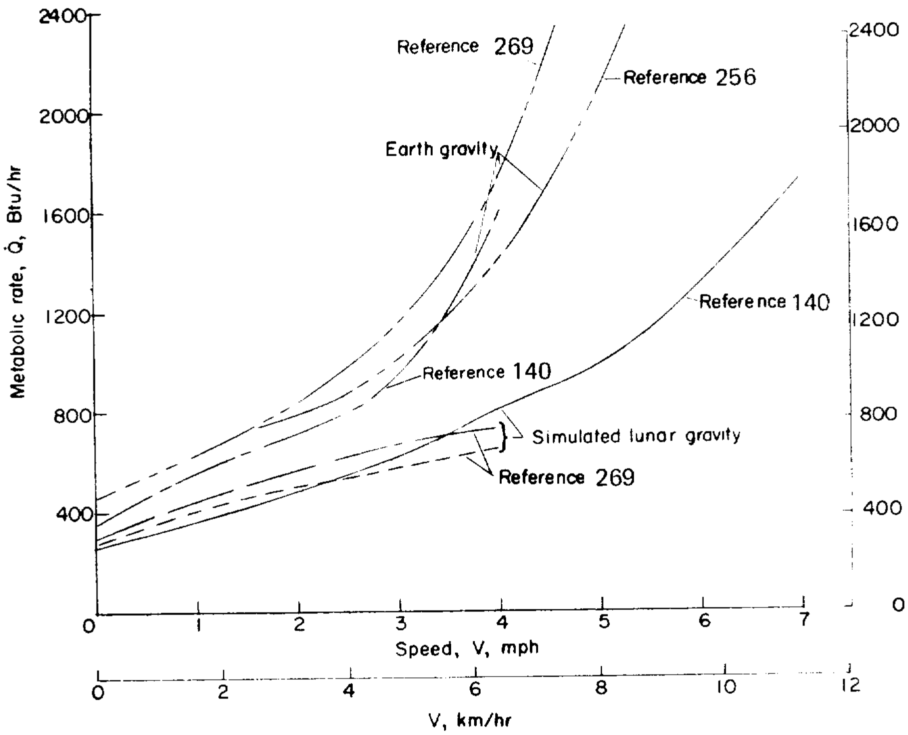
Metabolic Rate Comparison

(After Kincaide[129])

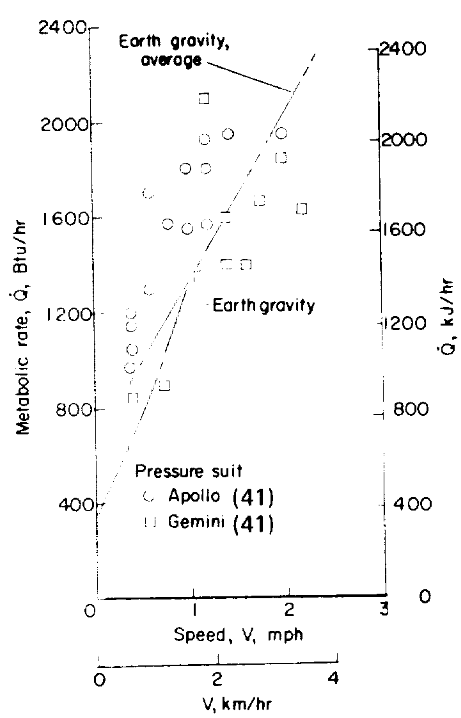
Figure 10-25

Comparative Test Data of Metabolic Cost of Locomotor Work in Subgravity with Pressurized Suits from Various Sources and for Different Conditions

(After Hewes[113])



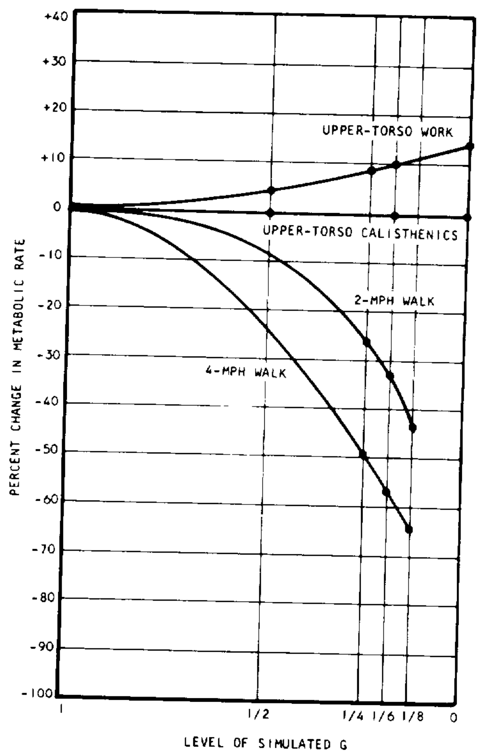
a. Shirt Sleeve



b. Pressure Suit

Figure 10-26

Effect of Gravity, Task, Suit, and Simulator Variables on Metabolic Cost of Work



a. (left) Change in Metabolic Rate for Classes of Tasks as a Function of Simulated Reduced Gravity (Shirtsleeves)

(After Wortz[267] from data of Wortz and Prescott[269] and Prescott and Wortz[199])

b. (bottom) Metabolic Rates for Walking in Different Pressurized Suits on Different Simulators

(After Robertson and Wortz[207]).

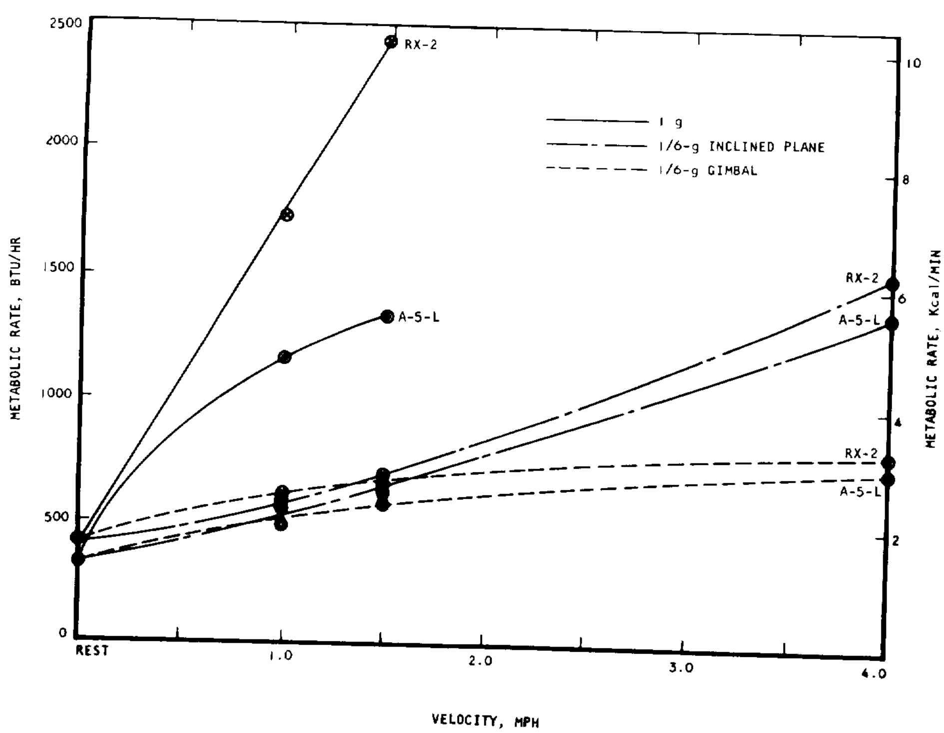
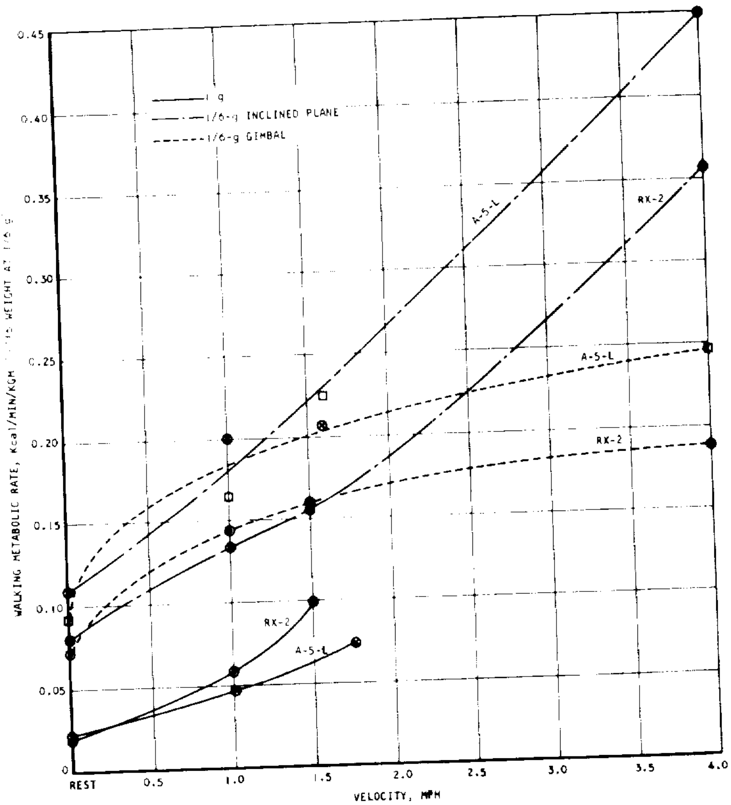


Figure 10-26 (continued)



c. Metabolic Rates for Walking in Pressurized Suits on Different Simulators

Data are normalized for body weights; lunar weight is used for lunar gravity simulated conditions; suits refer to Apollo prototypes.

(After Robertson and Wortz(207))

weight for the lunar gravity conditions. The higher cost of walking at 1/6th g (per kg on the lunar surface) indicates a substantial reduction in walking efficiency at 1/6th g. The higher cost (per kgM) for the A-5-L suit over the RX-2 suit indicates an increase in efficiency of work for walking with the heavier hard suit.

These results imply that the bulk and constraints of current pressure suits do not impose as severe penalties on the lunar explorer as has been supposed on the basis of Earth-gravity data. It is possible that this new knowledge will permit greater freedom in making pressure-suit-system trade-offs and selecting the optimum combination of suit features. A preliminary computer program is in preparation for prediction of combined, subgravity, suit-pressurization effects in locomotor tasks (140).

In the 1/6th subgravity, the mode of locomotion is altered by changes in step length, step frequency, and phasic support times (140, 206). Cyclograms of locomotion in pressurized suits on subgravity simulators are available (115, 140). Recent simulator data on non-pressure suited subjects indicate that: (115) the maximum lunar walking and running speeds are about 60 percent of those for earth gravity; for most speeds, the lunar stride was greater and the stepping rate was less than the corresponding Earth values by as much as a factor of 2. The natural or most comfortable gait for the lunar condition corresponded to a loping gait at about 10 feet per second (3 m/sec) which is much faster than the natural Earth walking gait of about 4.0 feet per second (1.2 m/sec). Sprinting and loping in the lunar conditions produced about the same running speeds, whereas sprinting produced significantly higher speeds in Earth tests. The subjects leaned further forward and swung their legs further forward for lunar gravity tests than for corresponding Earth gravity tests. Furthermore, the subjects tended to walk stiff-legged with very little flexing of the knees for the lunar tests. The theoretical basis for changes in gait and performance are available (56, 162, 211). However, the most "comfortable" lunar gait may not correspond to that requiring the least total expenditure or work. The energy losses incurred as a result of wearing a suit depend on both the rate and amount of flexing the suit. The high loping gait which requires much flexing of the suit and relatively more antigravity work is more costly of oxygen consumption than is a fast walk or run at an equivalent speed (266). More data are required on optimization of lunar gait from an energetic point of view. A compromise between the lope and fast walk or run may prove to be the most practical. More work is needed in this area.

Maximum performance characteristics such as forward velocity, maximum vertical jump height, and broad-jump distance have been attained in inclined plane simulation of 1/6th g as recorded in Table 10-27. (See also Table 7-73.)

Table 10-27

Effect of Subgravity Suit Pressurization on Human Locomotor Performance of Different Types

(After Hewes[112])

a.

Energy Cost of Locomotion - Unpressurized BTU/hr			
	1/6 g	1 g	Ref.
2 mph level	560	810	266
4 mph level	740	1700	
	850	1980	266
4 mph 10° incline	1300	2800	137

b.

Gravity	Suit pressure psi	Max. forward vel., fps	Vert. jump max. ht., ft	Broadjump horiz. dist., ft
1 g	0	11.3	1.7	5.4
	3.5	9.2	1.0	3.3
1/6 g	0	5.4	7.7	12.0
	3.5	4.0	4.6	7.0

Range and Duration on the Lunar Surface

Predictions have been recently made on the maximum work capabilities of distance and range of operations under limitation of fatigue assuming a back pack performance maximum of 2000 BTU/hr for 4 hrs. As was pointed out in the discussion of Figure 10-15, exercise of 2000 BTU/hr for 4 hrs is probably beyond the capabilities of most of the astronaut group. The back pack, therefore, has excess capacity built into it for emergency purposes. The weakest link in these predictions is the lack of adequate oxygen consumption data on pressurized subjects with back packs at 1/6th g. The range-penalty predictions incurred by wearing the pressure suit and back pack are illustrated in Figure 10-28. This shows the range reduction, in terms of percentage of shirtsleeve range, for various speeds under both lunar and Earth conditions. The restrictions of the pressure suit system on range capability were shown to be appreciably affected by both gravity and locomotive speed. The general effects of increased speed are a decrease in range penalties for lunar gravity and an increase for Earth gravity. These effects are attributed to the changes in gait characteristics (stride and stepping rate) required to produce the speed changes for the two different gravity conditions.

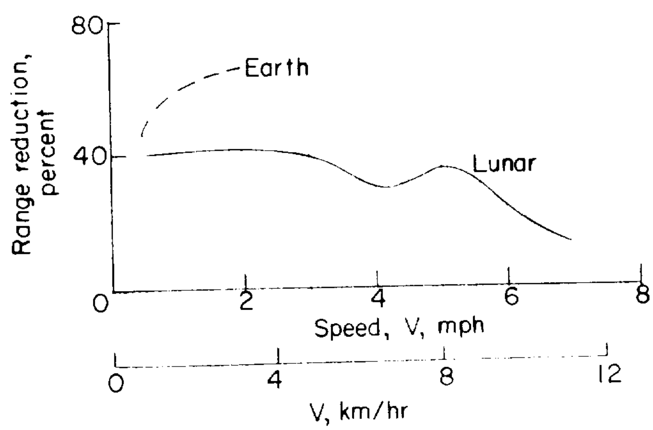


Figure 10-28

Estimated Combined Effect of Pressure-Suit-System Bulk and Stiffness on the Maximum Range of Lunar Explorers

(After Hewes[113])

Assuming no rest periods or optimization of work-rest cycles, range predictions can be made from the data of Figures 10-25, 10-28 and 10-15 (lower curve) under different locomotion rates and duration of activity. Figure 10-29 shows these predictions under Earth and lunar conditions for heat dissipation and fatigue limits. The straight lines radiating from the origin of Figure 10-29a correspond to constant rates of energy expenditure and are identified by the corresponding fatigue limits. The intersection (indicated by the symbol) of each line with the experimentally derived range-factor curves corresponds to the maximum speed which can be sustained for a specific period of time without exceeding the assumed fatigue limits.

The maximum range attainable for a given speed without consideration of other factors except total life-support-system capacity is determined by multiplying the range-factor value in Figure 10-29a by the value for the system capacity (assumed to be 4800 BTU or 5070 kJ for this analysis) and dividing by 1000. The maximum range for all speeds is shown in Figure 10-29b

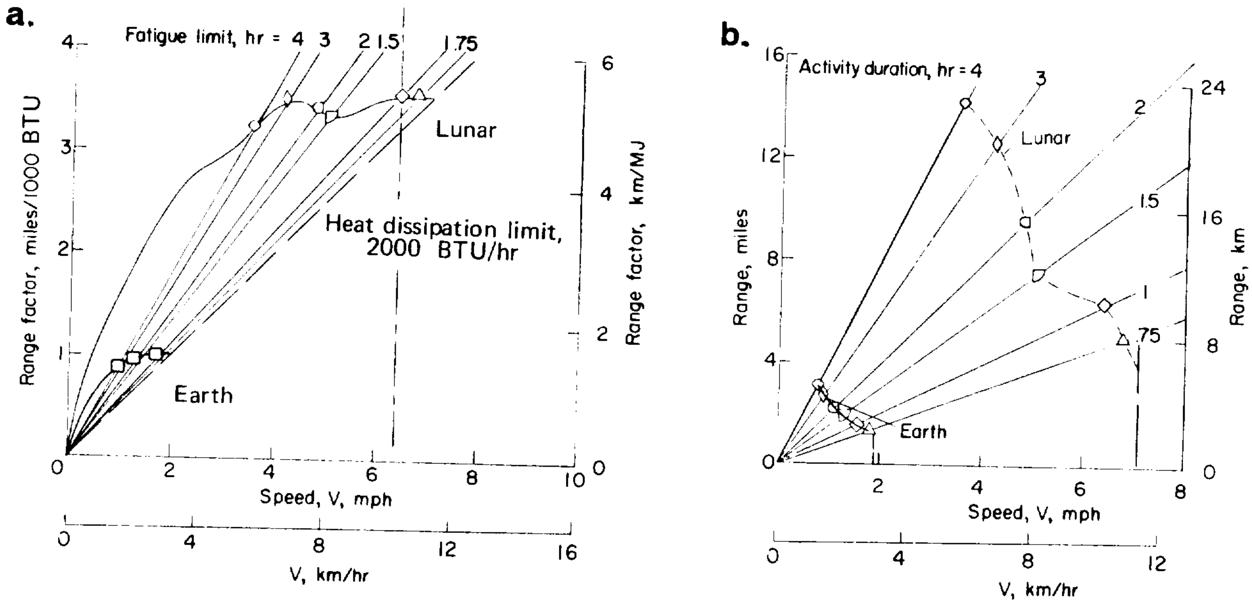


Figure 10-29

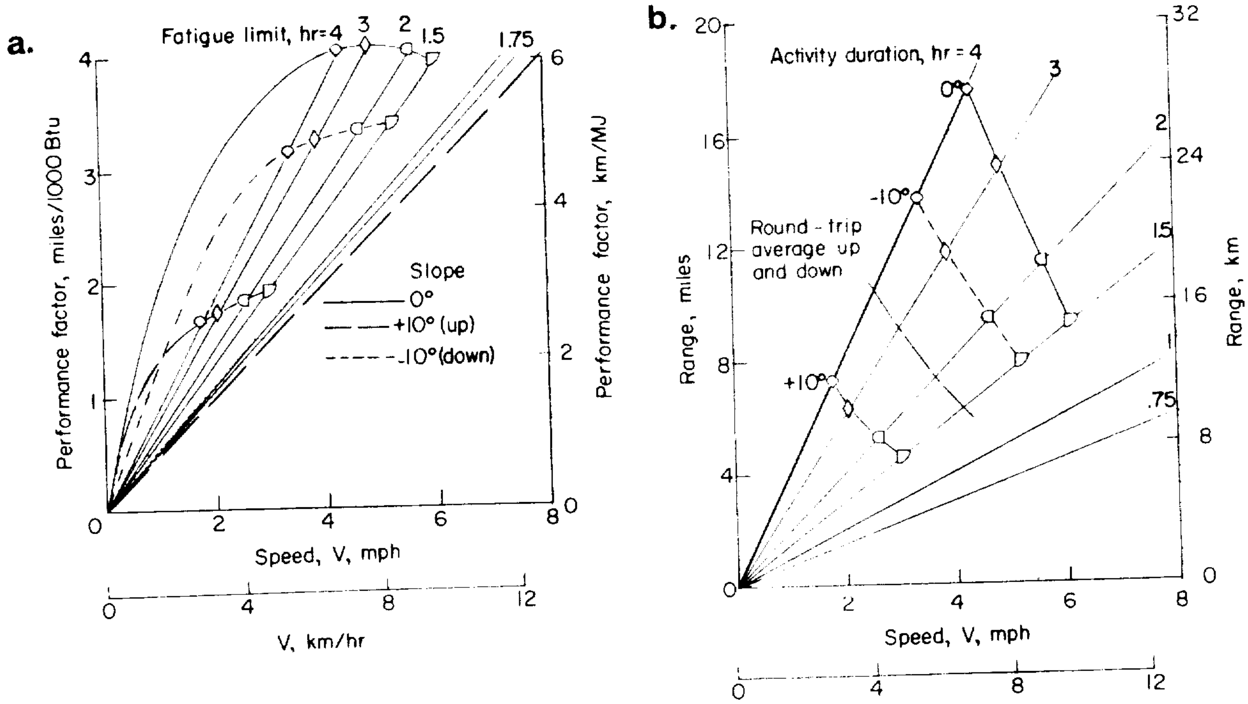
Estimated Effects of Speed, Activity Duration, Fatigue, and Suit System Limits on Range Capability of Lunar Explorers on Lunar Surface and Earth

(After Hewes(113))

by the solid curves which appear similar to the curves in Figure 10-29a. The maximum range attainable for a given speed, if only the duration of the mission is considered, is defined in Figure 10-29b by the straight lines radiating from the origin and designated by the specific values of activity duration ranging from 0.75 to 4 hours. The heavy straight line corresponding to a 4-hour period represents the maximum range as limited by the assumed maximum mission-duration limit. The effect of the assumed fatigue limits on the maximum range attainable for a given period of activity is determined by graphically projecting the various intersection points in Figure 10-29a to the corresponding activity duration lines in Figure 10-29b.

The resulting intersections in Figure 10-29b, denoted by symbols, are connected by the short-dash line which represent the fatigue boundary. The vertical lines in Figure 10-29b and heavy dashed line in Figure 10-29a represent the loci at which the metabolic rate reaches the maximum heat dissipation capacity of the life support system at 2000 BTU/hr.

Review of the limited reference data and study of one subject walking up and down slopes in 1/6th g, suggest that activity on a 10° sloping surface, whether ascending or descending, reduces the range capability with the effect of ascending being about three times that of descending (113, 139). Inasmuch as a complete round trip over sloping terrain will usually result in the same uphill distance as downhill distance traversed, the effects of the slope can be averaged together to give a more realistic indication for operating over uneven terrain. The average curves given in Figure 10-30 show that the range capability of 10° sloping surfaces is about half of that for a level surface. The curves are read in the same manner as Figure 10-29.



Curves are based on data from one subject(139)

Figure 10-30

Estimated Effect of Surface-Slope Variations on the Range Capability of Lunar Explorers (After Hewes(113))

In using the data of Figures 10-29 and 10-30, it must be remembered that the curves are extrapolations from several limited simulation studies. In the same simulator, energy consumption predictions vary ±15% (139). When the uncertainties of fatigue limits of the astronaut group are considered (Figure 10-15), the range estimations must be taken with a wide range of expected error (113). Optimization of work-rest cycle for maximum range remains to be accomplished.

A new back pack for lunar operations is under development (233).

Energy Requirements for Apollo

General thermodynamic requirements anticipated for the several phases of the Apollo mission are shown on Figure 15-5 of Water, (No. 15) (25). In addition to these general standards, Table 10-31 represents specific recommendations for different aspects of the orbital flight.

The hourly breakdown of metabolic activity anticipated for the orbital phase of the Apollo mission is seen in Table 10-32a and b. Hourly metabolic requirements for the LEM and lunar surface operational phases of the mission are seen in Figure 15-5 of Water, (No. 15). The post-landing requirements are related to wave height and thermal conditions as seen in Table 10-32c.

Activity	cal/hr	Btu/hr
Sleep	70	280
Eating	1.5× Basal	420
Exercise	2.5× Basal	700
Rest and relaxation	1.5× Basal	420
Work Program:		
Flight control	2× Basal	560
Reconnaissance	2–2.5× Basal	560–700
Scientific observation	1.5–2.5× Basal	420–700
Repair	2–4× Basal	560–1120
Suited environment (unpressurized): Add increase factors in percent as follows:		
Sleep		+10
Eating		+50
Exercise		+50
Rest and relaxation		+50
Work		+50

Table 10-31

Metabolic Requirements With Spacecraft Cabins in Orbit

(After Vinograd[255])

Table 10-32

Hourly Partition of Metabolic Rate Anticipated for the Orbital Phases of the Apollo Mission These data are on the conservative side for safety purposes.

(After Billingham[25])

a. Command Module Routine Flight

	Time Hours	Metabolic Rate $kcal/m^2$ hr	Heat Output kcal	BTU
Sleep	8	40	640	2,540
Off-duty	7	50	700	2,780
On-duty (suited)	8	65	1,040	4,130
Exercise	1	200	400	1,580
TOTAL	24		2,780	11,030

b. Command Module Emergency Decompression

A prolonged period of decompression is assumed and the work-rest cycle altered as follows:

	Time Hours	Metabolic Rate $kcal/m^2$ hr	Heat Output kcal	BTU
Sleep	8	40	640	2,540
Off-duty	8	50	800	3,170
On-duty	8	100	1,600	6,250
TOTAL	24		3,040	11,960

c. Post-Landing Metabolic Requirements

Metabolic Heat Load — 8.5 ft wave height-600 BTU/hr.
0.5 ft wave height-400 BTU/hr.

* Allowable Effective Temperature — 600 BTU/hr. heat load - 86.5F
400 BTU/hr. heat load - 88F

*Allowable effective temperature may be exceeded for four consecutive hours.

Storage Penalties for Oxygen Systems

Weight and volume storage penalties for gaseous and cryogenic oxygen (215) are covered with other gases in the Inert Gas Environment, pages 11-20 to 11-27 and Figures and Tables 11-10 and 11-12. Since penalties for solid chemical storage are closely tied to water production, R. Q., and other factors, they will be discussed here.

Because relatively stable forms of chemical compounds containing a high percentage of oxygen and nitrogen are available, this mode of storage appears particularly suitable for cabin pressurization, erection of inflatable structures, emergency breathing supplies, spacesuit backpacks, and nitrogen supplies for missions requiring small units with long standby time prior to operation. Several excellent reviews of the subject are available (32, 33, 53, 155, 165, 180, 190, 193, 194, 215).

Oxygen producing chemicals can be divided into four major groups: (1) Alkali and alkaline earth peroxides, superoxides, and ozonides, (2) alkali and alkaline earth chlorates and perchlorates, (3) hydrogen peroxide, and (4) water electrolysis.

Table 10-33 shows some of the pertinent physico-chemical properties of oxygen-producing chemicals suitable for space cabin use. Lithium peroxide is not available commercially, and calcium superoxide, because of its low yield per pound in commercially available material (50 percent impurity), is of value only in extravehicular suit backpacks where its resistance to fusion is of merit.

Potassium and sodium peroxides are compounds of primary interest in the first category. They absorb water and carbon dioxide and produce carbonates, bicarbonates, and oxygen. In terms of oxygen storage capacity, the ozonides are superior to corresponding superoxides (see Table 10-33). The potassium and sodium ozonides are readily prepared (194). As with the superoxides, lithium ozonide theoretically has the most desirable characteristics

Table 10-33

Comparison of Oxygen-Producing Chemicals

(After Coe et al[53] and Petrocelli[192])

	KO_2	NaO_2	Li_2O_2	NaO_3	$LiNO_3$	$LiClO_4$	$NaClO_3$	H_2O_2	H_2O_2
Available O_2 (theoretical), weight percent	33.8	43.6	34.8	56.3	23.2	60.1	45.1	47.1	47.1
Purity		0.90	([a])		1.00	1.00		0.90	0.98
Available O_2, lb/lb	0.32	0.392	0.375	0.56	0.232	0.601	0.40	0.423	0.461
Density, lb/in.^{3}	0.0237		0.0774		0.0861	0.0878	0.0815	0.0502	0.0515
Heat of reaction, Btu/lb[b]	[c] 415	[d] 635	[e] −363	+1515	−488	−596	+422	+1106	1214
H_2O balance, lb/lb	−0.0207	−0.0246		−0.136	0	0	0	+0.577	+0.539
H_2O balance, lb/lb O_2	−0.0862	−0.0862		−0.225	0	0	0	+1.34	+1.17
CO_2 balance lb/lb	0.31	0.40	0.96	0.31					

[a] 10 percent Li_2O_4.
[b] + Indicates exothermic reaction; − indicates endothermic reaction.
[c] $2\ KO_2 + 1.23\ CO_2 + 0.23\ H_2O = 0.77\ K_2CO_3 + 0.46\ KHCO_3 + 1.5\ O_2$.
[d] $2\ NaO_2 + 1.23\ CO_2 + 0.23\ H_2O = 0.77\ Na_2CO_3 + 0.46\ NaHCO_3 + 1.5\ O_2$.
[e] Li_2O_2.

in terms of oxygen availability (0.73 lb/lb of compound), but all attempts at synthesis have failed (194). Lithium peroxide has been synthesized. Chlorate candles are stable materials which can be burned in generators to produce oxygen at a constant rate. Hydrogen peroxide is a strongly oxidizing liquid which can be decomposed catalytically to generate oxygen, water vapor, and heat.

Superoxides, Ozonides, and Peroxides

The reactions of superoxides with water vapor and carbon dioxide to form oxygen have been reviewed, and much of the following discussion is based on this study (192). These reactions can be expressed by the following equations:

$$2MO_2(s) + H_2O(v) = 2MOH(s) + 3/2O_2(g) \tag{9}$$

and

$$2MO_3(s) + H_2O(v) = 2MOH(s) + 5/2O_2(g) \tag{10}$$

where s = solid, v = vapor, g = gas, l = liquid, M = alkali earth element.

In turn, carbon dioxide is removed from the breathing atmosphere through reactions with the product hydroxide which cause the formation of carbonates and bicarbonates:

$$2MOH(s) + CO_2(g) = M_2CO_3(s) + H_2O(l) \tag{11}$$

$$2MOH(s) + 2CO_2(g) = 2MHCO_3(s) \tag{12}$$

On the basis of these stoichiometries, the theoretical respiratory quotient (RQ), capable of being obtained with superoxide systems, ranges from 0.67 (carbonate formation only) to 1.33 (bicarbonate formation only). With ozonide systems, the theoretical RQ range is 0.40 to 0.80 for the corresponding stoichiometries.

The early concern about RQ mismatch with humans has been resolved by analysis of alternate reaction mechanisms. At first, superoxides were evaluated on the basis of a stoichiometry which involved the formation of the metal carbonate only (Equation 11). Thus, the RQ of the system was expected to be 0.67 and oxygen overproduction was predicted. The other factor which contributed to doubts about the superoxides is based on the experience gained from the use of potassium superoxide canisters in self-contained breathing apparatus for firefighting and mine rescue. Such canisters resulted in very inefficient utilization (about 80 percent) of the superoxide charge. The inefficiency of such canisters can be attributed to the formation of a hard crust of potassium hydroxide on the reaction surface of the superoxide, thereby preventing water vapor in the exhaled breath from contacting the unreacted superoxide. The discovery that bicarbonate does form under certain conditions of temperature and relative humidity has shown that the problem of oxygen overproduction, anticipated when only carbonates were thought to be formed, is insignificant. Semipassive superoxide systems have been designed to incorporate control of flow rates and relative humidity to achieve better than 90-percent oxygen recovery from the superoxide supply (127, 128, 166).

In effect, the following stoichiometry can be achieved in a properly designed superoxide reactor.

$$2MO_2(s) + 1.23CO_2(g) + 0.23H_2O(v) = 0.77M_2CO_3(s) + 0.46MHCO_3(s) + 1.5O_2(g) \quad (13)$$

Lithium peroxide (Li_2O_2) is of interest as an air vitalization material because in the presence of moisture it can be caused to react directly with carbon dioxide to yield oxygen and lithium carbonate: (165, 180)

$$Li_2O_2(s) + CO_2(g) = Li_2CO_3(s) + 1/2O_2(g) \quad (14)$$

Thus, it is possible to remove 0.96 pound of carbon dioxide with each pound of lithium peroxide from a closed breathing system and, at the same time, to return 0.35 pound of oxygen to the system. The RQ for a system employing only lithium peroxide would be 2.0. As a result, the use of this chemical would require an additional source of oxygen. The theoretical capacity of lithium peroxide for carbon dioxide is about 4 percent greater than the capacity of lithium hydroxide for carbon dioxide.

In the presence of water vapor, carbon dioxide absorption and oxygen evolution by lithium peroxide does occur, but oxygen generation lags far behind the amount anticipated on the basis of Equation (14) (165, 180). However, the absorption of carbon dioxide and the evolution of oxygen proceed by two different reactions; lithium peroxide and water vapor first reacting to yield the active carbon dioxide absorbents, LiOH, $LiOH \cdot H_2O$, and hydrogen peroxide:

$$Li_2O_2(s) + 2H_2O(v) = 2LiOH(s) + H_2O_2(l) \quad (15)$$

and

$$LiOH(s) + H_2O(v) = LiOH \cdot H_2O(s) \quad (16)$$

Carbon dioxide is then absorbed via:

$$2LiOH(s) + CO_2(g) = Li_2CO_3(s) + H_2O(l) \quad (17)$$

and

$$2LiOH \cdot H_2O(s) + CO_2(g) = Li_2CO_3(s) + 2H_2O(l). \quad (18)$$

Oxygen is evolved as a result of the decomposition of the H_2O_2:

$$H_2O_2(l) = H_2O(v) + 1/2O_2(g) \quad (19)$$

It has been shown that in order to achieve theoretical yields of oxygen, it will be necessary to develop a catalyst to insure the decomposition of all the H_2O_2 formed in Equation 15 (165).

The chemistry of lithium peroxide has been reviewed (63). Preliminary respiratory exchange of this compound has been studied (70). The state of the art of lithium peroxide, as an air revitalization material, is not nearly as advanced as it is for superoxides. Continued basic research is necessary in order to optimize lithium peroxide as a carbon-dioxide absorber and oxygen source.

Lithium superoxide (LiO_2) if it exists in a stable form would be of great value for air regeneration. Lithium superoxide potentially represents the lightest alkali metal oxide in terms of weight of agent per weight of oxygen produced. Experimental efforts to produce this compound have given ambiguous results. An effort has been made to estimate the thermodynamic properties of this compound, to determine whether further experimental efforts are worthwhile, to predict suitable experimental conditions, and to draw conclusions about the stability of the compound (240). Unfortunately the results of this study offer little encouragement for the availability of this material. Consideration of the free energies of various decomposition reactions showed that the tendency to decompose corresponds to 15 kcal from 100° to 300° K. This tendency is so much greater than the uncertainty of the estimates that lithium superoxide can be considered unstable at all temperatures. Furthermore, none of the usual methods of promoting stability are sufficiently effective to overcome this instability. Substances can be stabilized by putting them into solid solution. For example, phase data have shown the existence of solutions of sodium superoxide in sodium peroxide. It has been shown that, theoretically, no significant concentration of lithium superoxide can be stabilized in this way (240). This conclusion might be different if a mixed compound that has a definite heat and free energy of formation is formed. Such compounds do not usually have sufficient free energy to overcome the instability of lithium superoxide. Further attempts to prepare lithium superoxide do not appear promising. Even if the compound were prepared, it would tend to decompose spontaneously. It would probably not be safe to carry such an unstable compound in a manned space cabin.

Design equations as well as weight and power tradeoffs for the use of superoxide canisters in spacecraft have been reviewed (53, 215, 217). In any tradeoff study, a comparison must ultimately be made between the equivalent weight of carbon dioxide absorption by superoxide and LiOH with water and oxygen creditation. Weight of the potassium subsystem is considerably greater than the sodium (215). The total subsystem equivalent weight is the total of the sodium superoxide consumption, the canister weight, accessory weight, power-loss penalty, heat-rejection penalty, and material balances weight. When a deficit of water exists, the material balance requires additional water and causes a penalty. However, weight (lbs) of oxygen which is added by the system can be subtracted from the consumption weight by a factor of $W\,O_2 = 2.28\,N_\tau$, where N is the astronaut crew size and τ is the time in days. The system equivalent weight penalty is:

$$W_e = (W_{NaO_2} - W_{O_2} + W_{H_2O}) + W_{can} + W_{acc} + W_P + W_Q \qquad (20)$$

$$W_e = (5.52 - 2.28 + 0.185)\,N\tau + 3.423\,N^{2/3} + (5.2 + 1.79\sqrt{N}) + [(PL)_t(PP)] + 1.70N(RP) \tag{21}$$

where W= weight, can = canister, acc = accessories, P = power equivalent, Q = heat equivalent, e = system equivalent, τ = time in days, (PL) = power loss in watts, (PP) = vehicle weight penalty for power, R = gas constant, and t = total number.

The use of lithium chlorate candles does not appear to be competitive with that of the superoxides on a weight basis alone (215). Hydrogen peroxide as a source of breathing oxygen does also not appear favorable. The use of electrolytic systems, however, appears favorable when closed-loop systems of water salvage are considered (53, 215, 217). System integration with other processes is the determining factor in weight tradeoffs of this system.

PHYSIOLOGY OF THE OXYGEN AND CARBON DIOXIDE PARTIAL PRESSURE ENVIRONMENT

Evaluation of physiological response and performance in an altered oxygen and carbon dioxide environment requires an understanding of the distribution and role of these gases in the body.

Oxygen and Carbon Dioxide in the Lung

Figure 10-34 summarizes the key physiological interaction between the atmosphere and the lung-body system by comparing the composition (partial pressure) of tracheal and alveolar gases at different altitudes in subjects breathing (a) air, and (b) 100% oxygen. In both cases, inspired gases pick up water from the wet respiratory passages until the partial pressure of water vapor reaches saturation pressure of 47 mm Hg at body temperature (98.6°F or 37°C). Thus, the total pressure of dry gases in the trachea is always 47 mm less than the total barometric pressure (curves A and B), the tracheal oxygen and nitrogen pressures always being 9.9 mm Hg and 37.1 mm Hg, respectively,less than their dry air ambient pressures.

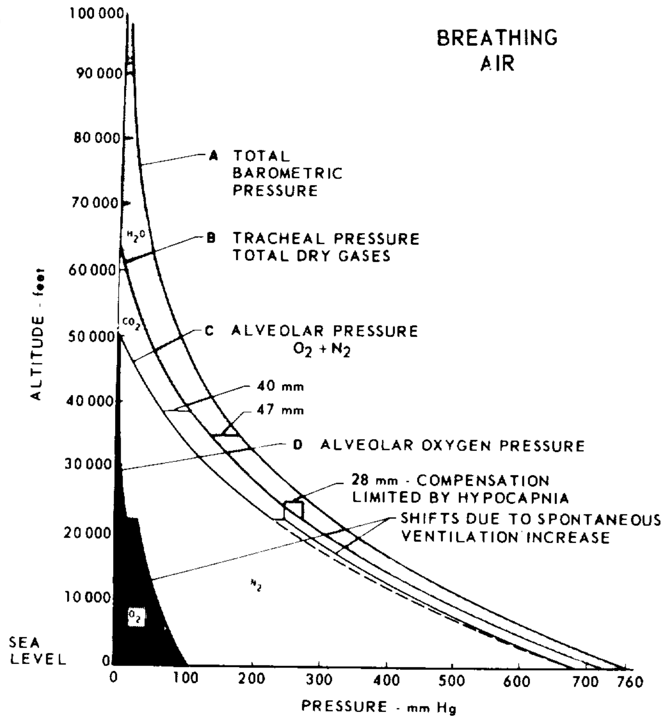
As inspired gases pass into the lungs they mix with residual air in the alveoli, lose oxygen to the blood and pick up carbon dioxide released by the blood. The carbon dioxide mixes with the alveolar gases to an equilibrium partial pressure of 40 mm Hg. The total partial pressure of oxygen and nitrogen in the lungs (alveolar gas, curve C) is therefore 40 mm less than that in the tracheal gas. In most subjects the body compensates automatically (within a limited range) for low oxygen pressure by increasing the breathing rate and/or depth (ventilation) until the point where hypocapnia (too low carbon dioxide concentration) sets in. This increases the partial pressure of oxygen (PO_2), within the compensatory range, as shown on curve D. This response sets the average "ceiling" at 24,000 ft instead of 17,000 ft where it would be without increase in ventilation. The abrupt cessation of the hyperventilation effect at 23,000 feet in graph 10-34a and at 45,000 feet in graph 10-34b represents lack of sufficient experimental points.

Figure 10-34

Partition of Gases in Trachea and Alveoli at Different Barometric Pressures

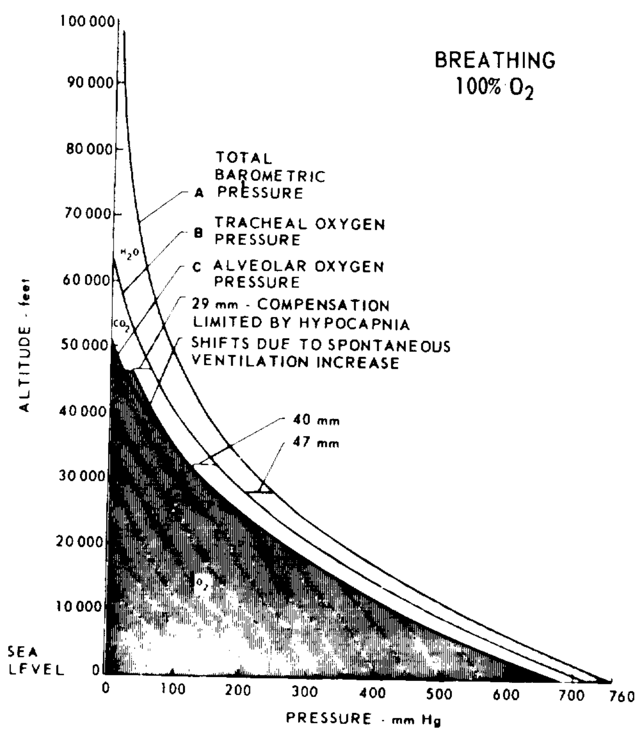
(After Roth and Billings[216], adapted from Hanff and Pegues[106])

a.



Altitude (feet)	Total Pressure (mm Hg)	N_2 Percentage	H_2O Percentage	CO_2 Percentage	O_2 Percentage	O_2 Pressure (mm Hg)
AMBIENT DRY ATMOSPHERE						
0	760.0	79.02	0	0.03	20.95	159.2
5000	632.3	79.02	0	0.03	20.95	132.5
10000	522.6	79.02	0	0.03	20.95	109.5
15000	428.8	79.02	0	0.03	20.95	89.8
20000	349.1	79.02	0	0.03	20.95	73.1
22000	320.8	79.02	0	0.03	20.95	67.2
TRACHEAL GAS						
0	760.0	74.13	6.18	0.03	19.66	149.4
5000	632.3	73.14	7.43	0.03	19.39	122.6
10000	522.6	71.91	8.99	0.03	19.06	99.6
15000	428.8	70.31	10.96	0.03	18.66	80.0
20000	349.1	68.38	13.46	0.03	18.13	63.3
22000	320.8	67.46	14.65	0.03	17.85	57.4
ALVEOLAR GAS						
0	760.0	75.00	6.18	5.26	13.55	103
5000	632.3	74.06	7.43	6.01	12.49	79
10000	522.6	72.45	8.99	6.89	11.67	61
15000	428.8	70.62	10.96	7.70	10.73	46
20000	349.1	68.49	13.46	8.59	9.45	33
22000	320.8	67.27	14.65	8.73	9.35	30

b.



Altitude (feet)	Total Pressure (mm Hg)	N_2 Percentage	H_2O Percentage	CO_2 Percentage	O_2 Percentage	O_2 Pressure (mm Hg)
AMBIENT DRY OXYGEN						
33000	196.3	0	0	0	100	196.3
36000	170.3	0	0	0	100	170.3
39000	147.5	0	0	0	100	145.5
42000	127.9	0	0	0	100	127.9
45000	110.9	0	0	0	100	110.9
46000	105.6	0	0	0	100	105.6
TRACHEAL GAS						
33000	196.3	0	23.94	0	76.06	149.3
36000	170.3	0	27.60	0	72.40	123.3
39000	147.5	0	31.96	0	68.04	100.4
42000	127.9	0	36.75	0	63.25	80.9
45000	110.9	0	42.38	0	57.62	63.9
46000	105.6	0	44.51	0	55.49	58.6
ALVEOLAR GAS						
33000	196.3	0	23.94	20.38	55.68	109.3
36000	170.3	0	27.60	22.31	50.09	85.3
39000	147.5	0	31.96	24.41	43.63	64.4
42000	127.9	0	36.75	25.80	37.45	47.9
45000	110.9	0	42.38	27.05	30.57	33.9
46000	105.6	0	44.51	27.46	28.03	29.6

In the few cases studied at 50,000 feet, even the non-acclimatized subject hyperventilates and lowers his P_{ACO_2} to 20-25 mm Hg, though not sufficiently to maintain a P_{AO_2} of 30 mm Hg critical for consciousness (13). The well acclimatized subject may maintain a sufficiently high P_{AO_2} to remain conscious "indefinitely," with P_{ACO_2} in the neighborhood of 12-15 mm Hg. Above 52,000 feet altitude, whether on air or 100% oxygen, the alveoli contain only water and carbon dioxide. Enriching the inspired air with supplementary oxygen will move curve D toward the right, as nitrogen is replaced with oxygen. The more oxygen is added, the farther to the right the curve shifts, until at 100% oxygen it becomes the same as curve C except for the portion shifted by the spontaneous increase in ventilation.

The physiological relations between the total pressure of the atmosphere and the % oxygen required for normal function has been reviewed in Figure 12-1 of Pressure, (No. 12). Nomograms and charts relating different pressures and partial pressures of oxygen and other constituents to equivalent alveolar P_{O_2}'s are available (157). One must consider the effects of both hypoxia and hyperoxia.

Hypoxia

The space environment and planetary atmospheres appear to be lacking in adequate oxygen (134, 174, 175, 184). Hypoxia is therefore a constant problem. Unfortunately, except for some oxygen stored in the myoglobin of "red muscle," the only oxygen stored by the body is that actually being transported by the blood stream. Muscles can function temporarily without oxygen, but in the process build up toxic fatigue products that limit their activity. The tissues most sensitive to oxygen deficiency, such as the central nervous system (brain and eyes) cannot function without oxygen. The capacity for anaerobic work appears to be preferentially restricted to the white muscle fibers, while the red fiber depends more on aerobic metabolism. The heart consists entirely of red muscle tissue and is, therefore, nearly as sensitive to oxygen lack as the central nervous system.

The brain in man is only 2% of the body weight but has about 20% of the total body oxygen consumption. As arterial oxygen tension falls, progressive impairment occurs in the central nervous system, as indicated in Figure 10-35 by zones of increasing density. These changes occur in resting men who are not fatigued or otherwise stressed. The oxygen saturation of arterial blood for resting men is also shown as a function of oxygen tension (the hemoglobin dissociation curve). A range of saturations for each value of tension is shown, because temperature and pH influence the saturation values. Individual variability and time dependency are characteristic of these data. The minimum and average duration of effective consciousness in human subjects following rapid decompression breathing air and oxygen are seen in Figure 12-12 of Pressure, (No. 12). Above 20,000 to 23,000 feet, unacclimatized subjects breathing air will lose consciousness after a variable period of time. Individual susceptibility varies widely except at the highest altitudes.

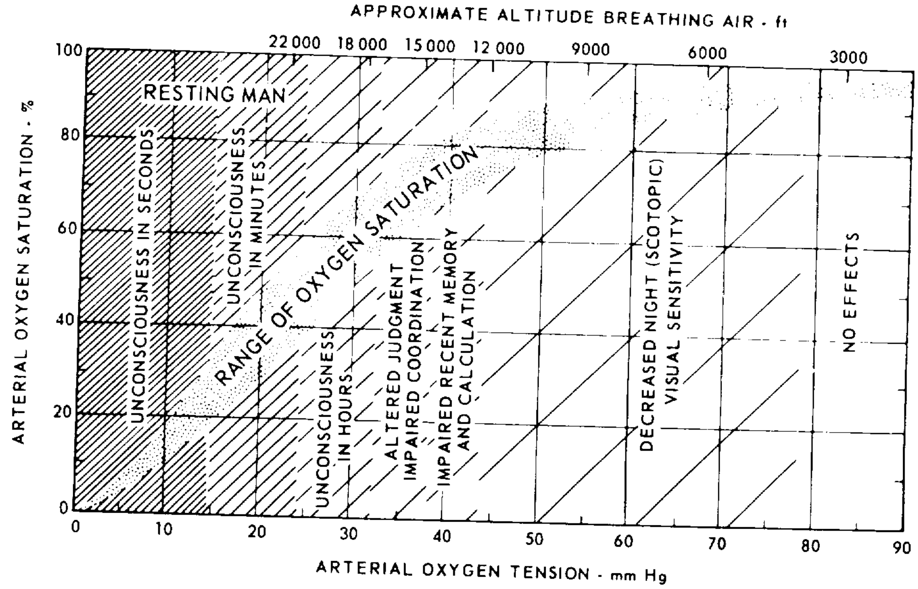


Figure 10-35

General Effect of Hypoxia on Arterial Saturation and Body Function

The ambient tracheal and alveolar pressure of oxygen corresponding to the altitudes and arterial oxygen tensions of this figure may be obtained from Figure 10-34.

(After Billings and Roth[26], adapted from USAF Flight Surgeon's Manual[248], McFarland[152], and Boothby, (ed.)[31])

The time required to reach hypoxic threshold after decompression of cabins of different atmospheric composition can be determined from Figures 12-1 and 12-9 of Pressure, (No. 12) and Figures 10-34 and 10-35.

The visual functions appear most sensitive to hypoxia. Figure 10-36 summarizes some of the thresholds of visual determination. A semi-quantitative review of visual performance after different degrees of hypoxia is seen in Figures 10-37 to 10-39. Sustained acceleration along the G_x axis will cause arterial unsaturation and produce similar decrement in performance. This relationship is noted for G_x in these figures. The degradation of vision by acceleration is covered in Acceleration, (No. 7).

Figure 10-37 represents the change in central brightness contrast discrimination at different arterial oxygen saturations and G_x values. The data can be used to evaluate human capability in detection tasks at luminance levels near threshold. (See Light, No. 2.)

Figure 10-38a summarizes visual performance decrements for dark adaptation, central brightness, contrast, central field extent and central acuity. The dashed portion of the curves are speculated.

Figure 10-38b compares the contrast sensitivity curves of Figures 10-37 and 10-38a. Difference in effect between P_{O_2} and $+G_x$ may be seen to be roughly constant at about 10-12% impairment. While this is a sizeable difference, it can be expected that differences in effect on non-sensory tasks

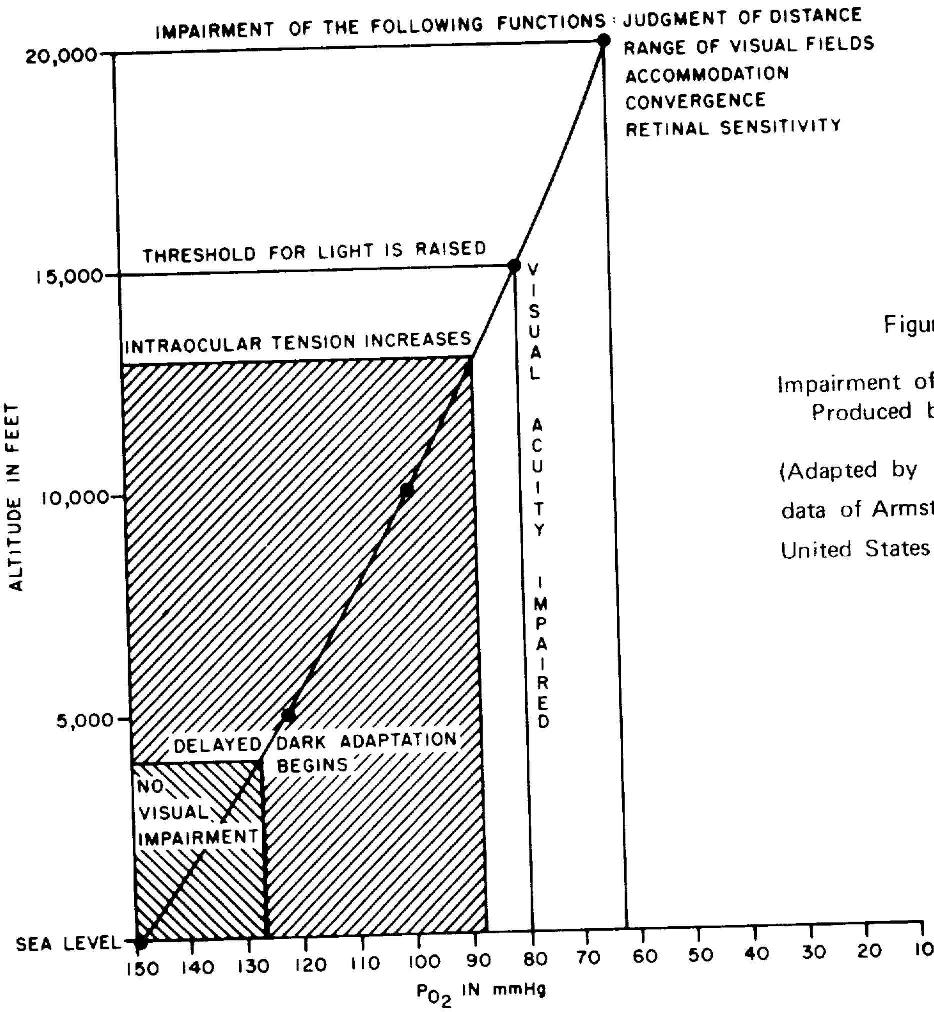


Figure 10-36

Impairment of Visual Functions Produced by Hypoxia

(Adapted by Finkelstein[82] from data of Armstrong[6] and the United States Air Force[249])

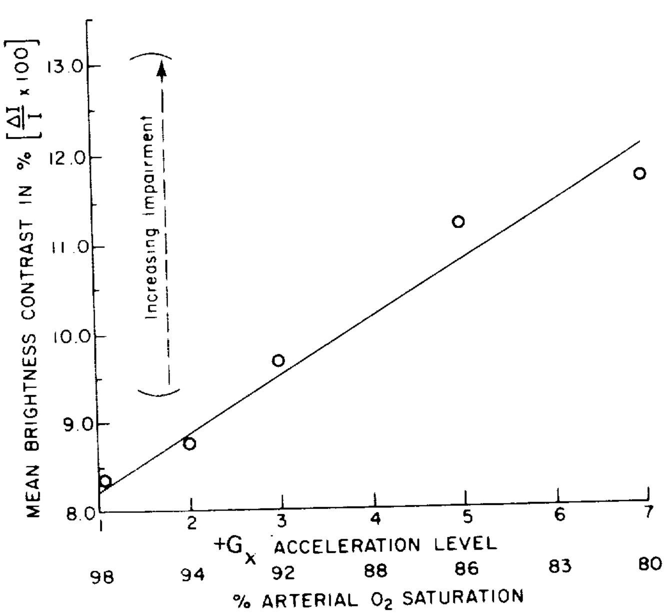


Figure 10-37

Brightness Contrast Discrimination at Given Arterial Oxygen-Saturation Level or G_x Level

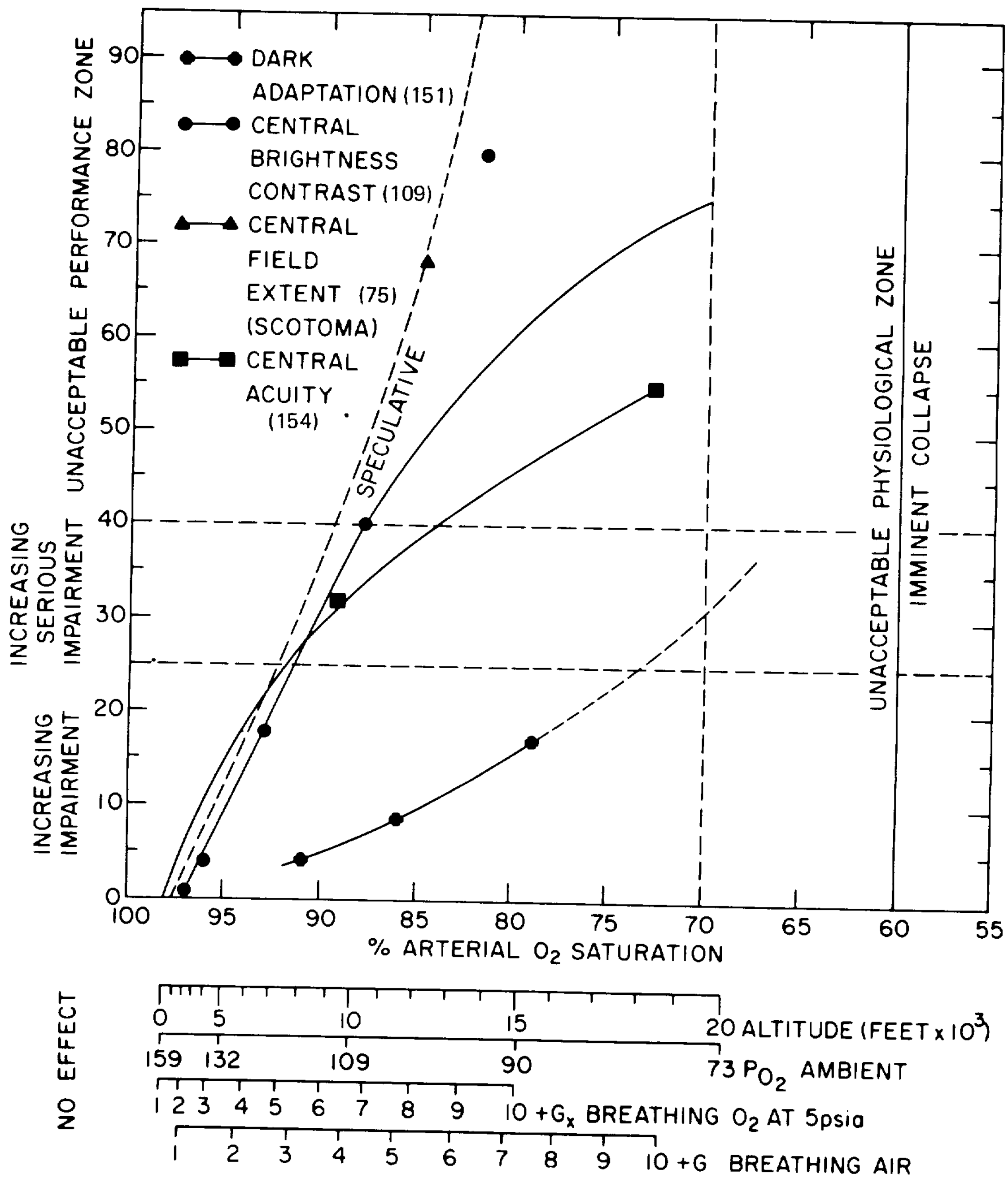
Data from exposures of 90 seconds at peak G.

(From the data of Chambers[47] and Alexander[4])

Figure 10-38

Effects of Hypoxemia and G_x Acceleration on Visual Performance

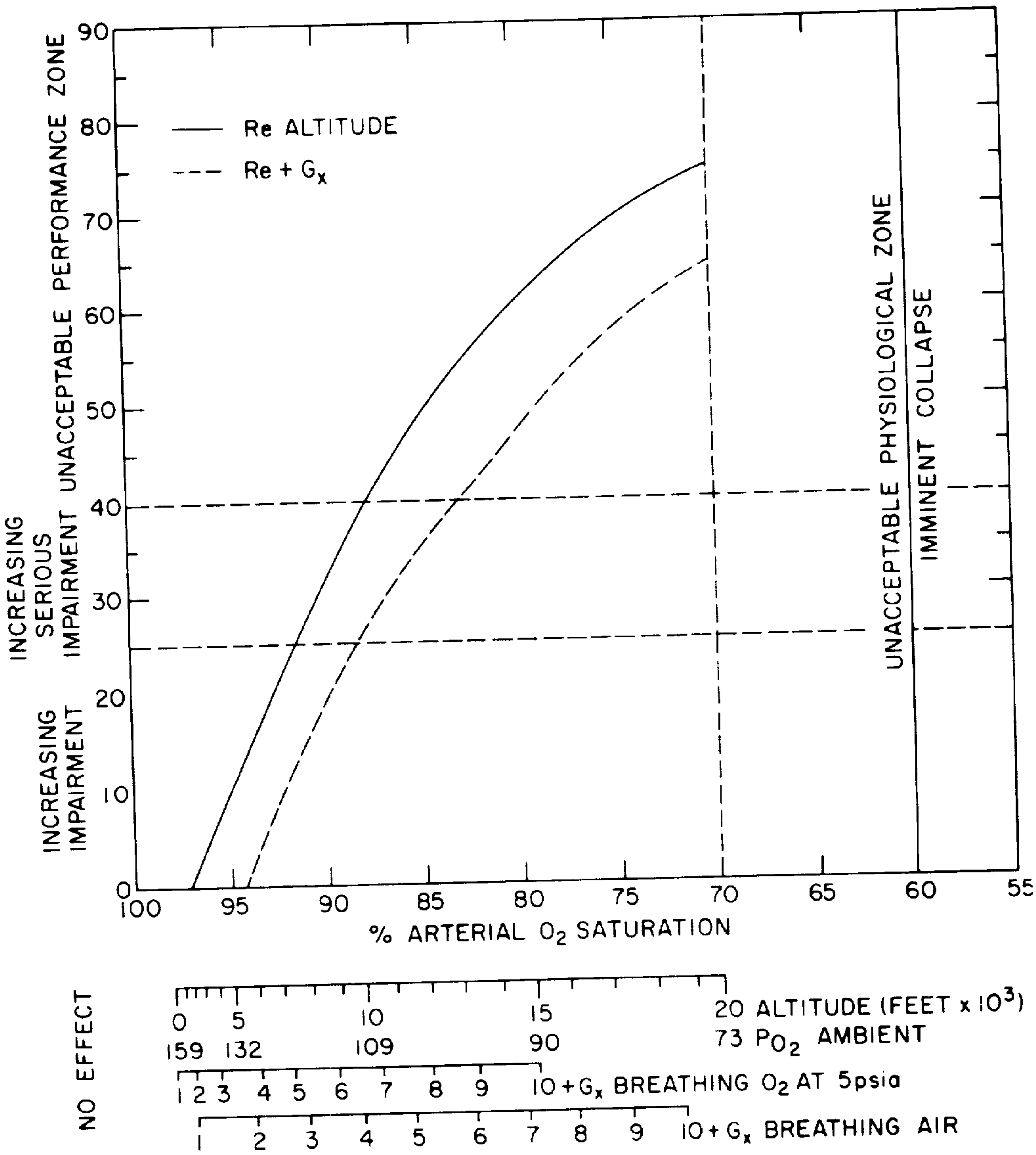
a. Response of Several Visual Functions to Hypoxemia



(Adapted by Teichner and McFarland[246] from the given sources)

Figure 10-38 (continued)

b. A Comparison of Visual Contrast Sensitivity Decrements Induced by Reduced Partial Pressure of Oxygen and Those Induced by Acceleration



(After Teichner and McFarland[246], adapted from Chambers[47] and Hecht et al[109]) would be considerably smaller. The closeness of the two curves is remarkable in view of the number and extent of data-leaps that were made. These upper limits of $+G_x$ arrived at by extrapolating from altitude-derived,blood oxygen curves are not too unreasonable in terms of the performance data that have been reported (46, 88). These data apply only to problems of low (near threshold) luminance. Target detection or dial reading at levels well above threshold probably present no significant problems during acceleration.

The effect of acute hypoxia on mental processes is a complex interaction. Figure 10-39 represents the effects of hypoxemia on several central processes. Comparison with Figure 10-38a indicates that with the exceptions of attention and fatigue, intervening mental processes are less sensitive to hypoxemia than are sensory visual processes. There is recent indication that acute exposure to 8,000 ft oxygen equivalence can result in decrease of complex reaction time during early learning of the skill (142). Visual performance becomes unacceptable above 13,000 feet; attention and fatigue above 15,000 feet; and the other intervening processes only above 19,500 feet, which is a physiologically unacceptable altitude.

The effect of hypoxia before and during exercise on maximum work output is seen in Tables 10-18 and 10-19 and the accompanying text. Such data are of value in planning for operational requirements after hypoxia emergencies.

The nature and treatment of the clinical syndromes during and immediately following hypoxic exposures have been covered by a recent review (42).

Hyperoxia

The unusual atmospheres proposed for space cabins have usually included an elevated partial pressure of oxygen. Table 11-8 summarizes the results of human experiments in these atmospheres. (See Inert Gas, No. 11.)

There is a wide spectrum of time-dependent symptoms of oxygen toxicity. (124, 213). Figure 10-40 indicates the time and pressure dependence of oxygen toxicity. The ordinate is partial pressure of oxygen. The abscissa is time to first symptoms. At high pressures of several thousand millimeters Hg, symptoms occur within 10 minutes and these are mostly of the central nervous system. In the zone of 1 atm. to 1/2 atm., the first symptoms are usually of the respiratory tract, such as bronchitis and pulmonary edema. Below 1/2 atm., the symptoms are variable. Atelectasis or alveolar collapse is seen in susceptible subjects, especially in the presence of high g loads. This is manifested by pains in the chest exaggerated by deep inspiration.

Human susceptibility to atelectasis in atmospheres of low pressure and high % oxygen appears to be a function of the collapsibility of terminal bronchioles in deep expiration (69) and may be associated with destruction of surfactant (212, 213). The airway conductance (liters/sec per cm of H_2O pressure per liter of lung volume) ranges from 0.14 to 0.35 in normal subjects but is down to 0.11 to 0.13 in subjects susceptible to atelectasis in 100% oxygen at 5 psia. With more studies, these data could possibly be used in the selection

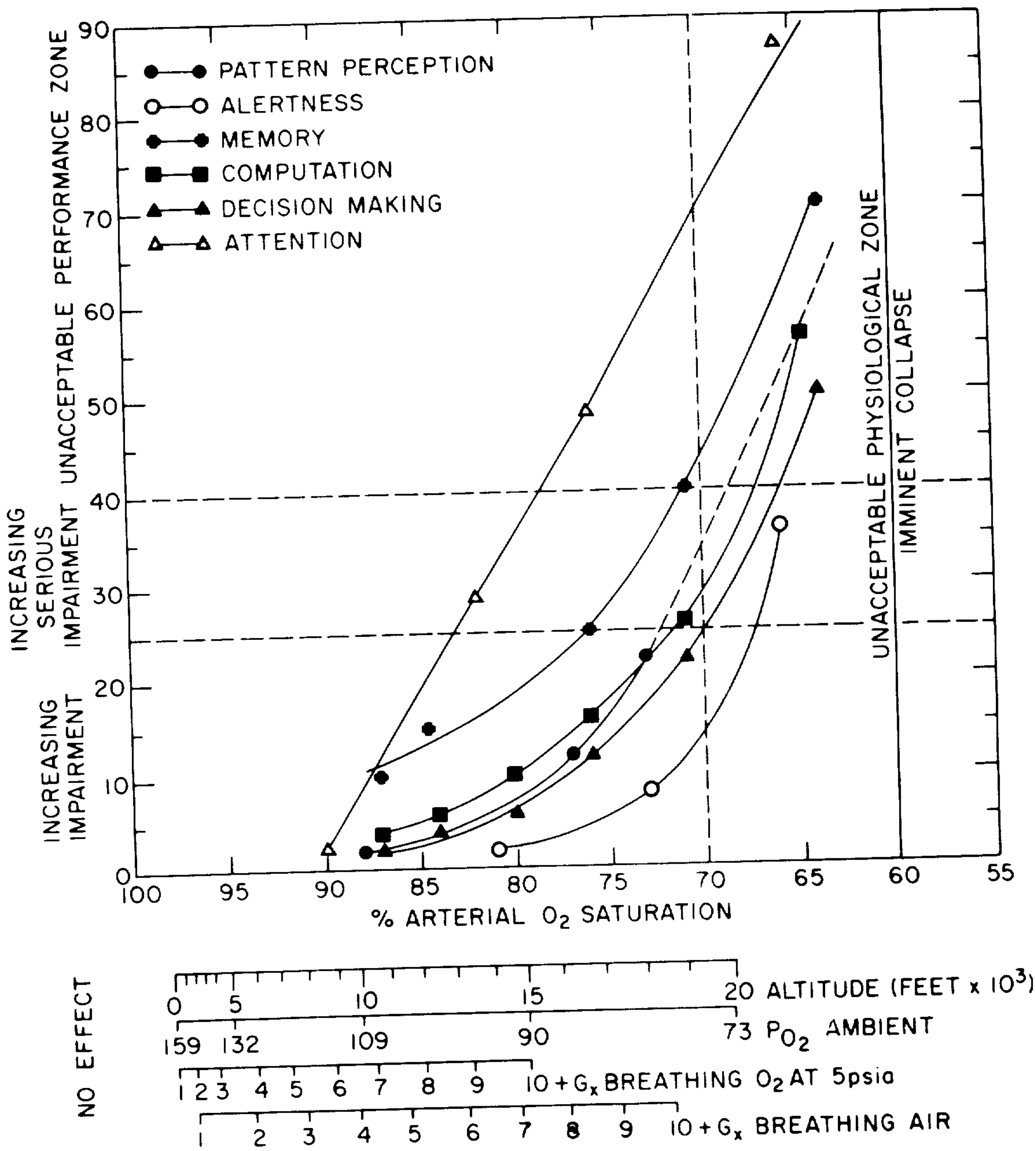


Figure 10-39

Effects of Hypoxemia on Some Intervening Mental Processes

(After Teichner and McFarland(246) from the data of McFarland(153) and Bills(27))

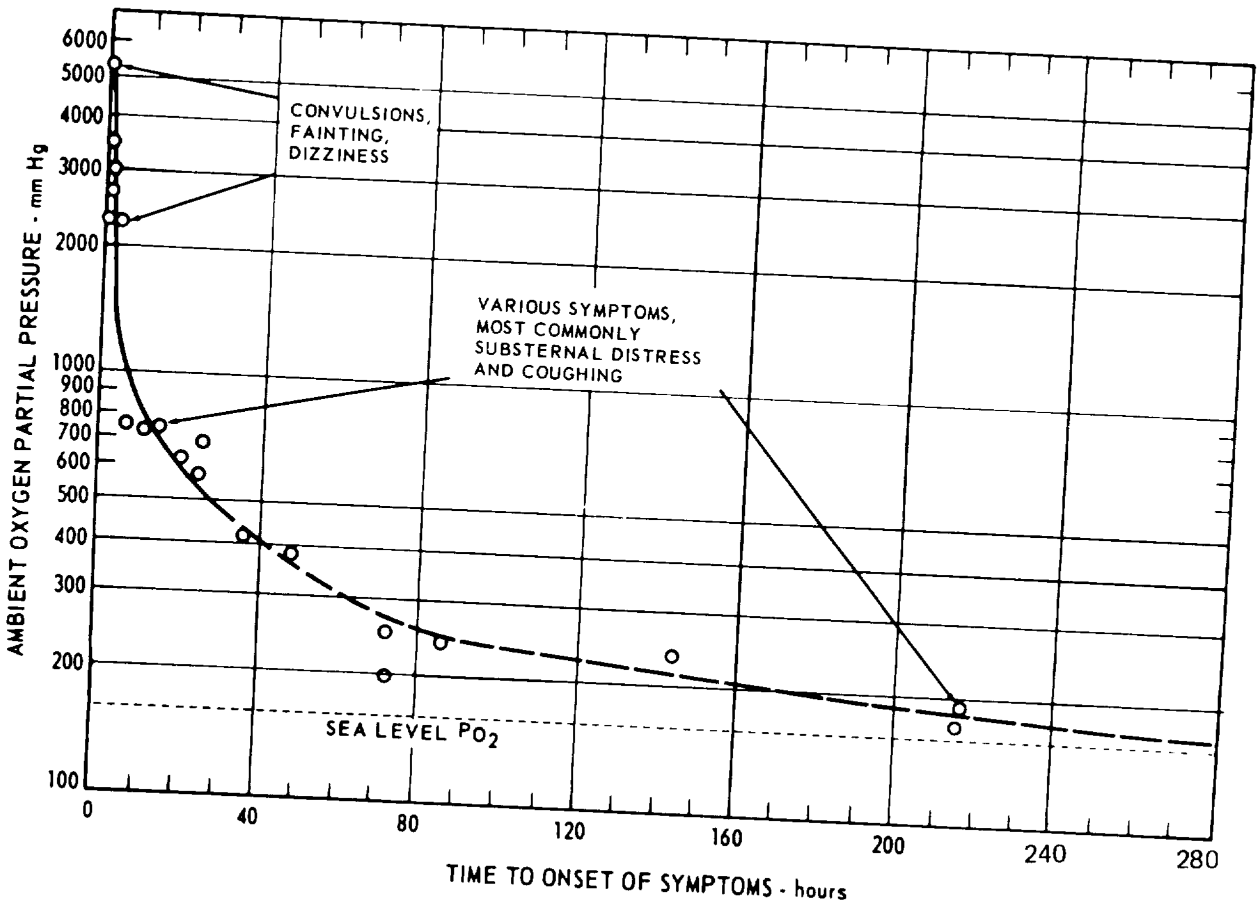


Figure 10-40

Times to First Symptoms of Oxygen Toxicity

(Adapted from Welch et al[259], Bean[22], and Roth[213])

of astronauts for resistance to atelectasis. Aural atelectasis is also a problem in 100% oxygen environments, but has not proved to be such during actual space flights (213).

Table 10-41 summarizes the hematological changes found in the early missions of the Gemini program. Interpretation of the volume changes are presented on pages 7-110 to 7-125 of the zero gravity section in Acceleration, (No. 7). The role of 100% oxygen in producing the reduction of red blood cells is not clear. Hemolysis of red cells with oxidative changes in the hemoglobin has been seen in one simulated study in 100% oxygen at reduced pressures (111) but not in all studies (213). In Gemini operations, the reduction in red-cell mass of up to 15-20% shown in Table 10-41 was accompanied by no evidence of hemoglobin oxidation (24). Other studies have shown reduction of tocopherol and increase in the lipid peroxides of the blood of Gemini astronauts suggesting a tocopherol-deficiency, hemolytic anemia (28, 124, 172, 173, 196). The relative roles of tocopherol deficiency, restraint, and weightlessness in the production of the anemia are not clear (124, 212). Tocopherol factors have been covered in Nutrition, (No. 14).

Table 10-41

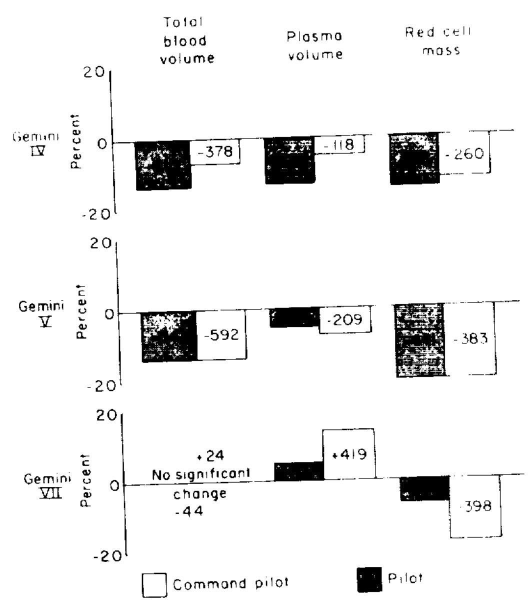
Summary of Hematologic Findings from Gemini IV, V, and VII Missions

a.

	GT4	GT5	GT7
Days	4	8	14
Hematocrit	N	N	N
Reticulocytes	-	↓	N
Total Blood Volume	↓	↓	N
Red Cell Mass	↓8%	↓20%	↓19%
$T_{1/2}$ CR_{51}	-	↓	↓
WBC	↑	↑	↑
Osmotic Fragility	-	-	↑
Serum Bilirubin	-	N	N
Liver/Spleen Scan Ratio	-	-	↑30%

(After Kaplan et al[124])

b.

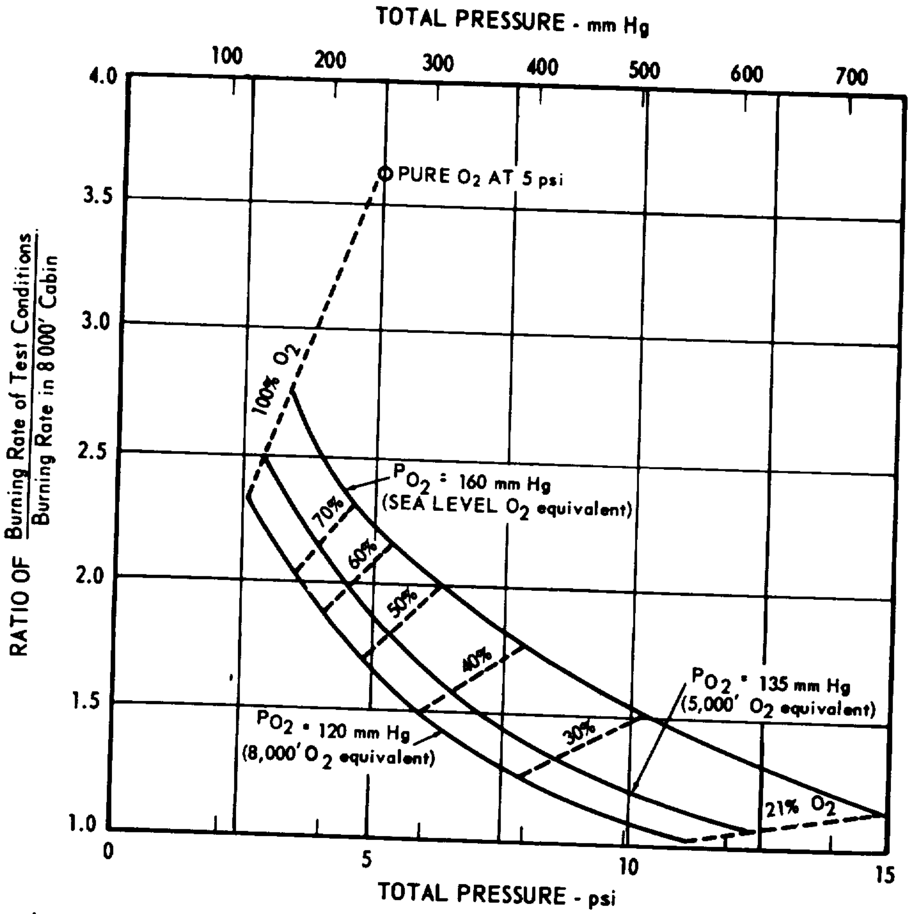


(After Berry et al[24])

Electron microscopic studies of damage to liver and kidneys of animals exposed to 5 psia - 100% oxygen are underway (78, 133, 167, 234). The relation of mitochondrial and other changes to human toxicity is not as yet clear.

Oxygen and Fire Hazards

One of the most serious effects of high partial pressure of oxygen in a space cabin is the fire hazard. Damage may be to both the spacecraft and crew. Data are available on the multifactorial aspects of the fire hazard in space cabin environments with high percentage of oxygen (118, 119, 214). Figure 10-42 represents the burning rate of cotton fabrics in different nitrogen-oxygen mixtures. Preliminary data are available on the damping effect by zero gravity on burning rate of insulated electrical wires in different gas mixtures (235). Mechanisms in the combustion of plastics are under study. (150)



Burning rate of cotton fabric is only one of many approaches to quantitation of fire hazard. In the graph, the burning rates in atmospheres of varied total pressure and percentage O_2 are compared with those in a standard aircraft cabin at 8,000 feet. Oxygen isopleths are shown for three partial pressures. The diluent effect of inert gas (nitrogen) is apparent.

Figure 10-42

Burning Rates of Cotton Fabrics

(After Klein[132])

In any gas mixture, the rate of burning of a solid is determined by the following oxygen-sensitive equation (118):

$$r = \frac{1}{d(c_s \rho_s - q_s / T_P)} \sqrt{\frac{Q}{M} \frac{k_\rho D f_{O_2}}{T_m} \log \frac{T_m}{T_P}} \qquad (22)$$

r = rate of flame spread

d = sheet thickness

c_s = heat capacity of solid

ρ_s = density of solid

q_s = heat released per unit volume of solid

T_P = pyrolysis temperature of solid

Q = heat of combustion per mole of O_2

M = molecular weight of gas (avg.)

k = thermal conductivity of gas

ρ = density of gas

D = diffusion coefficient of gas

The theory of flame spread over the surface of solid structures in oxygen and inert environments is now under study (150).

Regardless of the inert diluent present, the rate of burning is a function of the heat capacity of the mixture/per mole of oxygen present. The critical heat capacity per mole of oxygen above which flame will not propagate is determined by (118):

$$\log \frac{(C_p)_{crit.}}{\left[C_{p(O_2)} + n\, C_{p(x)}\right]} = kr \qquad (23)$$

$(C_p)_{crit}$ = critical heat capacity of mixture per mole of O_2

$C_{p(O_2)}$ = heat capacity of O_2

n = number of moles of inert gas per mole of O_2

k = slope factor (gas dependent)

r = rate of flame spread

Table 10-43 represents for several candidate atmospheres, the physical properties which determine the rate of burning. It can be seen from Table 10-43 that nitrogen mixtures have a higher heat capacity as well as a higher heat capacity per mole of oxygen, factors which are critical in establishing burning rates. Table 10-44 represents the critical C_p values for several

Table 10-43

Thermal Properties of Gas Mixtures at 25°C

(After Huggett et al[118])

Gas mixture	Heat capacity (cal/mole °C)	Heat capacity (cal/mole O_2 °C)	Thermal conductivity (cal/(cm^2) (sec.) (°C/cm))	Thermal diffusivity at test condition (cm^2/sec.)	Partial pressure of oxygen at test condition (mm Hg)
21% O_2-79% N_2	6.96	33.1	5.8×10^{-5}	0.186	160
20% O_2-80% He	5.38	26.9	24.0×10^{-5}	0.995	152
46% O_2-54% N_2	6.99	15.2	5.8×10^{-5}	0.372	175
46% O_2-54% He	5.90	12.8	15.6×10^{-5}	1.178	175
70% O_2-30% N_2	7.01	10.0	5.9×10^{-5}	0.567	181
70% O_2-30% He	6.41	9.2	10.5×10^{-5}	1.092	181
100% O_2	7.02	7.0	5.9×10^{-5}	0.567	258

Table 10-44

Critical Flame Spread Conditions

(After Huggett et al[118])

Material	$C_{p(crit.)}$ cal./°C mole O_2	Critical Inert Diluent Concentration mole % N_2	mole % He
Wood	35.0	80.2	84.8
Paper	45.0	84.5	88.4
Cellulose Acetate	27.0	73.3	80.1
Cotton Fabric	36.0	80.6	85.4
Foam Cushion	17.5	60.3	68.0
Plastic Coated Wire	21.2	65.0	74.0
Painted Surface	27.0	73.3	80.1

combustible materials which would be present in a space vehicle and the critical inert diluent concentration required to attain the critical C_p level. The critical concentrations are higher in He-O2 mixtures than in N_2-O_2.

The thermal conductivity of the helium-oxygen mixture is greater - another factor which controls ignition and burning rates. Tests indicate that the rate of burning of carbonaceous solids is somewhat more rapid in helium atmospheres than in nitrogen atmospheres of the same percent composition (118). (See also Table 10-44.) The rate of flame spread at constant atmospheric composition is approximately independent of pressure over the range studied (258-760 mm Hg).

In contrast to rate of propagation of flame, the ignition energy required to ignite carbonaceous solids is greater in helium than in comparable nitrogen mixtures. Table 10-45 represents these differences which are minor except

Table 10-45

Energy Required for Ignition of Materials in Various Atmospheres (Cal/cm^2)

(After Huggett et al[118])

Atmosphere	Air	20% O_2 80% He	46% O_2 54% N_2	46% O_2 54% He	70% O_2 30% N_2	70% O_2 30% He	100% O_2
Pressure	760 mm	760 mm	380 mm	380 mm	258 mm	258 mm	258 mm
Wood	25 $\pm$1	109 $\pm$11	25 $\pm$2	24 $\pm$0.5	25 $\pm$1	22 $\pm$1	23 $\pm$1
Paper	32 $\pm$1	39 $\pm$0.5	25 $\pm$2	26 $\pm$0.5	26 $\pm$0.5	25 $\pm$0.5	25 $\pm$1
Cotton Fabric	13 $\pm$0.5	NI	12 $\pm$0.5	17 $\pm$0.5	15 $\pm$0.5	16 $\pm$0.5	15 $\pm$0.5
Plastic Wire	20 $\pm$1	NI	16 $\pm$1	NI	17 $\pm$1	46 $\pm$1	16 $\pm$1
Painted Surface	30 $\pm$1	NI	56 $\pm$5	70 $\pm$4	61 $\pm$3	57 $\pm$5	36 $\pm$1

for the important ignition of plastic-coated electrical wire by current heating. The slightly higher ignition energies required to ignite different carbonaceous solids in comparable mixtures of helium-oxygen than in nitrogen-oxygen when a radiant heat source is used appears to be related to the sample surface. Samples of low specific surface and low thermal diffusivity such as wood show little atmosphere dependence. As the specific surface is increased as with paper and cotton fabrics, energy loss to the atmosphere is increased. In the case of thin layers of combustible materials on a support of high thermal conductivity, the energy loss is even greater and such fires are difficult to start in helium-oxygen. For any given electrical energy, the equilibrium temperature of an ignition wire will be lower in this atmosphere.

Data on the rate of burning of plastics clothing and integumentary structures in high oxygen environments and optimum extinguishing procedures in sub and zero gravity are now being gathered (1, 2, 54, 59, 60, 89, 128a, 136, 150).

A design guideline for use of non-metallic materials in spacecraft is now in preparation (89).

Carbon Dioxide

Toxic exposures to CO_2 as a result of failure of CO_2 absorption or use of CO_2 fire extinguishers may occur at altitude. Most data on CO_2 toxicity are recorded as dry gas at sea level conditions. Figure 10-46 a and b allows one to determine quickly the dry percent of CO_2 in a gas mixture at altitude that will give the same partial pressure in the lung (calculated as the equivalent P_{CO_2} in the tracheal mixture of CO_2, N_2, O_2, and water) as does a given percentage of CO_2 in inspired air at sea level. Figure 10-46b is an expanded scale of the lower barometric pressures which can be used in evaluating CO_2 effects in space helmets and cabins.

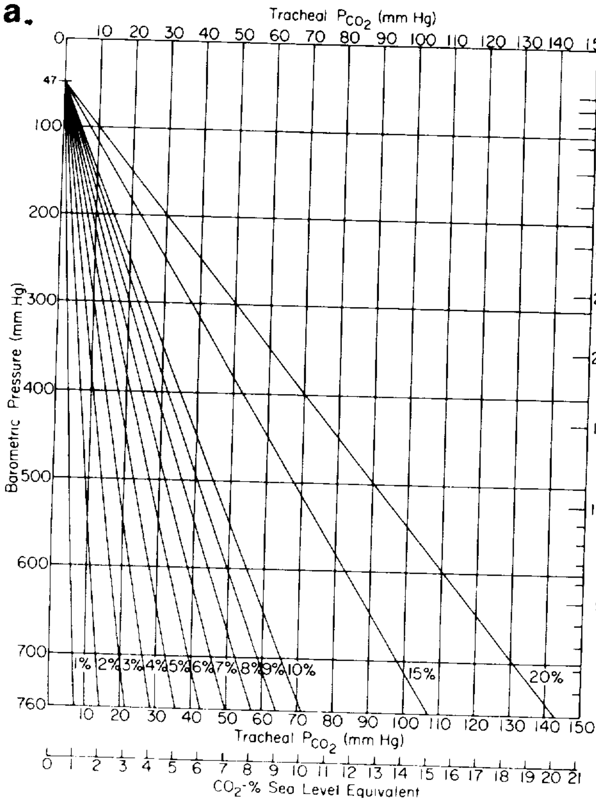
The toxic effects of CO_2 (given as % CO_2 at sea level in the atmosphere) are summarized in Figure 10-47a and b. Figure 10-47c gives the range of

Figure 10-46

Carbon Dioxide Equivalents at Altitude

(After Luft[145])

a.



a. Sea-Level Equivalents of Given % CO_2 at Altitude

b. Expansion of Figure a. in Regions of Lower Pressure

Data is more easily used for calculation of sea-level equivalent CO_2 in helmets of space suits.

b.

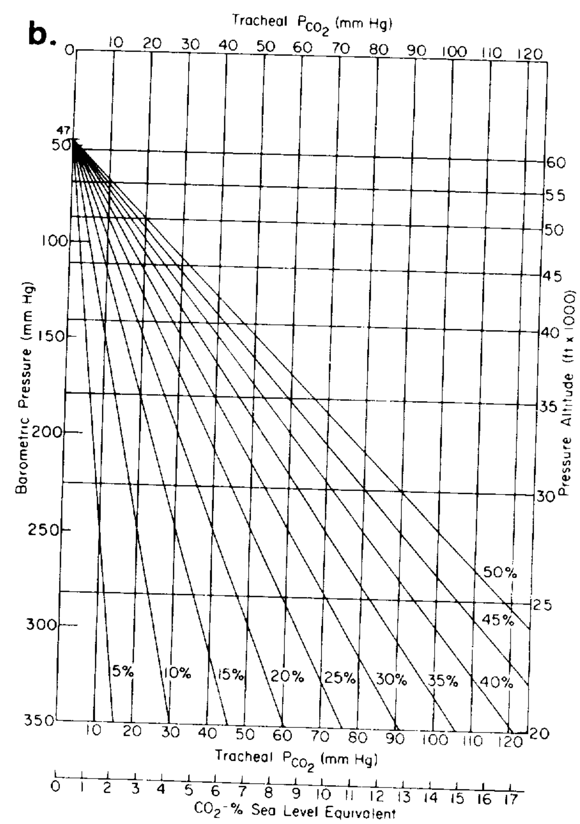


Figure 10-47

Symptoms and Thresholds of Acute and Chronic Carbon Dioxide Toxicity

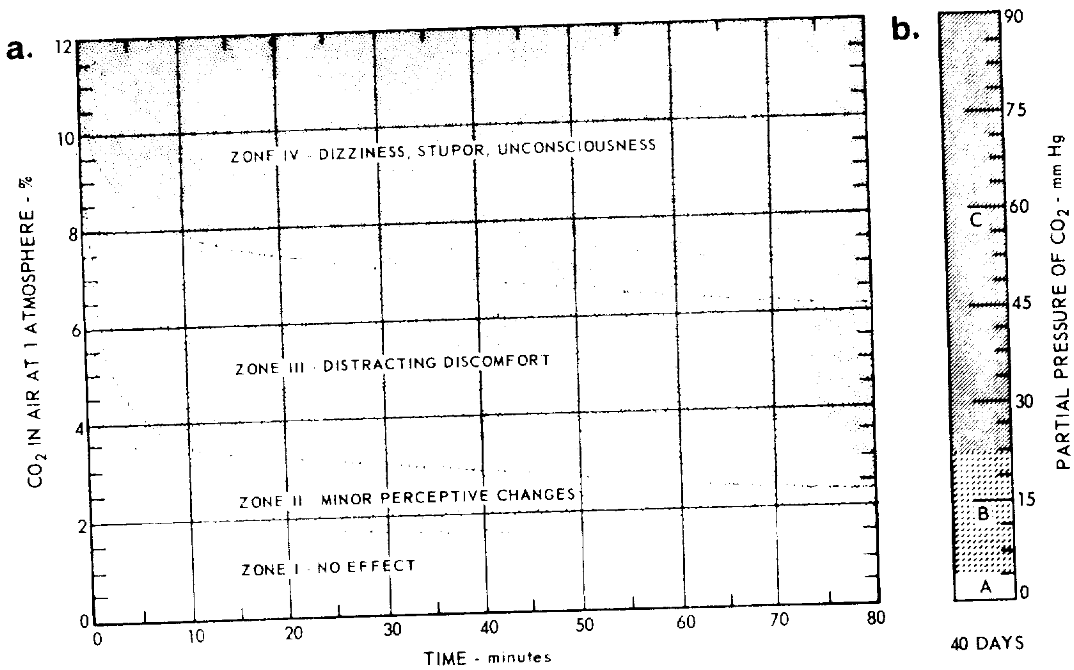


Chart a shows the general symptoms common to most subjects when exposed for the times indicated to mixtures of carbon dioxide in air at a total pressure of 1 atmosphere. In Zone I, no psychophysiological performance degradation, or any other consistent effect, is noted. In Zone II, small threshold hearing losses have been found and there is a perceptible doubling in depth of respiration. In Zone III, the zone of distracting discomfort, the symptoms are mental depression, headache, dizziness, nausea, "air hunger," and decrease in visual discrimination. Zone IV represents marked deterioration leading to dizziness and stupor, with inability to take steps for self-preservation. The final state is unconsciousness.

The bar graph b shows that for prolonged exposures of 40 days, concentrations of CO_2 in air of less than 0.5% (Zone A) cause no biochemical or other effects; concentrations between 0.5 and 3.0% (Zone B) cause adaptive biochemical changes which may be considered a mild physiological strain; and concentrations above 3.0% (Zone C) cause pathological changes in basic physiological functions and performance.

Table c gives the symptoms in 39 resting subjects who inhaled CO_2 for 15 minutes at the noted concentrations.

(Figures a and b after Roth and Billings[216], adapted from the data of King[130], Nevison[185], and Schaefer[221]; c after Schaefer et al[228])

	3.3% CO_2	5.4% CO_2	7.5% CO_2
Dyspnea	2	4	24
Headache	0	0	15
Stomach ache	0	0	1
Dizziness	0	0	6
Sweating	1	1	5
Salivation	0	0	1
Numbness of extremities	0	0	5
Cold sensations	1	1	3
Warmth sensations	1	1	4
Increased motor activity	0	0	10
Restlessness	0	0	10
Loss of control over limbs (overactivity)	0	0	4
Loss of balance (spatial disorientation)	0	0	7
Color distortion	0	0	2
Visual distortion	0	0	6
Irritability	0	0	4
Mental disorientation	0	0	2

symptoms experienced after exposure to different concentrations of CO_2. It is recommended that for long periods of time, the P_{CO_2} of a cabin be maintained below 4 mm Hg or 0.5% sea level equivalent (SLE); and for emergencies of less than 2 hours, the level of 15 mm Hg or 2.0% (SLE) not be exceeded. If possible, environmental control systems of space suits should be designed to maintain space suit helmet CO_2 below 1% (SLE) or 7.5 mm Hg. This would allow for some CO_2 accumulation and yet have the level of inspired CO_2 kept well below that which could adversely affect the astronaut at high work loads. As a maximum for several hours exposure, the helmet P_{CO_2} should not exceed 15 mm Hg during periods of stress.

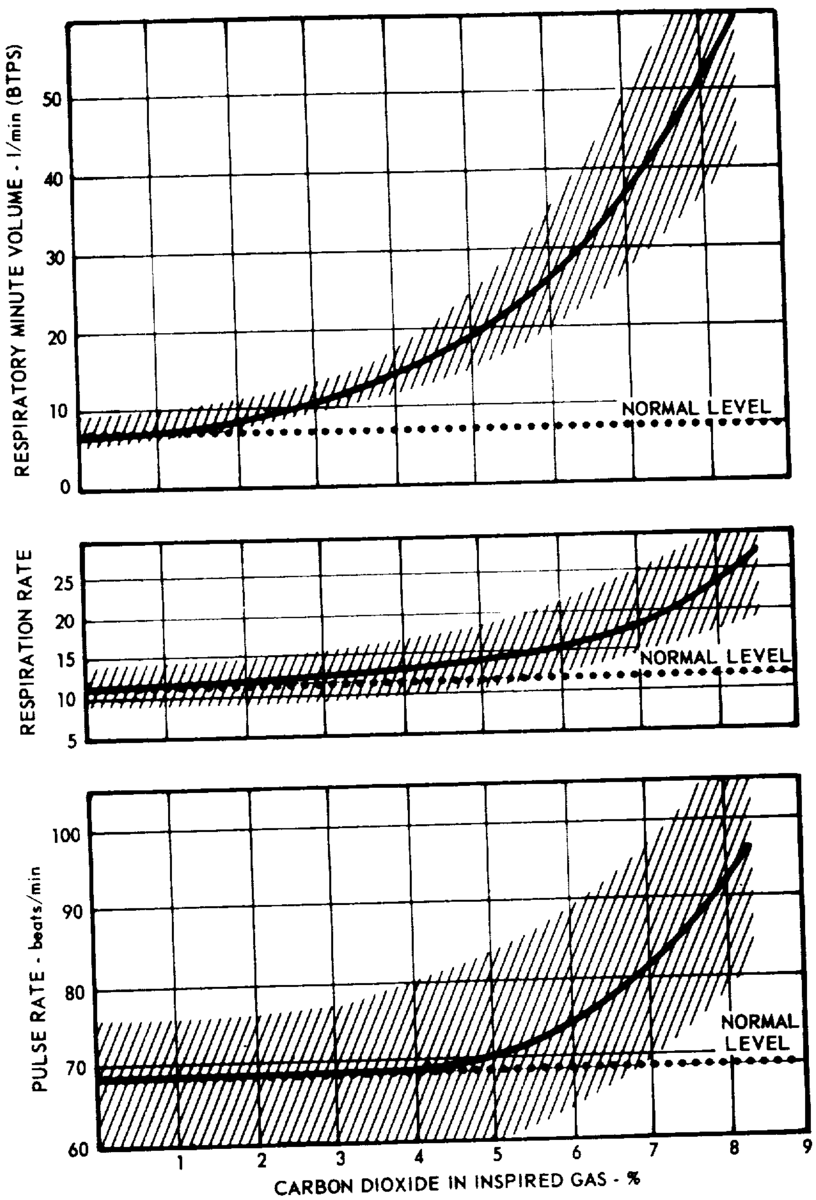
From test data gathered during manned qualification test and crew training runs with the Gemini EVA chestpack (ELSS), the partial pressure of the carbon dioxide in the inspired gas ranged from 7 to 13 mm Hg for work rates up to approximately 2400 BTU/hr (156). This range was, of course, subject to considerable variation, depending on the ELSS flow mode (medium, high, medium-plus-bypass, or high-plus-bypass) and the associated work levels. Although carbon dioxide control was accomplished by dumping gas from the suit loop, its washout was dependent upon the amount of gas being dumped; that is, if the primary gas flow rate was increased, the ventilation flow rate would increase proportionally, and the overboard flow would increase by the same amount as the primary. Carbon dioxide control was also dependent upon flow rate of fresh gas to the helmet oro-nasal area, or upon the suit ventilation efficiency. Modifications in one or both of these areas would have been required to reduce the level of inspired carbon dioxide, but since normal design workloads did not produce critical concentrations of carbon dioxide, these modifications were apparently not needed. At workloads well beyond the design limits, carbon dioxide concentrations may be objectionably high. A high carbon dioxide concentration may have contributed to the sudden fatigue and heavy respiration of the pilot during the Gemini XI umbilical EVA.

The cardiorespiratory response to CO_2 is a key factor in CO_2 toxicity. Figure 10-48a notes the cardiorespiratory response to carbon dioxide given in % (SLE). Respiratory minute volume appears to be most sensitive to CO_2. The population response characteristic appears to account to some degree for variations in tolerance to CO_2. It has been demonstrated that individuals with a relatively large tidal volume and slow respiratory rate show less of a respiratory and sympathetic nervous system response, and less symptoms while breathing low concentrations of CO_2 than individuals with a relatively small tidal volume and fast respiratory rate (227). Accordingly, knowledge of responses to CO_2 might have some practical value from a monitoring standpoint. An average effect of various inspired air-CO_2 mixtures upon the steady-state alveolar minute ventilation and partial pressure of CO_2 of normal resting man at sea level is shown in Figure 10-48b. It demonstrates the increasingly inadequate ventilation, notably paralleled by an accelerating rise of alveolar CO_2, as the ambient CO_2 increases. This dulling of man's ventilatory response to progressively increasing levels of CO_2 has been attributed to a combination of the narcotic effect of CO_2 on respiratory center neurons, the stimulation of pressure receptors in the thorax by hyperventilation and the fatiguing of respiratory muscles (65). Increasing the P_{O_2} of the breathing mixture decreases the sensitivity; and decreasing the P_{O_2} increases the sensitivity of the respiratory center. By stimulating ventilation with a

Figure 10-48

Cardiorespiratory Response to Carbon Dioxide

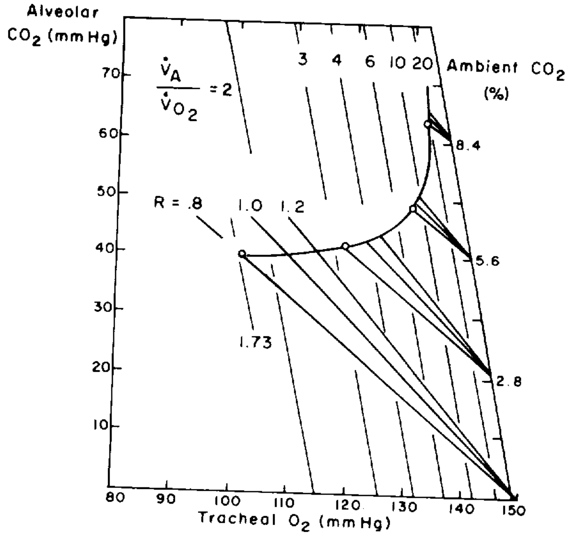
a. Ranges of Response of Normal Population to Acute Elevation of CO_2



The immediate effects of increased CO_2 on pulse rate, respiration rate, and respiratory minute volume are shown for subjects at rest. The hatched areas represent one standard deviation on each side of the mean. To convert percentage of CO_2 to partial pressure, multiply fraction of CO_2 by 760 mm Hg.

(After Roth and Billings[216] adapted from Schaefer et al[228] and Dryden et al[67])

Figure 10-48 (continued)



b. Effect of Inspiring Various CO_2-Air Mixtures Upon the Steady State Alveolar Gas Composition of Normal Man at Rest

The ratio V_A/V_{O_2} represents liters (BTPS) per minute of alveolar ventilation for every 100 ml(STPD) of oxygen consumed per minute. R represents the respiratory exchange ratio (volume of CO_2 output for volume of O_2 intake) and would be equal to the respiratory quotient (RQ) under steady state conditions at sea level.

(After Fenn[81], calculate from equations of Gray[100])

proper amount of CO_2 in the inspired air, the alveolar oxygen tension can be somewhat increased, and so performance and well-being at moderate altitudes maintained. However, since the major factor underlying this phenomenon is mainly the displacement of nitrogen in alveolar air by CO_2, with an associated elevation of the alveolar oxygen tension due to increased ventilation, it is readily apparent that CO_2 can not confer any protection from hypoxia in a pure oxygen space atmosphere (146). Moreover, it is doubtful if this effect could exist to a significant degree in proposed space atmospheres, which have a much lower inert gas percentage than does air (145).

Acute CO_2 Toxicity

The pathophysiology and the treatment of the various clinical syndromes resulting from acute and chronic CO_2 toxicity in space operations has been recently reviewed (42). Much of the following section is taken directly from this study. Rough calculations based on current suit data indicate that an astronaut who is walking on a lunar or planetary surface can increase his inspired CO_2 to a highly toxic level, within one to two minutes after a complete cessation of CO_2 absorption by his extravehicular life support system. Carbon dioxide storage by the body would have a significant retarding effect on rates of atmospheric CO_2 accumulation only in such a small rebreathing volume as that of a space suit (76, 86). In fact, recent evidence indicates that the immediate storage of CO_2 involves a body compartment with a volume corresponding to that of the extracellular space (86, 183). Carbon dioxide storage by the body should therefore be taken into account when attempting to predict such rates accurately. It is estimated that three astronauts who are carrying out normal intravehicular operational tasks would not, even in the confined volume of the Apollo Command Module, experience symptoms of CO_2 toxicity until about 6 to 7 hours after CO_2 removal from their atmosphere ceases (42). From such considerations, then, one can foresee the possibility of toxic levels of CO_2 being reached over a period of minutes in space suit atmospheres and over a period of hours in spacecraft cabin atmospheres.

The cardiorespiratory response to acute elevation of CO_2 has been covered above and in greater detail in Reference (42). Carbon dioxide levels in the body increase during sleep (29, 40, 42). The majority of normal individuals remain asleep until the ambient CO_2 reaches 4 percent or their alveolar CO_2 reaches 50 mm Hg. An astronaut exposed to an increasing level of inspired CO_2 while asleep may, on awakening, suffer from the clinical manifestations which can accompany CO_2 withdrawal. (See below.)

An elevated level of inspired CO_2 can lead to a decrease in body temperature, even in a comfortable or warm, high-humidity environment (35, 38, 219). A 1 to 3°F decrease in body temperature, with associated chilly sensations was noted during, and for many minutes after subjects breathed about 5 percent CO_2, which accumulated in their 72° to 77°F environment over a period of several hours (35). This lowering of the body heat store may be due to a combination of a number of CO_2 effects on the body. Increased heat loss will result from CO_2-induced cutaneous vasodilatation and hyperventilation (39, 219). A marked increase in sweating also accompanies acute exposures to toxic levels of CO_2 (35, 227). This phenomenon may be due to a lowering of the thermostatic setting of the hypothalamus, an increased sensitivity of cutaneous thermoreceptors, an increase in sympathetic nervous system activity, or an augmentation of sweat-gland effector activity (38). It has also been shown that toxic levels of CO_2 markedly suppress shivering which follows exposure to a cold environment (39). An acutely elevated CO_2 concentration could therefore increase an astronaut's susceptibility to cold, leading to a lowering of body temperature and associated symptoms sufficient to reduce his functional capacity.

The sympathetic response to CO_2 appears to be primarily responsible for preventing orthostatic intolerance both in subjects who breathed 4 to 7 percent CO_2 for varying periods of time after exercise and in quadriplegics who breathed 5 percent CO_2 during tilting (64, 169). However, it cannot be stated with certainty if CO_2 accumulation in an astronaut's ambient atmosphere would enhance his susceptibility to or protect him from orthostatic intolerance on return to a gravity environment, especially if he has sustained some degree of cardiovascular deconditioning during his exposure to weightlessness (42).

The diuresis produced by even low toxic levels of CO_2 is a physiologic reaction which might conceivably have adverse effects on an astronaut. Exposure of normal recumbent subjects to 5 and 7 percent CO_2 produced a three-fold increase in urine output over and above the normal diuretic response to recumbency (21). Also, exposure to 5 percent CO_2 for over 3 hours without replacing the fluid loss could lead to marked hemo-concentration. This response may result from stimulation of intravascular stretch receptors in the left atrium and pulmonary vessels through a CO_2-induced increase in central blood volume, by some mechanical action on the atrial wall from exaggerated respiratory movements, or by an increase on the atrial transmural pressure gradient (42, 252). If one or more of these mechanisms does operate to some degree, afferent connections from these receptors would inhibit the production of antidiuretic hormone by the neurohypophysis. Since voluntary hyperventilation, with alveolar CO_2 being maintained constant by inhaling a 2 percent mixture, has been shown to produce much less of a diuresis than CO_2

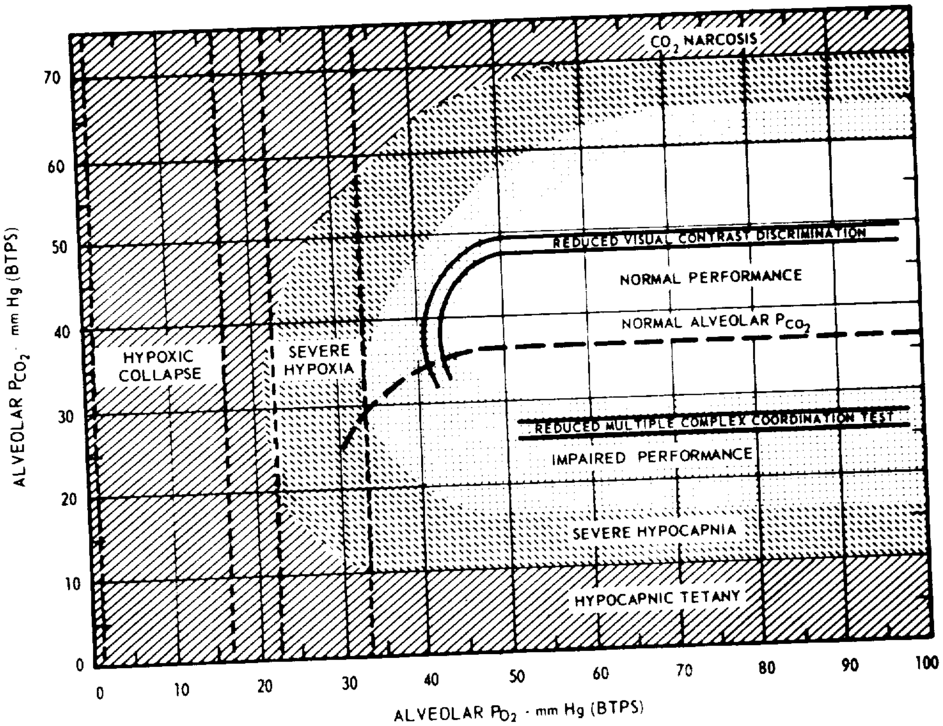
alone, it is also likely that CO_2 acts directly on the neurohypophysis or on the renal tubule (251, 252).

Since CO_2 exerts such a marked diuretic effect on man in the recumbent position, it is probable that this effect would be of similar, if not greater magnitude in the weightless environment (42). Study of the diuretic response to various concentrations of CO_2, especially with the exposed individual performing at various work loads, is indicated before potential hazards of such a diuresis can be implied. One would think that if a significant diuresis can occur at relatively asymptomatic levels of CO_2, exposure of an astronaut in a space suit to such levels might limit the duration of his extravehicular activity by virtue of a need to void urine. It should also be kept in mind that vasodilation and excess loss of body fluid may decrease tolerance to heat and cold and increase the orthostatic intolerance of an astronaut entering a gravity environment. (See zero gravity in Acceleration, No. 7.) The effect of combined CO_2 and heat stresses on man has apparently not been determined (42).

Figure 10-49 represents the combined effects of oxygen and carbon dioxide on general physiological effects and performance. The collapse level of 22 mm Hg P_{O_2} given for P_{ACO_2} of 20-40 mm Hg probably represents some degree of acclimatization in that the usual level for hypoxic collapse of unacclimatized individuals is about 30 mm Hg P_{AO_2} (13).

The effects of carbon dioxide on exercise tolerance is a key factor in spacesuit emergencies (42). Data in the literature regarding the relationship of concentration to work degradation have been quite equivocal (20, 55 96, 103, 116, 117, 122, 135). Variable experimental conditions may play a role. These data suggest that work output and motor performance may be limited by dyspneic responses at sea level equivalents of 2-3% of inspired CO_2. Preliminary studies suggest that at 2% CO_2 (15 mm Hg), given acutely, maximum aerobic capacity is reduced by 13% (83). Three out of 12 subjects at this level of CO_2 reported "suffocating sensations" at maximum work levels while none of the controls on air did so. Current studies are focused on performance and electrolyte changes in simulated carbon dioxide exposures (93, 95, 145). The duration of exposure to CO_2 may be a factor in exercise tolerance.

Since exercise appears to markedly affect man's tolerance to CO_2, one would not expect the results of resting exposures to be applicable to a situation in which an astronaut is exposed to elevated levels of inspired CO_2 while having to perform work, such as during extravehicular operations in space. It is also quite apparent that past experiments have actually yielded very little information on the time of onset and the degree of functional impairment which occurred during and in the immediate period after various acute exposures to CO_2. Although past experiments have yielded enough information for reasonable recommendations of maximum allowable levels of CO_2 for acute exposures to this gas in space, confirmatory data should be obtained in studies which simulate possible modes of exposure during operations in space, especially during various work loads in extravehicular activity.



This graph shows the relationship of alveolar O_2 and CO_2 composition to performance. The scales are partial pressures of the two gases, at body temperature and pressure, saturated with water (BTPS). Above the dashed line labeled "normal alveolar CO2" are zones of increasing hypercapnia, limited by the zone of CO_2 narcosis. Below the dashed line, marked as zones of increasing hypocapnia, are lower levels of alveolar CO_2, which are commonly the result of excessive respiratory ventilation. The left side of the graph shows low levels of alveolar P_{O_2}, labeled zones of "severe hypoxia" and "hypoxic collapse," and these hypoxic zones combine with hyper- or hypocapnia to affect performance as shown.

Normal performance is seen when the gas tensions fall in the clear area; impaired performance in a hand-steadiness test is shown by shading, and the results of two other performance tests are plotted also to indicate the variation to be expected when "performance" is variously measured.

Figure 10-49

Human Performance Under Abnormal O_2 and CO_2 Conditions

(After Roth and Billings[216], adapted from Otis et al[189], with additional data from Balke[17])

a. Behavioral Changes During Acute CO_2 Exposure

The decay in performance and symptoms noted by 39 normal resting subjects who were alternately exposed for 15 minutes to air and, in order, 1.5, 3.3, 5.4, and 7.5 percent CO_2 are recorded in Table 10-47c. No symptoms were reported at the 1.5 percent level. These symptoms usually appeared during the last 5 minutes of the 15-minute exposures to the indicated gas. Proficiency at card naming and sorting was unaltered during the exposure of 31 subjects to 5 percent CO_2 for 16 minutes. Although all of these subjects were moderately dyspneic, most reported fatigue, fogginess and an effort to concentrate; two experienced visual disturbances; and one failed to complete the last minute because of dizziness, marked dyspnea and impending fainting (261). It is noted that most of these individuals, many of whom were experienced pilots, were of the opinion that 5 percent CO_2 for a 16 minute period was close to a marginal concentration for the safe operation of an automobile or airplane (265). Other studies carried out at the 5 percent level have found a significant increase in the pain threshold and decrease in the fusion frequency of flicker (229, 237, 243).

Acute exposure to over 5% CO_2 gives variable symptoms affecting performance. Two observers who entered a 5.7 percent CO_2 atmosphere in which several individuals were tolerating a gradual increase of CO_2 immediately became so dyspneic that they were unable to make observations (35). Seven subjects tolerated 6 percent CO_2 for about 22 minutes, but experienced marked dyspnea, flushing and sweating of the face, and feelings of stupefaction and impending collapse, especially toward the end of the exposure (36). Visual intensity discrimination has also been shown to be affected in studies at the 6 percent level. Prolongation of the time required for addition and cancellation tests, and the existence of dissociation, perserveration and aberrant responses have been demonstrated in subjects breathing 6 to 7 percent CO_2 (91, 92).

In contrast to the symptoms reported in the above exposures to 6 percent CO_2, the "mental status seemed unaffected" in 7 subjects who breathed 7 percent CO_2 for 40 to 90 minutes, although all suffered from dyspnea and some complained of mild headache and burning of the eyes (34). Exposure to 7.5 percent CO_2 for 3.5 to 6 minutes has been tolerated, but symptoms had a shorter lag time than in 7 percent CO_2 (36). The 7.5 percent CO_2 level has also been found to decrease the inhibitory effect of light stimulation on brain waves (electroencephalographs) - a finding which demonstrated the depressive or narcotic action of CO_2 on the central nervous system (229). An experiment in which 42 subjects who breathed 7.6 percent CO_2 for 2.5 to 10 minutes yielded results similar to the other experiments near this CO_2 level, although one subject did lose consciousness (36, 228).

Individuals who have been exposed to 10 percent CO_2 have immediately experienced one or more of a number of clinical manifestations, such as extreme dyspnea, visual and auditory hallucinations, chilliness, nausea, and vomiting, a strangling sensation, burning of the eyes, cloudiness of vision and profuse sweating. They have usually become stuporous within 10 minutes and lose consciousness within 15 minutes (36, 42, 65, 80, 262). Although CO_2 concentrations of over 20 percent have been used for the treatment of mental disorders and experimentally for anesthesia, it is considered probable that if an individual who does not have the benefit of therapeutic support is exposed to CO_2 levels above 10 percent, he will rapidly suffer the sequence of respiratory depression, convulsion, "shock," and death (104, 144, 262, 177).

Data are available on the subacute exposure to CO_2 (35, 36, 104). Most of these studies allowed CO_2 to accumulate in closed systems with PO_2 above the hypoxic level. On one study, the chamber CO_2 was increased linearly over an 8 hour period to 6.4 percent while oxygen decreased to 13 percent (104). At about 4 percent CO_2, the subject became aware of increased breathing and began to complain of headache and nausea. For the last two hours of exposure, when CO_2 had passed about 5.2 percent, breathing was "painfully labored and required so much exertion as to cause great exhaustion." This marked dyspnea eventually caused termination of the experiment. Another subject showed a similar response, having to end his 7 hours in the chamber after linear CO_2 and oxygen changes to 5.8 and about 14 percent, respectively. In bag rebreathing to a maximum concentration of about 10 percent, attained in about 1.5 hours, they suffered from mental confusion and extreme perspiration in addition to the manifestations described above, as this level was reached. Other studies at intermediate rates have yielded similar results (36, 42, 108, 248). Fatigue, listlessness, headache, chilliness, nausea, and vomiting were reported as concentrations of CO_2 increased much above about 5%.

b. CO_2 Withdrawal

Symptoms can be experienced after the cessation of certain exposures to CO_2 and, as the examples given below will show, can result in even greater functional impairment than symptoms experienced during exposure. This reaction and its marked variability was well demonstrated by a study in which 5 subjects breathed 6.7 percent CO_2 for one hour (5). On cessation of exposure, one subject immediately vomited repeatedly and complained of nausea and headache; two experienced temporary, severe, incapacitating headaches; and two complained of only slight headache. In other studies, subjects exposed to 3 percent CO_2 for many hours apparently complained of only a mild headache on returning to air (52, 225). Headache was also reported after exposures to 5.2 and 6.4 percent CO_2 for 2 hours. A frequent symptom after cessation of exposures to 7.6 percent CO_2 for an average of 7.4 minutes and 10.4 percent CO_2 for an average of 3.8 minutes was temporar dizziness (65). Similar clinical manifestations have also occurred after withdrawal from exposure to gradually increasing ambient CO_2 levels (35, 36, 42, 104, 108). It is unlikely, except under rescue conditions, that CO_2 exposures in space will ever be severe enough to cause such serious consequences of CO_2 withdrawal as prolonged profound hypotension and grave cardiac arrhythmias which are prone to occur following marked CO_2 retention in anesthetized patients (42, 99, 187, 198, 201).

The cause of the above clinical manifestations of CO_2 withdrawal is unknown. Headaches resulting from exposure to CO_2, which increased to 5 to 7 percent over one to 3 hours, were much worse, occurred with greater frequency, and lasted much longer in subjects who breathed air as compared to those who breathed oxygen after exposure (108). Also, the brief hypotension which coincides with the temporary dizziness immediately after brief exposures to 7.6 and 10.4 percent CO_2 may be due to the vasodilatory action of CO_2 persisting beyond its sympathetic action in the immediate post-exposure period (65, 201). Other effects of altered sympatho-adrenal activity, which could accompany CO_2 withdrawal, might conceivably cause symptoms (42). Whether the temporary undershoot of alveolar CO_2, observed when 15-minute exposures to 5.4 and 7.5 percent CO_2 were terminated, might produce a hypocapnia of a sufficient magnitude to produce a symptom such as dizziness remains to be determined (228). Finally, it is conceivable that a cerebral vasomotor phenomenon caused by exposure to, then withdrawal from a CO_2 environment might be a major etiologic factor (219).

Certain symptoms which are not really specific effects of CO_2 withdrawal often occur in the post-exposure period. Marked general fatigue and soreness in the region of the diaphragm have been reported after most of the prolonged acute exposures to over 4 percent CO_2 described above. Such symptoms could no doubt limit an astronaut's physical work capacity for several hours after such an exposure. Also, intense shivering might be experienced after certain exposures to CO_2 (42).

There is at present no specific practical measure which might be used to combat the acute withdrawal effects of CO_2 on an astronaut (42). Since the acidosis accompanying acute CO_2 toxicity corrects itself within a few minutes, after even a prolonged acute CO_2 exposure, it is important to remember that the administration of a buffering agent to an astronaut who has suffered a severe exposure would probably not be effective. It would be more important to assure him adequate ventilation and to treat the consequence of possible associated hypoxia.

Chronic Carbon Dioxide Toxicity

Several causes of chronic carbon dioxide exposure lasting days to months can be envisaged. A spacecraft life-support system could malfunction for a prolonged period of time, possibly until the completion of a mission. Also, the upper limit of atmospheric CO_2 specified for a normally operating spacecraft life-support system may be too high, the decision for this limit being implied from ground-based studies which have been too short in duration to have elicited clinical manifestations. As well, an elevated partial pressure of CO_2 in space atmospheres may be needed to increase the efficiency of physical, chemical and biotic CO_2 scrubbers under emergency conditions (215). Table 10-47b summarizes the response to chronic effects of CO_2.

In assessing the possible clinical problems resulting from 90 days exposure to 1-1.5% CO_2 in submarines, minor physiological alterations were recorded on 23 men during the 42 days of exposure (220, 222, 230, 231, 232, 233). No alterations in basic physiologic parameters, such as blood pressure, pulse rate, weight and temperature, occurred. On the other hand, data on respiration, acid-base balance, calcium and inorganic phosphorus metabolism, adrenal cortical activity, and cardiovascular capacity revealed significant changes, some of which might have important clinical implications. Most of the changes occurring in this study continued throughout the 9 day post-exposure study period; all had essentially returned to pre-exposure levels after 4 weeks of breathing air.

Alterations of blood and urine pH and urine CO_2 clearly indicated the existence of a phase of slight, uncompensated respiratory acidosis lasting for 23 days, followed by a phase of compensated respiratory acidosis for the remainder of the 42-day exposure (232). (See Table 10-50a.) The anatomical and physiological dead space, as well as arterial-alveolar CO_2 and O_2 gradients in Table 10-50b are shown to be increased during the exposure and

Table 10-50

Respiratory Acidosis from Chronic Exposure to 1.5% CO_2

(After Schaefer[224])

a. Erythrocyte Cation and Anion Exchange in Chronic Respiratory Acidosis*

Condition	Control	35-41 Days Exp to 1.5% CO_2	9 Days Recovery on Air	4 Weeks Recovery on Air
Na, mEq/liter red cells	13.5	21.6 †	24.4 †	12.8
K, mEq/liter red cells	86.0	78.9 †	76.2 †	79.9
HCO_3 mM/liter red cells	14.3	17.0 †	17.0 †	16.3 †
CL, mEq/liter red cells	55.8	58.3	56.9	58.8

* Ten subjects.
† Statistically significant.

b. Dead Space and Arterial-Alveolar pCO_2 and pO_2 Gradient in Chronic Respiratory Acidosis*

Condition	Control	40 Days Exp to 1.5% CO_2	9 Day Recovery on Air	4 Weeks Recovery on Air
Physiological dead space	169	273 †	262 †	174
Physiological dead space % tidal volume	29%	35%	37.6%	27%
Anatomical dead space	157	214 †	213 †	163
Alveolar dead space	12	59 †	49 †	10
Alveolar pCO_2 mmHg	38.2	39.6 †	39.9 †	37.4
Arterial pCO_2 mmHg	39.4	44.9 †	43.9 †	38.3
Arterial—alveolar pCO_2 mmHg	1.3	5.3 †	3.8 †	0.8
Arterial—alveolar pO_2 mmHg	10.6	24.9 †	20.3 †	13.4

* Ten subjects.
† Statistically significant.

during the nine-day post exposure period. Normal values were reached after four weeks of recovery. Physio-chemical and perhaps temporary pathological changes in the lungs of the subjects might have contributed to these changes (231). Whether these changes increase the susceptibility of the exposed lungs to secondary infections or to effects of low level contaminants is an open question. The respiratory changes have been compared with changes found in emphysema patients, who usually have high CO_2 levels (231). A marked increase in physiological dead space has recently been found in submarine patrols - with CO_2 exposures averaging around 1.1% (219).

The venous plasma calcium mirrored the blood pH changes showing a decrease during the uncompensated phase of respiratory acidosis, a return to normal values during the compensated phase of respiratory acidosis and rose above control values during the 9-day post exposure period (233). These findings suggest that the long time period of adaptation and CO_2 retention (23 days) was related to the slow equilibration of the bone CO_2 store (mainly carbonate) with the elevated blood CO_2, which is supported by other findings in the literature. A plasma calcium tide, occurring 8 days post exposure, commensurate with increased CO_2 retention, indicated a release of the previously stored CO_2 from the bones.

It is known that increased urine pH and calcium levels do frequently result in urinary calculus formation. Since the urine pH was elevated above control values during the compensated phase of respiratory acidosis (24-42 days of exposure) and both the urine pH and urine calcium were higher than control values during the 9-day post exposure period, it is probable that chronic exposure to CO_2 could result in calculus formation in the urinary tract. This suggestion is supported by evidence from animal experiments. An increased incidence of kidney stone formation was found in rodents exposed to 1.5% CO_2 from 40 days to 90 days (222, 230).

Since it has been noted that urinary calculus is a rather frequent occurrence on submarine patrols, studies of calcium-phosphorus metabolism are presently being carried out on these vessels (219).

An increase in adrenal cortical activity was found during the 42 days of exposure to 1.5 percent CO_2 and the 9 day post-exposure study period (131). This response, mirrored by an increase in the ketosteroid output in the urine and a decrease in the absolute number of circulating eosinophils, was greater during the phase of compensated respiratory acidosis and post-exposure study period than early in the phase of uncompensated respiratory acidosis. It was also noted that the number of complaints showed a trend opposite to changes in adrenal cortical activity. The relative roles of confinement, anxiety, and chronic respiratory acidosis in producing the stress syndrome are not clear (42).

Cardiovascular capacity, as measured by various tests of cardiovascular function when the subjects were subjected to various work loads, decreased significantly throughout the exposure to 1.5 percent CO_2 and during the 9 day post-exposure study period. Although the subjects were undoubtedly carrying out less physical activity during the period of confinement, this reduction of circulatory reserve has been attributed mainly to CO_2 (224).

Subjects have been exposed to 3 percent CO_2 in air for periods of up to 144 hours (223, 226). The phase of uncompensated respiratory acidosis lasted only 2 to 3 days, indicating that renal mechanisms rather than bone CO_2 stores were primarily responsible for the return of blood pH to normal values (224). Subjective complaints, performance, and physiological findings suggest that the phases of uncompensated and compensated respiratory acidosis were associated with respective increases of sympathetic and parasympathetic nervous system tone. Increased "sympathetic tone" was characterized by significant increase above control values of resting pulse rate, neuromuscular excitability, responsiveness of the circulatory system to exercise and heat production after a cold load. The most undesirable clinical manifestations from breathing 3 percent CO_2 appeared during the "phase of increased parasympathetic tone," which was characterized by decrease of the above physiologic parameters to below control values. This phase continued for about 5 days into the post-exposure study period and could be maintained if subjects extended their exposure to 3 percent CO_2, but breathed this gas for only 8 hours daily. Chronic exposures of submarine crews to CO_2 levels in the range of 3 percent, showed that the concomitant lowering of the level of oxygen in the submarine atmospheres would not have been sufficient enough to have played a significant role in causing the effects noted above (225).

Another study with 3 percent CO_2 has more closely simulated possible chronic exposures to CO_2 in low pressure, oxygen enriched, space atmospheres (56). Eight normal individuals successively breathed, for periods of 4 days, atmospheres of air at 700 mm Hg; air at 700 mm Hg, containing CO_2 at 21 mm Hg; air at about 747 mm Hg; oxygen at 200 mm Hg; and oxygen at 200 mm Hg, containing CO_2 at 21 mm Hg. There was no difference in either the ventilatory response to CO_2 or the increase of the partial pressure of alveolar CO_2 produced by breathing CO_2 at these different ambient atmospheric pressures. The respiratory acidosis, as noted by changes in blood pH was essentially compensated in 3 days in each CO_2 exposure period. This blood pH change has also been observed in a recent study in which normal individuals breathed air at 700 mm Hg, containing CO_2 at 21 mm Hg for 5 days (94). These and other recorded physiologic parameters have clearly demonstrated that the partial pressure of inspired oxygen being the same, the response of man to CO_2 in a low pressure atmosphere is essentially the same as for an equivalent partial pressure of CO_2 at sea level pressure.

A chronic, compensated exposure to CO_2 may significantly alter an astronaut's physiological, and hence clinical tolerance to an acute CO_2 exposure, but few direct data are available on this issue. Electrolyte response curves in chronically exposed subjects are under study (97, 270). Also, the marked predisposition of patients suffering from emphysema and other hypoventilatory states to develop peptic ulceration has been well documented and could be a problem in space operations (42). Although an epidemiologic study has never been undertaken, peptic ulceration does not appear to have been a problem of World War II submarine crews who were exposed for weeks at a time to ambient CO_2 levels of up to 3.5 percent (219). Unfortunately, there can be marked species differences in CO_2 tolerance. Monkeys, for example, exposed to 3 percent CO_2 in air for 93 days, exhibit no demonstrable changes in any of the numerous physiologic parameters studied (242).

Behavioral Changes During Chronic CO_2 Exposure

No signs or symptoms which could be attributed directly to CO_2 appeared during or after the 42 day exposure of 21 normal individuals to 1.5 percent CO_2 (77, 221). This CO_2 level did not alter the performance of a number of tests of psychomotor function.

In contrast, chronic exposures to 3 percent CO_2 have usually produced a characteristic clinical picture. Various investigators have reported that for the first day breathing 3 percent CO_2, experimental subjects and submarine crews have manifested signs and symptoms of mild nervous system hyper-activity, such as increased motor activity, a feeling of excitement, euphoria, mental keenness and sleeplessness (23, 222, 226). During the second day, they often complained of headache. Of a greater significance, however, is a state of nervous system depression which set in at this time. This was characterized by a feeling of mental depression and cloudiness, the belief that memory and attentiveness were decreased, somnolence, mood alterations, and decreased appetite. Although this state improved somewhat after the third day of exposure, subjects never returned to normal during exposure. The somnolence has reportedly disappeared after 2 weeks exposure during submarine operations, but beyond this time, unexplained irrational ideas and bizarre behavior have usually appeared (222). The transition to air has often induced a temporary headache; it has taken 4 to 6 days until subjects felt completely well again.

Results of psychomotor tests have shown improvement during the first day of exposure to 3 percent CO_2; but thereafter and for several days into the post-exposure period, a significant impairment in performance (221, 223). Most individuals were aware of increased breathing at the 3 percent CO_2 level, particularly when performing light physical work or when fatigued. This symptom reportedly disappears after 2 to 3 days of exposure (94). The capacity to do physical work which would probably be initially limited at this CO_2 level, as in acute exposures, but may also improve with time. From an operational standpoint, it would also be important to know the effect this level of CO_2 has on fatigability and on recovery after strenuous activity.

It is important to note that the above studies of CO_2 on performance have never definitely ruled out the contribution of confinement to the production of signs and symptoms attributed to CO_2 toxicity. A recent, comprehensive review of confinement cites many confinement studies which were character-ized by clinical manifestations identical to and occurring often in the same sequence after individuals were confined as those reported from chronic exposure to CO_2 (87).

The treatment of the clinical manifestations resulting from a chronic exposure to an elevated inspired CO_2 level has not been covered in the literature. As was discussed under "Acute CO_2 Toxicity," there are at the present time no practical specific therapeutic measures for treatment of the CO_2-induced acidosis in space (42). A suitable oral analgesic might alleviate the headache which can manifest initially on exposure to CO_2. Successful use might also be made of an orally administered tranquilizing agent, such as reserpine or chlorpromazine, which might control the alterations in sympatho-adrenal activity that apparently cause the sleeplessness and excitement in the early stages of CO_2 toxicity. It is also possible that an oral central nervous system stimulant, such as dextroamphetamine or methylphenidate, might combat the state of depression which can apparently occur after compensation to CO_2. An amphetamine might also be proven successful for decreasing the fatigability associated with CO_2 exposure. More work is needed in this area.

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