A portion of Title 30, Part II, CFR calls for a Man Test, which is a series of regimens performed with a breathing apparatus. The respiratory responses to the tasks in the Man Test were established on coal miners and students. Based on these responses, the minimal metabolic requirements were derived for the use of breathing apparatuses with a service life of 30 minutes or more.

Steady state respiratory responses to tasks used in Federal testing of self-contained breathing apparatus

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NOTE: All volumes given in this paper are reported for STPD conditions.

Introduction

The Mining Enforcement and Safety Administration (MESA) and the National Institute for Occupational Health and Safety grant certificates of approval for a self-contained breathing apparatus after it has fulfilled specific engineering requirements. In addition, successful apparatus must meet the user's O_2 demand, provide for CO_2 elimination and have a low breathing resistance for selected work tasks during man testing.

The testing procedure, listed in Title 30, Part II, Code of Federal Regulations (CFR),[1] includes a combination of testing by machine and man. The Man Test begins with walking to allow subjects to become familiar with the breathing apparatus. Thereafter, more difficult tasks, such as running, crawling, ladder climb-

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ing, pulling weights and carrying loads, are attempted. This regimen introduces circulatory and respiratory responses which are relative to the intensity of each activity. Information on the expected respiratory responses to the variety of the physical activities in the Man Tests would be helpful for design and testing of self-contained breathing apparatus.

A cooperative research program with the Bureau of Mines was initiated in order to obtain this information. Our approach was to measure the steady state responses to each of the above mentioned activities. Steady state responses refer to the state at which the supporting systems, i.e., respiratory and circulatory systems, deliver the amount of O_2 needed by the working muscles. The stage at which the increased responses of the supporting systems reach the levels that meet the muscle's O_2 demand lags a few minutes behind the onset of the exercise. The transient period between the onset of exercise and the steady state response accrues O_2 deficit during which the muscles resort to anaerobic processes. The O_2 deficit is repaid as soon as the exercise ends. Thus, during man testing of breathing apparatus, where repetitive short activities are followed by predetermined rest periods, the O_2 cost and CO_2 elimination will sum up to the amount the muscles call for, *i.e.,* the amount equivalent to that observed during steady state.

This paper summarizes the steady state respiratory responses obtained for the following: (1) the individual work tasks used in man testing of self-contained breathing apparatus (30 CFR, Part 11); (2) some of the tasks of 30 CFR, Part 11, performed at different work rates (both higher and lower rates) than those specified in the Man Test; and (3) work on a cranking ergometer. The additional information under items 2 and 3 was obtained to provide a basic reference should changes in Part 11, 30 CFR, Man Test requirements be considered.

Experimental work equipment

Treadmill

Walking, carrying, and crawling were tested on a level treadmill. Walking and carrying were performed at 3 mph ($4.8\ km \cdot hr^{-1}$). The carrying involved holding a 45-pound (20-kg) package on the arms with the elbows at 90°. The knees were padded for crawling at 1.5 mph ($24\ km \cdot hr^{-1}$).

Overcast

An overcast is an enclosed airway in underground mines which allows one air current to pass over another without interruption. During mine rescue and recovery operations, rescue teams are expected to perform activities on the overcast. The Mining Enforcement and Safety Administration (MESA), Pittsburgh, Penna., has an overcast that meets 30 CFR, Part 11 requirements. It consists of: (1) a 114 inch long ramp that rises to a height of 71.5 inches; (2) a 96 inch horizontal platform at a distance from the ceiling small enough to require a person to crawl or duck walk along the passage; and (3) two uneven ramps, separated by a step, down to the floor. One round of the overcast consists of carrying a 50-pound (23-kg) sack on the overcast and then walking 24 inches along the floor from the last step to the bottom of the ramp.

Pulley

Each pull raised a 45-pound (20-kg) weight to a height of 5 feet (152 cm). The subject chose his position, posture, and distance from the handle.

Laddermill

The "vertical treadmill" of the Man Test refers to a motordriven ladder with rungs spaced at 14 inches (35.46 cm) and with adjustable tilt and control speed. MESA, at its Pittsburgh Station, has a laddermill which, when tilted at 15° from vertical, makes each step about a 1-foot vertical rise. A step per second was therefore taken as 1 ft. per second.

Our laboratory has a ladder mill with rungs spaced at 1 foot (30.48 cm). Using it at 30° from vertical required the laddermill to be operated at 80 rungs per minute to make the prescribed speed of one foot vertical rise per second.

Cranking ergometer

Arm cranking was performed on a modified electrical ergometer with specially fitted handles instead of pedals. Subjects cranked above their heads either while kneeling on one knee or while sitting with their legs stretched on the floor. Three resistance levels were administered for each posture: 200, 300, and 400 kg•m/min.

All tests were carried out at room temperature (22-25°C).

TABLE I
Characteristics of Subjects as Means and Standard Deviations

SUBJECTS WITHIN TASKS		AGE YRS.	MINING EXP. YRS.	HEIGHT cm	WEIGHT kg
Pulley & Overcast					
Miners	$\overline{X}$	32.1	8.8	180.2	87.2
n = 25	S.D.	11.8	12.3	5.3	10.9
Non-Miners	$\overline{X}$	27.6	—	178.1	74.7
n = 8	S.D.	5.6	—	4.8	6.6
Walking					
Miners	$\overline{X}$	43.7	21	176	86
n = 17	S.D.	17.1	17	5	11
Non-Miners	$\overline{X}$	21.4	—	176	78
n = 7	S.D.	1.9	—	6	17.5
Running					
Miners	$\overline{X}$	39	17	176	82
n = 10	S.D.	14	15.5	4.8	9.0
Non-Miners	$\overline{X}$	20.6	—	174	69
n = 5	S.D.	1.1	—	4.0	8.7
Crawling					
Miners	$\overline{X}$	25.6	—	182	90
n = 9	S.D.	8.4	—	4	10
Carrying					
Miners	$\overline{X}$	27.3	1.9	184	94
n = 9	S.D.	8.4	0.7	4	12
Non-Miners	$\overline{X}$	21.7	—	177	77
n = 3	range	20-24	—	166-142	70-89
Laddermill with Backpack					
Non-Miners	$\overline{X}$	—	—	180.2	78.8
n = 7	range	21-28	—	170-193	66-107

Procedures

Tests were conducted between 9 a.m. and noon. Following test preparation, which included placing chest electrodes to monitor heart rate and adjusting the respiratory unit to measure expired air, subjects rested for at least 30 minutes. Heart rate and respiratory responses were measured at the end of this resting period.

Pulley and overcast tasks were performed alternately within one session. Random assignments of rate and type of pacing were made within each task. Ten to twenty rests were given between tasks. In other sessions subjects were randomly assigned to walking, running, carrying, ladder climbing and cranking. Recovery time between tasks was variable, but it was long enough to allow heart rate to return to within five beats per minute of the pretest resting value.

Sampling

Volume of expired air and O_2 and CO_2 concentrations for the overcast and pulley tasks were measured for the total of the prescribed performance period plus a recovery period. Performance required 1 to 9 minutes. The recovery period, defined as the time in which O_2 uptake resumed pretest resting values, was at least 5 minutes. The O_2 demand for the task was calculated as the total O_2 uptake less the resting value associated with recovery. For all the other tasks, performances lasted 5 minutes to ensure steady state responses, and the respiratory measurements were made during the last minute.

Gas measurements

A hard hat fitted with a two-way valve, mouthpiece and hose was adjusted to each subject. Inspired room air was expired either into a Douglas bag or through a portable, dry-gas spirometer (Max Plank Instrumentation Associates). Douglas bags were hung on a rack adjusted to the subject's back, expired air collections were timed, and volume was later measured in a Tissot spirometer and a pump which forced .06% aliquots of each passing breath into a bladder. Beckman's C-2 Analyser and LB2 were used to measure the concentrations of O_2 and CO_2, respectively.

Subjects

Subjects were paid volunteers who were either coal miners or college students. Table I lists the characteristics of the subjects in each task. Some miners participated in more than one task, so the groups listed in Table I overlap somewhat.

Pace

Both the overcast and the pulley were administered as paced or self-paced tasks. In a paced task, the subject was advised to perform the task at a steady rate which used all the time allowed (e.g., 4 overcast rounds in 8 minutes or 15 pulls 1 minute). While performing, the paced subject could watch a clock to time himself and/or the investigator instructed him. In a self-paced task, the subject performed at his own pace. Self-pacing always used less than the time allowed, so the subject was reqûired to remain still from the time he finished the task until the end of the prescribed time so that direct comparison of metabolic requirements between paced and self-paced tasks could be obtained.

Results and discussion

Walking

The energy expenditure for walking has been investigated extensively in recent years,[2,3,9-13] so that testing a group of college-age subjects at the same time as a group of miners would provide some comparison between the two groups and between our data and the literature. Table II gives means and stand deviations (S.D.) of the obtained lung ventilation (V_E), O_2 uptake (VO_2), and Respiratory Quotient (RQ) of each group. V_E was significantly higher for miners as compared to students ($P < 0.05$, using t-test). This difference between miners and students could have been a result of the groups' age differences. As for VO_2, there was no significant difference (at the 95% level) between miners and students.

In a previous compilation of the data from the literature[7] the following prediction was found reasonably accurate and convenient for O_2 cost during walking:

$$VO_2 = 7.06 + 0.001S^2 + 0.012 \cdot GS \qquad (1)$$

where VO_2 is in ml per kg body weight per minute, S is walking speed in meters per minute, and G is the uphill grade in percent. The data in Table II are somewhat above the obtainable values using the equation: 14.8 and 15.2 ml/kg•min for miners and students compared with a predicted value of 13.5 ml/kg•min.

The Man Test involves carrying the breathing apparatus on the back, which adds to body weight. However, experiments on young adults walking with and without external loading on the back have shown that the energy cost of carrying up to about 30 kg is equivalent to carrying additional body weight.[2,4] Hence, the above equation could be used to standardize the VO_2 to the combined weight of the body and apparatus.

Running

The running speed we have used was lower than the 6 mph specified in the Man Test because some of the older miners found it hard to cope with this rate. Therefore, we reduced the speed but compensated for it by elevating the treadmill to a slope of 2.5% so that the VO_2 and V_E data can be treated as those for running 6 mph.

Table II gives means and S.D. of V_E, VO_2 and RQ for miners and students during running. The mean values of V_E for miners are about 10 liters/min higher, but because of the relatively high S.D., there is no significant difference (t-test, at 95% level) between students and miners. The statistically insignificant difference could be a result of the smaller number of miners tested, for even at the 2.5% grade and 5.8 mph, some miners could not perform the task. Therefore, for the purpose of testing under the 30 CFR, 11h, miners should be considered to ventilate at higher rates. This higher rate of ventilation was

TABLE II

Ventilation (V_E), Oxygen Uptake (VO_2), and Respiratory Quotient ($RQ = VCO_2/VO_2$) for Steady-State Walking and Running on the Treadmill.

GROUP		WALKING LEVEL 3 MPH				RUNNING UPHILL, 2.5%, 5.8 MPH			
		V_E	VO_2		RQ	V_E	VO_2		RQ
		L/min	L/min	ml/kg•min		L/min	L/min	ml/kg•min	
Miners	$\bar{X}$	29.1*	1.29	14.8	0.94	81.3	2.91	35.6*	1.13
	S.D.	8.3	0.24	1.7	0.07	10.0	0.33	3.4	0.08
Students	$\bar{X}$	23.4*	1.18	15.2	0.88	69.8	2.75	41.0*	0.97
	S.D.	6.6	0.32	2.7	0.04	14.8	0.37	2.2	0.08

*Indicates significant difference at the 0.05 level between miners and students.

probably due to the miners' reduced physical fitness for running, as compared to the students.

O_2 uptake $(VO)_2$ was significantly smaller ($p < 0.05$) in miners than in students during running. For most of the miners the 5.8 mph at 2.5% was either close to or at their maximal aerobic capacity. At this level of exercise, hyperventilation is expected, in particular, for unfit persons.

Lower physical fitness and performance at the maximal aerobic capacity are also reflected in higher RQ, which was found in miners as compared to students during the running (Table II). Since the students were at above average fitness even for their age. VO_2 at 41 ml/kg•min was well below their maximal aerobic capacity, which is reflected in both lower V_E and lower RQ.

Previously, we suggested a predictor for running based on data obtained on fit subjects and reported in the literature:[7]

$$VO_2 = 4.5 + 0.2S + 0.012 \cdot GS \qquad \textbf{(2)}$$

(VO_2, S and G units same as for walking). The data in Table II agree favorably with this equation: 41 ml/kg•min for the students compared with a predicted value of 40.3 ml/kg•min using this equation. The 35.6 ml/kg obtained on the miners who could run for 3 minutes further suggests their lack of fitness to perform the task aerobically. We have not tested running with a backpack. The values for

TABLE III

Ventilation (V_E), O_2 Uptake, and CO_2 Elimination for Carrying 20 kg at 3 mph (level.)

GROUP		V_E L/min	O_2 UPTAKE L/min	CO_2 ELIMINATION) ml/kg*•min
Miners	$\bar{x}$	46.1	1.82 (1.66)	21.0 (19.2)
n = 9	S.D.	8.0	0.22 (.37)	3.6 (3.4)
Students	$\bar{x}$	32.0	1.52	19.8
n = 3	S.D.	2.4	0.12	1.6
Combined	$\bar{x}$	42.6	1.75	20.7
	S.D.	9.0	.28	3.4

*body weight in kg.

TABLE IV

Ventilation (V_E), O_2 Uptake (VO_2) and RQ for the Pulling Tasks*

PULLS MIN	MODE	V_E LITERS	V_{O_2} (ml) TOTAL	PER PULL	RQ
15	paced	50.4	2037	136	—
1		13.8	403	27	—
		5	7	7	—
	self-aced	57.9	2524	168	1.07
		9.6	320	21	.07
		8	8	8	3
30	paced	95.0	3574	119	—
2		27.7	364	12	—
		5	7	7	—
	self-paced	99.8	3690	123	1.06
		19.0	618	21	0.09
		9	8	8	3
36	paced	125.6	4631	129	—
3		24.7	613	17	—
		7	8	8	—
	self-paced	137.5	5168	144	1.04
		14.5	1055	29	0.18
		10	9	9	5
60	paced	230.8	8360	139	—
5		22.9	1342	22	—
		5	6	6	—
	self-paced	218.6	8366	139	0.98
		54.0	1607	27	0.11
		9	9	9	4
60	paced	210.0	9180	153	—
6		24.6	1080	18	—
		8	8	8	—

*Each set of numbers in vertical order are: mean, standard deviation, and number of participants (n) running with a backpack might even be higher than just including the cost as for back weight. This should be investigated.

Carrying 20 kg

The respiratory responses obtained for carrying 20 kg at 3 mph were summarized in Table III. Unlike plain walking, the VO_2 for miners is higher than that for students. This could explain the higher V_E revealed by miners. The difference between students and miners in V_E and VO_2, normalized for body weight (ml/kg•min), was found to be statistically insignificant. This mode of carrying on the hands in front of the trunk is less efficient then carrying a backpack. In a previous study of students, we demonstrated that carrying 20 kg in front of the trunk at 3 mph incurs an efficiency loss of 15%.[6] This means that for each kg carried on the arms, the cost is 15% more than the cost for each kg carried on the back.

Crawling

The crawling speed is not specified in the Federal Regulations. The typical comfortable speed of level crawling was 1.5 mph. The mean values ± S.D. in liters per minute for the nine miners (Table I) were as follows:

$V_E = 55.3 \pm 8.2$; $VO_2 = 2.07 \pm 0.22$; $VCO_2 = 2.15 \pm 0.21$.

It is interesting to note the acceptable slow crawling rate and the relatively low efficiency for crawling.

Pulling

Table 4 summarizes the V_E, VO_2 and RQ for paced and self-paced pulling. In the self-paced mode of pulling, the miners completed the total number of pulls in less than the allowed time. Although in most of the pulling regimens V_E and VO_2 were higher for the self-paced groups than for the paced groups, analysis of covariance of the VO_2 and V_E each on the number of pulls indicated that the differences were not significant.

The breakdown of VO_2 into cost per unit of work; i.e. the milliliters of O_2 per one pull (Table IV) provided the means to estimate the cost of pulling even if the specifications for repetition and/or the allowed time for a pulling regimen differed from the current specification in 30 CFR, Part 11. As can be seen in Table IV, VO_2 per pull was similar for the self-paced and paced modes of pulling. Although the differences in V_E and VO_2 for the two modes of pulling were statistically insignificant, since self-paced is the most used method, we decided to use the average values obtained for the self-paced: 143 ± 29 ml O_2/pull or, for a given pulling rate, PR (pulls per minute) VO_2 in l/min could be predicted:

$$VO_2 = 0.143\ PR \quad (3)$$

The ventilation during the self-paced performance, normalized in terms of V_E per pull, was 3.66 l./pull (± .67). This value was suggested as predictor for V_E during pulling.

Overcast

Table V summarizes the V_E, VO_2 and RQ for paced and self-paced performances on the overcast. Similar to the pulling regimen, the self-paced overcast performance was accomplished in less than the time allowed. It can be seen in Table V that VO_2 was higher for the self-paced as compared to paced performance. The difference was found to be statistically significant. Analysis of co-variance for the regression of VO_2 in ml/kg against the number of rounds showed $F(1, 72) = 4.00$ thus $p < 0.001$.

To be on the safe side in predicting the O_2 cost during overcast performance, we suggest the use of the VO_2 values that were obtained for self-paced rounds.

The values in Table V are grouped in terms of total cost, i.e., ml per one round and in the relative terms of ml per kg weight per round.

The pooled data on the self-paced performance were averaged, yielding the following means and s.d. for VO_2:

2,200 ± 420	ml/round
24.5 ± 3.8	ml/kg•round

These values for the total O_2 cost are for an average body weight of 87 kg (pooled from all the miner participants in this study). The expected total O_2 cost for the miners' population could be expressed in ml per minute:

$$VO_2\ ml/min = 2{,}200\ R \quad (4a)$$

where R is the total rounds divided by the time (in minutes) allowed for the particular test.

Such use of total cost is applicable to tests with small breathing apparatus (less than about 15 pounds) where the added weight is not expected to significantly change the total

VO_2. However, when heavier breathing apparatus are used in man testing, the use of VO_2 in ml/kg•round is suggested. The average values that were obtained from the pooled data can be incorporated as follows:

$$VO_2 \text{ ml/kg}\cdot\text{min} = 24.5\cdot R \qquad \textbf{(4b)}$$

where R represents the number of rounds divided by the time allowed for the particular test. This value of VO_2 per kg weight per minute can be multiplied by the sum of the body and apparatus weights, in order to get a better representative for the total O_2 cost during the overcast performance.

The ventilation during self-paced performance normalized in terms of V_E per round was 46.7 l./round (±6.9). This value was suggested as the predictor for V_E during the overcast performance.

Laddermill

We have extensively studied the VO_2 cost for laddermill climbing. The information, obtained on students, male and female, was published elsewhere[5,8] and has been compared to data reported by others on conventional ergometers.[7] In these previous studies we have used laddermill inclinations of 10° to 30°.

The data pertinent to the Man Test are for climbing an almost vertically inclined laddermill. Since we have converted our information to units of vertical climb, the difference between the 15° specified for the Man Test and the 10° we have often used in the past is slight, and for all practical purposes, can be ignored.

In general, we have established for non-miners[8] that VO_2, standardized in ml per kg b.w., provides the best regression on the vertical climbing speed (VS) in meters per minute:

$$VO_2 = 6.5 + 2.0\cdot VS \qquad \textbf{(5)}$$

This equation was then found applicable to miners who were tested in our laboratory over a wide range of speeds. It should be noted that equal VO_2 does not necessarily mean that students and miners revealed the same V_E, as will be discussed later.

Equation 5 was found reasonably applicable when weights were added to the body so

TABLE V

Ventilation (V_E), O_2 Uptake (VO_2), and for carrying 23 kg on the Overcast*

ROUNDS MIN.	MODE	V_E LITERS	VO_2 (ml) TOTAL	PER ROUND	PER kg	PER kg•ROUND	RQ
1/1	paced	37.0 12.6 7	1898 204 8	1898 204 8	20.9 1.7 8	20.9 1.7 8	—
	self-paced	44.6 8.0 8	2505 587 8	2505 587 8	25.1 5.9 8	25.1 5.9 8	0.87 0.04 3
2/3	paced	91.7 22.7 7	3771 315 8	1885 157 8	41.6 3.8 8	20.8 1.9 8	—
	self-paced	85.4 11.7 9	4409 617 9	2205 300 9	48.7 7.5 9	21.3 3.8 9	0.90 0.05 4
4/6	paced	183.8 30.6 6	7966 616 7	1992 154 7	86.4 6.7 7	21.6 1.7 7	—
	self-paced	204.3 22.4 8	8923 1520 7	2231 380 7	101.2 18.2 7	25.3 4.6 7	1.06 0.04 4
4/8	paced	202.0 43.8 5	8170 333 6	2043 83 6	88.0 4.1 6	22.0 1.0 6	—
	self-paced	199.5 26.8 8	8213 1479 8	2053 345 8	92.5 13.1 8	23.1 3.3 8	0.97 0.12 3
6/9	paced	247.1 40.1 8	10701 1098 8	1783 183 8	118.3 13.6 8	19.7 2.3 8	—
	self-paced	273.6 31.1 7	12054 1647 7	2009 275 7	133.6 10.0 7	22.3 1.7 1	0.96 0.14 3

*Each set of numbers in vertical order are mean, standard deviation, and n.

TABLE VI
Ventilation (V_E), O_2 Uptake (O_2), and the V_E/VO_2 Ratio for the Laddermill Climb with a Backpack

BACKPACK (kg)		0			10			20			30		
Climbing (m/min)		7.7	10.8	13.9	7.7	10.8	13.9	7.7	10.8	13.9	7.7	10.8	13.9
$\dot{V}_E$ (l/min)	M	43.29	62.24	80.08	57.07	81.32	109.39	66.11	98.88	123.33	87.44	115.92	128.0
	S.D.	14.20	19.76	25.33	15.05	26.65	29.85	15.72	28.95	29.86	22.13	28.39	29.1
$\dot{V}O_2$ (l/min)	M	1.78	2.40	2.90	2.27	2.86	3.64	2.61	3.33	3.83	2.99	3.38	3.7
	S.D.	59	.73	.77	.63	.57	.74	.55	.54	.72	.59	.64	.7
$\dot{V}_E/\dot{V}O_2$	M	24.36	25.90	27.62	25.10	28.39	30.03	25.34	29.73	32.19	29.23	34.30	33.8

that the line of gravity did not shift backward; for example, with weights carried on a belt around the waist or with heavy boots. However, the cost for backpack loading, when the line of gravity shifts backwards, was higher than the cost without the shift. This was shown in a series of tests with seven nonminers (Table I) who climbed with backpacks weighing 10, 20, or 30 kg each at vertical speeds of 7.7, 10.8 and 14 m/min. Table VI summarizes the V_E and VO_2 responses for this series of tests.

The regression of VO_2 in ml/min on work rate for each load of the backpack was as follows:

Load kg	Intercept	Slope Coefficient ml/kg•m
0	42	2.47
10	234	2.45
20	737	2.06
30	1516	1.37

The multiple regression of VO_2 against mass; body plus backpack in (kg) and; work load (kg•m) was calculated from the pooled data and yielded the equation:

$$VO_2 \text{ ml/min} = 1.7 \text{ (kg•m/min)} + 19.5 \cdot \text{kg} - 800 \quad (6)$$

Thus, the increase in VO_2 due to the backpack could be predicted.

The VO_2 demand on the ladder is at maximal aerobic capacity (or above) expected from miners. In this respect it will be similar at least to the running. Therefore, the minimal V_E expected for climing could be similar to that expected for running, The derived V_E for VO_2 ratio from the values for running (Table II) is about 28. We used this value to derive the expected climbing V_E of 100.8 $\pm$ 15.7 l/min.

In addition, it can be seen in Table VI that there was a proportional increase in the ratio V_E/VO_2 with this increase in load and to some extent with increase in climbing rate. Therefore, when high climbing speed involving a heavy backpack is expected, allowance should be given for higher V_E.

Cranking

The data for cranking in the two postures were similar and thus, were pooled. The VO_2 response was linearly related to the load:

$$VO_2 \text{ ml/min} = 2.1 \text{ kg•ml/min} + 540 \quad (7)$$

The coefficient for the slope of VO_2 on the cranking load was similar for cycling and for climbing a ladder without a backpack.[5,8] The coefficient of VO_2 on cranking load reported in the literature by others was higher, indicating a lower efficiency than our data indicate. Previous compilation of the published information yielded a regression coefficient of 2.77 ml/kg•m for cranking.[7] The discrepancy between our coefficient and that derived from other studies could be a result of the posture employed; i.e., kneeling on one knee or sitting while cranking above the head in our tests instead of standing while cranking at chest level in the test reported by others.

General considerations

Rest

During the periods requiring no external work (sampling and readings, and lying on side or back), but not at basal state, it is reasonable to use: V_E = 10 1/min and VO_2 = 0.35 1/min.

RQ

The values for CO_2 elimination or RQ in Tables II, III, IV, and V, as well as general knowledge of work in excess of 30 minutes, indicate that the RQ for any task in the man test will not exceed 1.0 though it is often close to it. Therefore, a conservative estimate of CO_2 elimination is that value which equals the O_2 cost. There will be transient variations above and below RQ of 1.0, but they should not significantly effect the overall assumption.

Substituting Tasks

Since some of the tasks of the Man Test are unique, manufacturers of breathing apparatus might find it inconvenient to use these tasks prior to submitting it for approval. Therefore, alternatives to some of the tasks, in particular to the overcast and the laddermill ("vertical treadmill"), could be helpful. It is also specified in 30 CFR, Part 11: "vertical treadmill or equivalent." The most common equivalent are ergometers such as treadmills and cycle ergometers; the latter can be easily converted for arm work (cranking). The equations relating VO_2 to work load that are suggested above are useful in substituting a task on readily available equipment, such as treadmill or cranking ergometer for tasks meant for laddermill or overcast.

Either of the two VO_2 equations for the treadmill or cranking could be used for predicting laddermill VO_2. Similarly, a known VO_2 demand for the overcast could be equated with a treadmill speed and grade of inclination, or a pulley demand could be equated with a cranking load. The treadmill walking equation predicts 5 to 10% lower VO_2 than was found in testing miners, which for all practical purposes is not a significant difference.

To demonstrate the nature of the substitution of one ergometer for another we present the following four examples:

1. **Substituting treadmill for pulley.** The equations suggested above were for pulling:

$$VO_2 = 0.143\ PR \qquad \textbf{(See 3)}$$

for level walking:

$$VO_2 = 7.06 + 0.001S^2 \qquad \textbf{(See 1)}$$

VO_2 for the pulley is 1/min and for walking is in ml/per kg. Therefore, for level walking

$$VO_2\ (1/min) = (7.06 + 0.001S^2)\ wt/1000 \qquad \textbf{(8)}$$

Equating (1) and (8), rearranging the equation and solving for S,

$$S = [143 \cdot \frac{PR}{wt} - 7.1]^{1/2}\ (31.6) \qquad \textbf{(9)}$$

Taking wt. for our average miner as 87 kg, treadmill speed (S) for pulling rate (PR) will give: •

PR = 12; S = 112 m/min (4.2 mph)
PR = 15; S = 132 m/min (4.9 mph)

2. **Substituting cranking for pulling.** Similarly equating **(3)** and **(7)** yields

$$Kg \cdot m/min = 68.1\ PR - 257 \qquad \textbf{(10)}$$

Substituting cranking load (kg•m/min) for pulling rate (PR) will give:

PR = 12; load = 560 kg•m/min
PR = 15; load = 765 kg•m/min

3. **Substituting treadmill for overcast.** Equating equation **(4b)** with equation **(1),** rearranging and then solving the resulting quadriatic equation for S yields:

$$S = [36G^2 + 24500 \cdot R - 7100]^{1/2} - 6G \qquad \textbf{(11)}$$

Substituting S at a level walk (G = 0) for the given rounds of overcast per minute (R) will give:

R = 1; S = 132 m/min (4.9 mph)
R = 0.67; S = 97 m/min (3.6 mph)
R = 0.5 S = 72 m/min (2.7 mph)

If the treadmill walking were to be arranged at 15% grade (G), with

R = 1; S = 70 m/min (2.6 mph)
R = 0.67 S = 42 m/min (1.6 mph)
R = 0.5 S = 25 m/min (0.9 mph)

4. **Substituting uphill walking on a treadmill for laddermill.**
Equating **(1)** to **(5)**

$$S = [36 \cdot G + 2000VS - 600]^{1/2} - 6G \qquad \textbf{(12)}$$

fixing the grade (G = 15%)

$$S = [7500 + 2000VS]^{1/2} - 90,$$

for VS 18.3 m/min.

S = 120 m/min (4.5 mph)

Basic values

Table VII provides a summary of the mean with the standard deviation and the 95 percentile (= mean + 1.65 × S.D.) values for pulmonary ventilation and oxygen uptake per unit of measurement of the Man Test activities (30 CFR, Part 11). The units were given in 1/min except for the pulley and overcast which were given in 1/pull and 1/round, respectively. In the case of the laddermill, equation 6 was used, applying from our sample of miners, a mean ± S.D. of body weights of 87 + 11 kg.

TABLE VII

Summary of Ventilation and O_2 Cost per Unit of Measurement of the 30 CFR, Part 11 Man Test Activities from the Data Collected on Coal Miners

TASK		MEAN + S.D.	PERCENTILE*
Walking:	V_E	29.1 ± 3.8 l/min	42.8
	VO_2	1.29 ± 0.24 l/min	1.69
Running:	V_E	81.3 ± 10.0 l/min	97.8
	VO_2	2.91 ± 0.33 l/min	3.45
Carrying:	V_E	46.1 ± 8.0 l/min	59.3
	VO_2	1.82 ± 0.22 l/min	2.18
Crawling:	V_E	55.3 ± 8.3 l/min	68.8
	VO_2	2.07 ± 0.22 l/min	2.43
Pulling:	V_E	3.66 ± 0.67 l/pull	4.77
	VO_2	0.143 ± 0.029 l/pull	0.191
Overcast:	V_E	46.7 ± 6.9 l/round	58.0
	VO_2	2.20 ± 0.42 l/round	2.89
Laddermill Climbing:	V_E	100.8 ± 15.7 l/min	126.5
	VO_2	3.60 ± 0.56 l/min	4.52
Rest:	V_E	10.0 l/min	10.0
	VO_2	0.35 l/min	0.35

*95 percentile = mean + 1.65 x S.D.

It should be noted that these values do not include the possible effect of an apparatus such as the temperature of the gas inhaled, breathing resistance, and to some extent the unit's weight, and hence represent minimal values.

Man testing

By using the data on Part 11, minimal metabolic requirements of the miners performing 30 CFR, Part 11 Man Tests can be obtained, as shown in Table VIII. The data in Table VIII do not include the effects of a breathing apparatus because of the variety of weights and profiles of apparatus, and front and back mounting of units, all of which effect metabolic response. Thus, Table VIII represents a *minimum* of the oxygen requirments and CO_2 elimination.

The table can be used as follows: Should a manufacturer wish to design a 60-minute breathing apparatus, Table VIII shows for 95 percentile requirement that 105 liters of O_2 are necessary and 105 liters of CO_2 are produced during the hardest man test (test four). Thus for 95% of expected male users, a manufacturer must provide at least as much O_2 and CO_2 absorbance (assuming a closed circuit device) in order to be assured that the device will meet the needs of the schedule testing. This of course does not mean a device will automatically pass the tests, because other requirements (heat, breathing resistance and other engineering factors) are part of the approval program.

The sample and reading periods may yield different results because of transient considerations and the varying times of completion of self-paced tasks. This is being evaluated currently together with the requirements for apparatus of less than 30-minute duration.

TABLE VIII

Minimal Values in Liters for Pulmonary Ventilation (V_E) and Oxygen Consumption (VO_2)* for 95 percentile and 50 percentile Expected Values for Man Tests One, Two, Three, and Four using the Summary Data of Table VII.**

DURATION (MIN)	95 PERCENTILE						50 PERCENTILE					
	30	45	60	120	180	240	30	45	60	120	180	240
Test One												
V_E	1020	1660	2310	4610	6920	9220	720	1160	1590	3190	4780	6370
VO_2	40	65	91	181	272	363	31	51	70	140	210	280
Test Two												
V_E	1200	1890	2510	4690	4690	4690	918	1434	1882	3457	3457	3457
VO_2	49	76	102	194	194	194	38	59	79	150	150	150
Test Three												
V_E	1170	1550	2100	4400	4400	4400	891	1170	1570	3160	3160	3160
VO_2	45	59	81	172	172	172	36	47	64	134	134	134
Test Four												
V_E	1370	2020	2530	4570	7150	9460	1050	1550	1930	3370	5110	6700
VO_2	55	82	105	184	286	377	43	64	81	142	221	291

*Note: $VCo_2 = VO_2$
**30 CFR, Part 11

Summary and conclusions

There are several objectives to the testing of respirators. One primary objective is to evaluate the durability and physical performance of the unit itself. Another equally important objective is to test the respirator's adequacy with respect to the user's physiological responses.

This study was undertaken solely with the second objective in mind. It was assumed that values such as pulmonary ventilation, O_2 requirements and CO_2 elimination, expected when a respirator was tested under the 30 CFR, Part 11, will be helpful to those involved with the manufacturing and the testing of self-contained breathing apparatus.

Although the Man Test includes simple tasks which are considered to simulate the strain of rescue operation, the evaluation of the respiratory responses is complicated for the following reasons: (1) some of the activities are performed in less than 3 minutes, a period not long enough to bring about a plateau (steady state) in the physiological responses; (2) the design of some repetitions of the tasks imply that despite the transiency in these short-term activities, the total sum of the repetition and the recovery in-between will yield a response equivalent to the steady state response; and (3) the periodic sampling is not uniform. If the activity previous to the sampling is self-paced (pulley or overcast), the recovery time for each individual will differ, being longer for those with the faster pace.

Therefore, we have decided to provide values either for the steady state stage of a given activity or a close approximation of it by averaging the O_2 cost for the performance from onset until the end of recovery.

The steady state information was then used to compute the total cost, in lung ventilation and gas exchange, to suit the portions of the prolonged performance under the Man Test (30 minutes and above) where the responses do resemble steady state. The basic values for the computations are given in Table VII, and the expected minimal values of V_E and VO_2 for all man tests of 30 minutes and above are summarized in Table VIII.

Because of the probability that a vendor does not have all the facilities for man testing as provided for in 30 CFR, Part 11, suggestions are made for the substitution of the overcast, laddermill or pulley with a more conventional ergometer such as a treadmill which may be more available to the vendor. Finally, self-paced tests for the pulley and overcast tasks are preferable because this is the mode of performance during certification and the average O_2 cost is higher for self-paced as compared to a paced mode of performance.

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