

Human Factors Related to the Testing of Self-Contained Breathing Apparatus: A Review

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This manuscript summarizes the literature dealing with human factors related to the testing of self-contained breathing apparatus (SCBA). As a means of facilitating further development, the historical background of Human Use Testing in the United States is first outlined. The manuscript then reviews international literature examining: metabolic rates and working environments of SCBA users; factors influencing metabolic rates (including weight, SCBA type, heat stress, and oxygen and carbon dioxide concentration); continuous monitoring; and performance criteria related to breathing resistance, temperature, carbon dioxide and oxygen concentrations, and comfort. Evaluation of the literature indicates that current methods and performance criteria used in testing SCBA in the United States do not reflect the advancements in technology that have occurred over the past few decades. Revision of the procedures is indicated and should be based on metabolic rates and working environments of the SCBA user, continuous monitoring, and criteria based on physiologically safe tolerances. The intent is to present scientific information that may be used in recommending performance criteria and improved testing of SCBA. Additionally, the information contained in this review may be used to develop new research strategies to address these issues.

Introduction

The purpose of this review is to summarize and evaluate the literature dealing directly with or related to human subject testing of self-contained breathing apparatus (SCBA). A SCBA is defined as "an atmosphere-supplying respirator in which the source of air or oxygen is contained within the respirator independent of any other source."¹ Current methods and performance criteria used in testing

SCBA in many countries do not reflect the advancements in technology that have occurred over the past two decades. As an example, the review of human subject testing procedures in the U.S. (dating from 1919 to current 30CFR11 requirements) will show that the procedures need to be revised to ensure that commercially available SCBA will offer protection to the increasing variety of individuals who utilize SCBA (i.e., firefighters, miners, rescuers, and haz-

ardous-material cleanup workers) under widely variable environmental conditions and metabolic requirements. It has been suggested²⁻⁶ more relevant and specific procedures need to be developed which: (1) closely simulate metabolic rates and working environment of the SCBA user, and (2) incorporate criteria based on physiologically safe tolerances and improvements in testing technology.

History and Background of Human Use Testing of SCBA

The need for respiratory protection in hazardous atmospheres was recognized as early as 23 A.D. in the Roman mines.⁷ During the first World War, the United States government recognized the need to protect soldiers from poisonous gases. The gas mask was developed in response to this need. However, a problem arose after the war when the soldiers returned home with their gas masks and attempted to use them inappropriately for protection from various hazards at their worksites.

SCBAs were introduced into the U.S. in 1907, although manufacturing in this country did not commence until 1918.⁷ The first set of testing procedures for respiratory-protective devices in the U.S. was published by the Bureau of Mines in 1910. Table 1 summarizes, historically, the stated purpose of the man test procedures.

Until very recently, human-use tests of respiratory-protective devices were referred to as man tests or "working tests." Tests prior to 1968 did not use motorized treadmills. In 1929, the man test procedures were described as a 30-minute test performed by a man wearing the apparatus in a chamber containing irrespirable gases.¹² This man test was performed only after the apparatus had passed laboratory tests and visual examinations. While in the chamber, men would perform exercises (walking, running, sawing, lifting and carrying) in an attempt to increase their respiratory rate and thereby observe how the unit functioned under simulated working conditions. In order to receive final approval, the apparatus had to provide the wearer with good protection from the irrespirable gases, comfort, good vision and freedom of movement.

Most early man test requirements were subjective in nature, as is indicated in this excerpt from Schedule 13C (1946):

The physiological effects of the apparatus on the wearer will be noted in each test; they include the comfort of the wearer, ease of breathing and lack of interference with normal body functioning as determined by questioning the wearer of the apparatus during and after testing.¹³

In 1946, the only objective measurements obtained during the man tests were inspired air temperature and concentrations of oxygen and carbon dioxide in inspired air.¹³ With regard to inspired air temperature, Schedule 13C simply mandated that if the external air temperature did not exceed 29.4°C (85°F), inspired air temperature should not exceed 43.3°C (110°F).⁹ However, this schedule suggested that a much lower inspired-air temperature was desirable.

Although Schedule 13 man-test procedures remained virtually unchanged from 1919 through 1946, several revisions were made between 1956 and 1972 (Table 2). Virtually no technological changes have occurred in the man-test procedures since 1968. As Held and Harder¹⁶ expressed several years ago, "tests and approval schedules in the U.S. are woefully out of date. Manufacturers design old-style devices to meet the old requirements in these schedules, but our technology has moved ahead sufficiently to make improvements in these 25-50 year old test procedures."

Table 1. "Man test" purposes.

Date	Schedule of Code	Stated Purpose
March 5, 1919	13	None.
Jan. 21, 1930	13A	None.
August 12, 1935	13B	"The tests used are designed to represent conditions and work to which the wearer of a SCBA may be subjected while wearing apparatus under actual conditions in mine or plant." ⁸
July 9, 1946	13C (30 CFR 11)	Same as 13B. ⁹
Sept. 22, 1956	13D (30 CFR 11)	Same as 13B.
July 19, 1968	13E (30 CFR 11)	"The following tests represent the workload a man would perform while wearing an apparatus in the mining, mineral and allied industries." ¹⁰
March 25, 1972	30 CFR 11	"The man tests described in Tables 1, 2, 3, and 4 represent the workload performed in the mining, mineral or allied industries by a person wearing the apparatus tested. . . . These tests will be conducted to: (1) Familiarize the wearer with the apparatus during use; (2) provide for a gradual increase in activity; (3) evaluate the apparatus under different types of work and physical orientation; and (4) provide information on the operating and breathing characteristics of the apparatus during actual use." ¹¹

Metabolic Rates and Working Environments of the SCBA User

Revised human-use tests should reflect the diverse uses of SCBA. In order to best accomplish this task, the metabolic requirements of the SCBA user as well as the effect of the SCBA on those requirements must be considered. When testing of SCBA was first mandated in the U.S., most of the human-use test activities were directed toward the mining industry. However, in today's society many diverse groups of industrial workers use SCBA.

These groups include, but are not limited to, miners, firefighters, hazardous-material cleanup workers, workers in rocket-fueling operations, and workers who must handle nuclear/radioactive materials, as well as workers in construction, foundry, shipyard, and metal industries. Additionally, tasks requiring use of SCBA range in intensity from just above resting to supramaximal levels of exertion.

Table 2. Major changes in man test procedures.

Date	Schedule	Revision
Sept. 22, 1956	13D (30 CFR 11) ¹⁴	(1) Recording of pulse and respiratory rate added.
March 13, 1968	13E (30 CFR 11) ¹⁵	(1) Specifies temperature range in which tests will be conducted (65–85°F) and provides more specific maximum permissible temperatures based on SCBA service life and relative humidity of inspired air. (2) Breathing resistance in mouthpiece is measured during a 2 minute sampling period. (3) Motorized horizontal and vertical tread mills were used. (4) Appearance of man tests (in table form) exactly as they appear presently. (5) Tests were no longer required to be performed in a chamber containing irrespirable gases. (6) Introduction of 3 and 4 hour tests.
March 25, 1972	30 CFR 11 ¹¹	(1) Testing site was moved from the BOM laboratory in Pittsburgh, PA to the NIOSH laboratory in Morgantown, WV.

Mining Three studies were reviewed that dealt exclusively with energy expenditures associated with mining. In the first study,¹⁷ energy expenditure was estimated from heart rate recordings from 12 miners while performing their daily work in the mine. The heart rate-oxygen uptake relationship was determined on each subject via a bicycle ergometer test. The results indicated that the median exertion level of the miners tested was 3.3 MET* (11.5 mL O₂/kg/min) and that approximately 10% of

their time on task was spent working at a rate in excess of 22 mL O₂/kg/min. These exertion levels must be interpreted with caution since they are estimates based on heart rate, and heart rate can be influenced by many factors other than exertion (including body temperature, environmental temperature, time of day, hydration status, stress, changes in posture, and alcohol ingestion).

In the second study¹⁸ pulmonary ventilation (V_E), oxygen uptake (VO₂), and heart rate were measured continuously (on a magnetic tape) in six miners performing a simulated escape maneuver. The average V_E, VO₂, and heart rate reported were

* MET is the expression used to describe the energy cost of work. One MET represents the energy cost during rest; 3.3 METs corresponds to 3.3 times the resting value.

49 L/min, 1.63 L/min, and 143 beats/min, respectively. The peak values for these variables were 52 L/min, 1.92 L/min, and 161 beats/min. Based on maximal oxygen-uptake determinations made in the laboratory, it was estimated that during the escape procedure the miners were working at 64% of their maximal capacity, with peak efforts at 70% of maximum. Although various types of locomotion were used in the escape efforts (i.e., crawling, stooping, running, and walking) the authors reported that the average and peak values for VE, VO₂, and heart rate were similar for all activities. It was reported that although escape time was inversely related to maximal oxygen consumption, there was a sizeable discrepancy between oxygen uptake observed during the escape and VO₂ max. The investigators discussed various factors (such as darkness, terrain and roof conditions, mode of locomotion, and fatigue) which could have contributed to this gap. It should be noted that these data are the result of only one investigation and therefore should be interpreted cautiously.

In the third study¹⁹ the metabolic costs of mining tasks of drilling, barring down, bolting, and loading powder were reported as follows:

TASK	MEAN METABOLIC COST		
	VO ₂ (L/min)	kcal/min	(range)
Drilling	0.85	4.30	(2-8)
Barring down	1.22	6.16	(3-8)
Bolting	0.98	4.94	(1-8)
Loading Powder	0.62	3.12	(1-6)

Although the three studies presented here examined different aspects of coal mining work requirements, similar energy requirements were reported. The results from the study by Harber et al.¹⁷ are equivalent to a mean VO₂ of approximately 1.15 L/min with a peak value of approximately 2.21 L/min. Kamon et al.'s¹⁸ data indicated an average VO₂ of 1.63 ± 0.36 L/min with a peak value of 1.92 ± 0.44 L/min. Burford et al.'s¹⁹ examination of the energy requirements of coal mining tasks indicated

a mean VO₂ ranging from 0.62 L/min to 1.22 L/min with peak levels of approximately 1.58 L/min.

Firefighting The metabolic requirements of firefighting have been examined in several studies. Only one study reviewed actually quantified the metabolic requirements of firefighting in terms of oxygen uptake.²⁰ However, several others were useful in establishing baseline maximal capacity data and/or heart-rate response.²¹⁻²⁶ A common conclusion of these studies is that firefighting involves performance of tasks of very high intensity for relatively short periods of time. Lemon and Hermiston²⁰ classified firefighting as "heavy physical work" requiring 60-80 percent of one's maximal capacity even when external stresses (such as heat, humidity and stress) were not present. It was estimated that 41-73 percent of the total energy costs for specific firefighting tasks was supplied through anaerobic metabolism. Manning and Griggs²⁵ found that "routine firefighting is an anaerobic activity, generating high heart rates." These investigators reported that heart rates typically increase rapidly to 70-80 percent of maximum within the first minute, then plateau at 90-100 percent of maximum until the task is completed. Davis et al.²² similarly reported that firefighters worked at 90% of maximum heart rate while performing simulated tasks. The average VE was 80 L/min.

In one of the earlier studies published on metabolic requirements of firefighting, Barnard and Duncan²¹ reported that during firefighting extremely high heart rates were maintained for prolonged periods of time. However, these investigators attributed those high heart rates to elevated anxiety levels and elevated environmental temperatures. It is important to note that although anxiety and temperature may affect heart rate, metabolic expenditures in firefighting tasks (as measured by oxygen uptake) are quite high even in their absence.²⁰ Thus, although the worker may fatigue sooner than usual due to elevated environmental temperatures, the demand placed on the SCBA may not be greater than usual.

Other Industries Modern technology and industrialization has provided a variety of hazardous

atmospheres to which today's workers can be exposed. This phenomenon has resulted in SCBA use in many more occupations than mining and firefighting. SCBA are used in atmospheres containing asbestos, nuclear waste, viral or bacterial agents, as well as those containing known or unknown hazardous materials. Studies dealing specifically with the energy requirements of these occupations are not plentiful. However, several papers are available that have evaluated the energy requirements for specific occupational tasks.²⁷⁻²⁹ Zenz and Berg²⁸ found the average energy cost of a 20 foot ladder climb to be 8.4 kcal/min or 1.68 L/min of oxygen consumed. The

oxygen consumption of production machine operators was found to range between 0.33 L/min (1.66 kcal/min) in the morning and 0.55 L/min (2.6 kcal/min) in the afternoon.²⁹ Passmore and Durnin²⁷ provided one of the most extensive summaries of energy expenditure available to date. Table 3 lists some of the occupational tasks and energy expenditures that might be associated with those occupations identified previously. As can be seen, energy expenditures vary from less than 2 kcal/min for low-intensity tasks up to greater than 10 kcal/min for high-intensity tasks such as shoveling.

Table 3. Summary of energy expenditures for SCBA user-related occupational tasks.

Task	Table Number*	kcal/min	VO ₂ (L/min)
Sitting	37	1.63	0.326
Standing	37	1.80	0.36
Walking	37	4.90	0.98
Carpentry	5	3.00	0.60
Sweeping floors	9	1.70	0.34
Simple work sitting	9	1.70	0.34
Polishing	9	2.40	0.48
Scrubbing standing	9	2.90	0.58
Scrubbing kneeling	9	3.40	0.68
Scrubbing floors	9	3.60	0.72
Light turning	12	2.50	0.50
Heavy turning	12	3.30	0.66
Tool setting	12	3.40	0.68
Loading chemicals	11	6.6	1.32
Shoveling	16	7.5-10.5	1.50-2.10
Digging trenches	16	8.5	1.70
Measuring wood	18	2.4	0.48
Machine sawing	18	2.4	0.48
Measuring and sawing	18	3.5	0.70

*Table number denotes location of this information in Passmore and Durnin.²⁷

Factors Influencing Metabolic Requirements While Wearing SCBA

In order to adequately evaluate the performance of SCBA, a basic understanding of the effect of the SCBAs on human metabolic requirements is necessary. The interrelationship involved is important with human-use testing, where the responses of the individual wearing the SCBA are dependent upon the performance of the SCBA. Thus, an interactive effect occurs with human testing of SCBA. This interaction is not present with traditional simulator testing, underscoring the limitations of this type of testing.

Weight Many research and review articles have addressed the influence of SCBA weight on energy expenditure.^{24-26,30-34} Blume and Furst³⁰ evaluated the effects of respiratory protective devices on workers at submaximal workloads. The wearing of such devices was found to affect both the circulatory system (heart rate) and respiratory system (VE). When comparing heart rates with and without SCBA use, a difference of 20.5% was revealed. The 7 L/min increase in VE (38 L/min to 45 L/min) was also attributed to the added weight of the air cylinder. White and Hodous³⁵ similarly reported substantial increases in heart rate and VE in response to wearing respirators and protective clothing. With low-intensity exercise, heart rate was elevated 15 beats per minute (BPM) due to the wearing of the SCBA, while VE was elevated 14 L/min. Even larger increases were noted with the addition of a firefighter or chemical ensemble (up to 50 BPM and 32 L/min for heart rate and $\dot{V}_E$, respectively).

Lenhart's review²⁴ reveals some very useful information relating carried weight to increased energy expenditures. He cited the work of Pandolf, et al.³⁶ who derived the following equation to predict metabolic rate, taking several factors into consideration:

$$M = 1.5W + 2.0(W+L)(L/W)^2 + n(W+L)[1.5V^2 + 0.35VG]$$

where M = metabolic rate in watts; W = subject's weight in kg; L = weight of additional load in kg; n =

terrain factor (1.0 for treadmill, 2.1 for sand, 4.1 for 35 cm soft snow); V = walking speed in meters/min; G = % grade). Based on the curves constructed by Pandolf,³⁶ Lenhart²⁴ concluded that one would expect to find a 1.2% increase in metabolic rate for each kilogram of added weight. This relationship is supported by Raven et al.³³ who concluded that the weight of the 15.8 kg SCBA utilized in their study was primarily responsible for the 20% decrement in performance of treadmill work. Myhre et al.²⁶ also found a performance decrement of 20-30% associated with the increased weight of an SCBA (15 kg). Louhevarra et al.³⁷ found a 17% decrement in performance of firefighters when performing a treadmill test with SCBA. Based on these studies it appears that the relationship described by Lenhart²⁴ between metabolic rate and added weight may slightly underestimate actual findings. However, this information should prove useful to manufacturers and those who evaluate SCBA performance.

Warncke³⁴ provided additional information concerning the effects of SCBA weight on the wearer's metabolic requirements. When comparisons were made between a 1.6 kg (air-supplied apparatus), a 15.4 kg SCBA, and a 19.8 kg SCBA, there was a significantly higher VE during a 30 min treadmill exercise when subjects wore either of the two SCBAs than the lighter air-supplied apparatus. It was also noted that although the additional 4.1 kg load of the heavier SCBA did not appear to affect VE during the first five minutes of exercise, after that point the effect was considerable. The 20 kg load was perceived as being "uncomfortable" by all subjects and even "unacceptable" by some. Based on the results of this study it was concluded that respiratory-protective equipment should weigh less than 15 kg if possible so that work capacity is reduced no more than necessary. It was also pointed out that weight has a greater effect on energy expenditure with apparatus weighing 15-20 kg than with apparatus weighing between 10 and 15 kg. Further support of the lighter-weight devices is provided by Warncke's³⁴ observation that the increased air supply provided by the 20 kg apparatus (vs the 15 kg device) supplied only enough additional

air to prolong work by six to eight minutes. This small increase in endurance does not appear to be a reasonable price to pay for the rather large increase in energy expenditure and physiological responses associated with the use of such a heavy SCBA.

In another study²⁵ of firefighters performing short-duration anaerobic tasks (134–191 seconds at heart rates of 90–100% maximum) using either no SCBA, light SCBA (7 kg), or a heavy SCBA (15 kg), no significant difference was seen in either the heart rate or task performance time when the three units were compared. However, as noted earlier, these investigators concluded that firefighting is an anaerobic activity and therefore attributed the high heart rates to the task requirements, rather than the use or weight of the SCBA. Manning and Griggs²⁵ also recommended decreasing the weight of respiratory protective devices, noting that such a decrease would result in improvements in the speed with which tasks could be performed and/or decreases in the duration of the anaerobic phase of exertion.

SCBA Type Several investigators have examined respiratory, circulatory, and exertional responses to wearing demand and pressure-demand SCBAs. Bishop et al.³⁸ found that tidal volume (TV), mean inspiratory flow rate, mean expiratory flow rate, and $\dot{V}_E$ increased in response to 5, 10, and 15 cm H_2O of positive-pressure breathing. At high pressures (up to 30 cm H_2O), increases in respiratory rate along with decreases in cardiac output have been reported.^{39–41} However, these investigators also noted that hyperventilation and/or exercise helped to reverse these effects even at 30 cm H_2O . Several studies provide evidence that energy expenditure is not significantly different between demand and pressure-demand modes.^{26,33,42} Raven et al.³³ reported that breathing mode (demand, pressure-demand, no facemask, and no apparatus) did not have a significant effect on performance. However, it was noted that only during work in the demand mode with facemask and apparatus did subjects (8 out of 15) cite lack of air as a reason of termination of a maximal stress test. In a later investigation, Raven et al.⁴³ reported that at workloads below 50% $\dot{V}O_2$ max, end tidal CO_2 was lower in the pressure-demand mode

than with a mouthpiece only. This was not the case with demand-type units. Additionally, it has been noted that pressure-demand units produce negative facepiece pressures with moderate to high workloads, which could result in inward leakage.^{33,44}

Two papers were reviewed that compared closed and open-circuit apparatus. Laverne and Leigh⁴⁵ examined temperature differences between the two devices. The increase in inspired air temperature between the start and end of exercise (exceeding one hour in duration) was significantly greater in closed-circuit units (15.9°C increase; 26.9°C to 42.8°C) than in open-circuit units (7.3°C increase; 30.2°C to 37.5°C). No significant differences at the end of the test were observed in either rectal temperature (39.3°C—closed-circuit; 38.8°C—open circuit); oral temperature (38.1°C—closed-circuit; 37.8°C—open circuit) or heart rate (145 beats/min—closed-circuit; 138 beats/min—open circuit). Lenhart²⁴ stated that “when compared to open-circuit SCBA, the lighter weight, increased duration, and increased O_2 content of closed-circuit breathing apparatus are important attributes when the physiologic demands of firefighting are considered” (p. 31). Thus, it appears that each type of apparatus has its advantages and disadvantages both in terms of physiologic considerations and practical applications.

Heat Stress Another factor that may influence metabolic response to SCBA use is elevated temperature. Increases in temperature, whether it be environmental, body, or inspired air temperature, generally result in an increased circulatory load, as indicated by an increase in heart rate without a concomitant increase in energy expenditure. This is important to note since energy expenditure is often estimated based on the linear relationship between heart rate and oxygen consumption. The literature indicates that this linear relationship may not exist under certain conditions, particularly heat stress where blood redistribution and dehydration contribute to increased heart rate.⁴⁶ Thus, the problem is not the immediate increase in energy expenditure associated with increased environmental temperatures, but rather the decrease in cardiac output available for physical exertion. Raven et al.,⁴⁷ in a

review on physiological responses to respirator wear, stated that "heat stress has been a primary factor in the use of respirators in numerous working situations."

Several experimental studies have addressed the effects of heat stress imposed by respiratory-protective devices on physiologic response. Killick⁴⁸ examined subjects in a cool environment inspiring either hot/humid or hot/dry air. Inspired air temperature, body temperature (axillary), respiratory rate, heart rate, and blood pressure were measured both at rest and during work. The results indicated that only respiratory rate and rhythm were affected by temperatures increasing to tolerable limits. Lind⁴⁹ also indicated that the point at which inspired air temperature exceeds body temperature was critical. The explanation for this "critical point" was that as long as inspired air temperatures are less than body temperature, there remains a viable avenue for heat loss. As soon as this is no longer true, heat cannot be lost by this means and may, in fact, be gained. Additionally, SCBA use decreases the body area available for evaporative cooling. Facepiece or mask use with the concomitant elevations in temperature (whether they be actual or perceived) have been associated with discomfort and work tolerance limitations.^{26,50-54} Cotes⁵⁰ referred to "discomfort due to heating of skin [under the facepiece] as a real problem."

Two studies examined physiologic responses to mask wear by studying subjects with and without facemasks under otherwise identical conditions.⁵³⁻⁵⁴ The first study concluded that even with training, decreases in endurance time attributable to mask wear were not eliminated, although endurance time was reported to have improved with training.⁵³ The latter study found facemask wear to impose a heat stress on users, which increased as workload increased. Evidence of this stress was seen in heart-rate elevations that could not be attributed to body temperature increases alone.⁵⁴ Myhre²⁶ examined perceptions of mask temperature and found this variable to increase as workload increased. However, in reality, mask temperature was decreasing as workload increased. As might be expected, the

subjects in this study rated an SCBA without a mask as being significantly cooler than those with masks. The results, however, indicated that actual forehead temperatures were always cooler when utilizing a facepiece. This indicates the importance of considering perceived thermal sensations of the subjects as well as actual temperatures.

Oxygen and Carbon Dioxide Concentrations Oxygen (O₂) and carbon dioxide (CO₂) concentrations in inspired air are additional factors associated with SCBA use that can influence the metabolic requirements of the wearer. The main effect of increases in CO₂ concentration is an increase in VE, while decreases in O₂ concentration will result both in increased VE and increased cardiac output.⁵⁵ Stegemann⁵⁵ points out that compensation for inspired O₂ deficiency via ventilatory and cardiac output increments is normally not complete, resulting in decrements in work capacity. The increased VE as a result of high CO₂ concentration is also responsible for a more rapid utilization of available air supply⁵⁶ and impaired maximal exercise tolerance.⁵⁷ Interestingly, Graham and Wilson⁵⁸ found no limitation in performance at 65% of VO₂ max with increased CO₂ concentrations, up to 6% for 30 minutes.

Several investigators have addressed the effects of increased concentrations of O₂ on performance and physiologic functions.^{50,59-60} Dressendorfer et al.⁵⁹ reported significant increases in anaerobic threshold, VO₂ max, peak heart rate, and endurance time when breathing 35% oxygen. With regard to higher concentrations of O₂, it has been found that there is a certain point, perhaps between 50 and 66% O₂, beyond which performance no longer continues to improve.^{50,60} Cotes⁵⁰ found that both 50% and 100% O₂ resulted in improved exercise performance, but that the 50% O₂ concentration was more effective than 100% O₂ in a respiratory-protective device. Hartwell and Senneck⁶⁰ cited a study by Bannister and Cunningham⁶¹ which compared endurance times for 66% O₂ vs 100% O₂. Although the hyperoxic concentrations resulted in significantly better performances than room air, the 66% concentration always resulted in better performances than 100% O₂, perhaps due to nausea, fatigue, vomiting, numbness and

substernal pain associated with breathing 100% O₂ for an extended period of time.²⁴ The increased flammability potential associated with pure oxygen

is another negative element that must be considered in certain applications.¹⁶

Continuous Monitoring

Current technology permits work and exercise physiologists to monitor exercising subjects continuously with little difficulty. Several physiologic responses, including $\dot{V}_E$, $\dot{V}CO_2$, $\dot{V}O_2$, breathing resistance, and air temperature are known to decrease significantly within 30 seconds after exercise ceases.^{31,62} Thus, figures that are recorded during the sampling periods of the currently employed man tests are not indicative of what is occurring during high levels of activity and may, in fact, be as much as 30% lower than what would be seen if continuous monitoring during activity were employed.⁶² LaViolette³¹ and Stein⁶ have recommended employ-

ing continuous monitoring rather than the intermittent sampling techniques currently used. Stein⁶ believes that continuous monitoring is more advantageous than intermittent monitoring for two reasons: (1) it provides a more accurate indication of how the apparatus performs under actual exercise conditions, and (2) it provides for monitoring of subjects during the most hazardous periods (during exertion), thereby improving the safety of such test administrations. The feasibility of utilizing continuous monitoring during SCBA human use testing is currently being examined by the NIOSH Division of Safety Research.

Related Performance Criteria

Current regulations in the U.S. (30CFR11) mandate human-use test evaluation of a variety of parameters including breathing resistance, breathing temperature, carbon dioxide and oxygen concentrations, and wearer comfort. The following sections provide a review of the literature addressing each of these areas and follows with a description of 30CFR11 requirements.

Breathing Resistance Physiological response to increased breathing resistance is a topic that has received a great deal of attention in the literature. Killick⁶³ conducted one of the earliest studies on this topic. It was found that breathing through a resistance caused CO₂ production ($\dot{V}CO_2$) to decrease and that this decrease was amplified as resistance and/or minute ventilation ($\dot{V}_E$) increased. She noted, as have others since that time, a relationship between resistance and the individual's subjective feelings of discomfort or distress.^{32,64} Bentley et al.⁶⁴ noted that 90% of a given population should experience no discomfort when exercising with breathing resistance, provided that pressure swings across the mouth do not exceed 17 cm H₂O. Others

appear to support this finding.^{32,65} Raven et al.⁴³ also found that half of their subjects were unable to complete ten minutes of high-intensity exercise when pressure swings exceeded 24 cm H₂O. The specific effect of increased inspiratory resistance on breathing patterns has also been described.^{63,66} Killick⁶³ and Hermansen et al.⁶⁷ noted a "slowing and deepening" of the pattern. However, others have noted decreases in tidal volume (depth) with increased levels of exertion.^{68,69} Killick⁶³ similarly noted that as resistance increased to high levels, depth of breathing tended to decrease while respiratory rate increased. Thompson and Sharkey⁷⁰ reported that at higher workloads, resistance levels and oxygen consumption are positively correlated.

The relationship between exercise, breathing resistance, and ventilatory parameters was highlighted in classic work by Silverman et al.^{71,72} Moderate resistances of 64 mm H₂O at 85 L/min (inspired) and 41 mm H₂O at 85 L/min (expired), resulted in lower oxygen uptake ($\dot{V}O_2$) than with minimal resistances of 6 mm H₂O at 85 L/min (inspired) and 3 mm H₂O at 85 L/min (expired), but only

when workloads (on a bicycle ergometer) exceeded 830 kg/min. It was also pointed out that the combined, moderate resistances caused almost a 20% reduction in VE at high workloads.⁷¹

Several investigators suggest that the additional respiratory work associated with increased breathing resistances, in combination with exertion, limits performance.⁷³⁻⁷⁵ Others have concluded that respiratory muscle fatigue associated with increased breathing resistances during exercise probably does not limit performance, but that it does significantly affect subjective feelings of discomfort.^{26,76} The negative effect on performance has been demonstrated even at levels of resistance as low as 6 mm H₂O (inspired) and 14 mm H₂O (expired) at 4 L/s when compared to no added resistance.⁷⁷

While agreement on an ideal, maximum allowable breathing resistance has not yet been elucidated, several suggestions have been reported.^{50,59,60,65,78,79} James⁷⁸ pointed out that there is also disagreement regarding the flow rate at which resistance should be measured (i.e., 85 L/min vs 120 L/min). Deno et al.⁷⁵ reported that a resistance of 8 cm H₂O at 120 L/min would not affect maximal performance of a one-hour continuous exercise at all intensities the subject could otherwise perform without the external resistance. This figure, according to the investigators, allows for a 2:1 margin of safety.

Another issue that has been raised relates to facepiece pressure of pressure-demand (or positive-pressure) SCBA. The concern is that with human use in conditions of moderate to heavy exercise, the facepiece pressure may become negative on inspiration.^{26,42,43} Wilson⁸⁰ reported a negative pressure at an oxygen consumption of 1.5 L/min with an average of -7.65 cm of water pressure at maximal exertions levels (the range was -19.84 to -0.83 cm of water). Raven has raised this issue, being unable to demonstrate in currently available apparatus, a device that maintains positive pressure under moderate to severe metabolic demands.^{33,47}

Current federal regulations¹ for SCBA mandate that inhalation and exhalation resistance be tested on a breathing machine. Inhalation resistance on an open-circuit unit shall not exceed 32 mm of water at 120 L/min, while for a closed-circuit unit the difference between exhalation and inhalation shall not exceed 10 cm of water. Requirements for exhalation resistance are as follows: demand open circuit shall not exceed 25 mm of water at 85 L/min; pressure-demand open circuit shall not exceed 51 mm of water static pressure in the facepiece; static pressure at 0 L/min shall not exceed 38 mm of water; and in closed-circuit units exhalation resistance shall not exceed 51 mm of water.

Breathing Gas Temperature Several investigators have made recommendations concerning tolerable inspired air temperatures. Based on the fact that air cooled to 10°C (even when saturated) provides physiological and possible psychological benefits to the user of closed-circuit SCBA, Hartwell and Senneck⁶⁰ recommended that inspired air temperatures not exceed 10-15°C. A comprehensive study on physiological responses to breathing hot air in a cool environment under both resting and working conditions was conducted by Killick.⁴⁸ She recommends wet-bulb temperature limits ranging from 54.4°C (130°F) to 186.1°C (367°F) depending on the work intensity and humidity of the inspired air.

On the other hand, Lind reported respiratory discomfort at 39°C (102.2°F), considerably less than that reported by Killick.⁴⁸ He attributed this discrepancy to the fact that those earlier figures would not apply to the closed-circuit apparatus that he was observing. McCutchan and Taylor⁸¹ reported that, in their subjects, 49°C (120°F) was not sensed as being different from room air, and 71°C (160°F) was sensed as being "warm" or "dry." In this same study, at 93°C (200°F) and the highest vapor pressure (30 mm Hg), three of their five subjects felt that the air "set their teeth on edge."

Gallagher and Vercruyssen⁸² also examined the effect of elevated wet-bulb temperatures (ranging from 18.9-49.3°C) on tissue temperature and ratings

of discomfort. These investigators suggest that maximum permissible temperatures should be set using inspired wet-bulb temperature. They also noted that the only test condition that caused any perceptible burning or mouth redness were 46.9 and 49.3°C wet bulb. Dahlbeck and Jorfeldt⁵¹ similarly reported that gas inhaled at temperatures above 50°C was rated as very uncomfortable. Gwosdow et al.⁸³ reported that acceptability of the respirator decreased as lip temperature increased above 34.5°C or when respirator dew-point increases above 20°C. These investigators also reported that respirator condition influenced the subject's judgment of acceptability of the surrounding environment.

Current federal regulations mandate the maximum allowable inspired air temperatures (dry bulb) based on the service life of the apparatus and the relative humidity of the inspired air. The maximum allowable temperature ranges from 35°C (95°F) for long-duration units to 57°C (130°F) for short service life units.¹ If the apparatus is designated as "escape only" the maximum permissible temperatures are increased by 5°C (10°F).

Carbon Dioxide Concentrations

The effect of breathing elevated levels of CO₂ is a marked increase in ventilation, primarily due to increased tidal volume (up to 70% of vital capacity)⁷⁸ followed by an increase in respiratory rate. Other effects include decreased mental performance, headaches, and nausea. Therefore, CO₂ concentration is a critical factor with regard to work performance. A NIOSH criteria document was issued in 1976 addressing the effect of high levels of CO₂.⁸⁴ Present certification procedures require that CO₂ concentration be measured during both machine and human use testing. Performance criteria has been established for both open and closed-circuit SCBA. Various investigators have made recommendations regarding maximum allowable CO₂ concentrations for SCBA. Schaefer⁸⁵ noted differences in acid-base regulation in response to inspired CO₂ levels of 3% and greater. Love et al.⁸⁷ similarly concluded that CO₂ concentrations at

or above 3% are not well tolerated, particularly in combination with exercise. Hartwell and Senneck⁶⁰ suggested that the CO₂ concentration of inspired air should not exceed 0.5%. They also suggested that when tested at 40 L/min with a 5% CO₂/air mixture (saturated at 37°C), the mean CO₂ concentration coming from the canister (of a closed-circuit apparatus) should not exceed 0.20% after 120 min. and 1.0% after 150 minutes.

Love et al.⁸⁶ found that VE increased linearly with inspired CO₂ concentrations, (F_ICO₂) from 31% above a fresh air value at 2% F_ICO₂ to a 73% increase at 5% F_ICO₂. Shock and Soley⁸⁷ reported VE increases (at rest) of 14, 34, and 100% when breathing F_ICO₂ concentrations of 1, 2, and 4%, respectively. Unlike Love et al.⁸⁶ the data from Shock and Soley⁸⁷ suggested that the increase in VE in response to CO₂ is not linear.

Current federal regulations¹ for CO₂ concentration mandate that the maximum average dead space CO₂ concentration for both open and closed-circuit apparatus be between 1 and 2.5%, depending on the service time of the unit. During human-use testing of closed-circuit units, the CO₂ concentration downstream from the sorbent shall not exceed 0.5%–1.5%, depending on the type of apparatus.

Oxygen Concentration Hartwell and Senneck⁶⁰ recommended that the O₂ concentration of inspired air should be no less than 21% and that for closed-circuit apparatus this figure should be closer to 60–70%. Cotes⁵⁰ suggested that 50% O₂ concentrations be used with closed-circuit SCBA since exercise tolerance is improved at this concentration and the detrimental side effects of 100% O₂ are avoided. Present federal regulations mandate that the O₂% of gas supplied for SCBA shall not be less than 19.5%.¹ However, no maximum limit is set forth. The reader is referred to the NIOSH Guide to Industrial Respiratory Protection for additional information on oxygen deficiency.⁸⁸

Wearer Comfort and Psychological Factors

"A major area of concern is the subjective effect that each specific respirator has on each individual..."⁴⁷ This factor may become more significant when the apparatus is worn for lengthy periods of time. Under those circumstances, Shephard⁸⁹ points out that physiological cost may not be the limiting factor, but rather the total psychological response to claustrophobic feelings as well as feelings of discomfort resulting from irritations such as pressure on the skin and sweat accumulations inside the facepiece. Louhevarra et al.³⁷ suggest that structural improvements in the SCBA harness coupled with use of lighter weight tanks might have beneficial effects in performance using SCBA.

Morgan^{32,76} has completed some comprehensive work examining psychological problems associated with respirators, including the screening of individuals who may be hypersensitive to carbon

dioxide or otherwise psychologically unsuited for wearing respirators. A review of the psychophysiological aspects of respirator wear has been published by Wilson et al.⁹⁰ Myhre et al.²⁶ and Mihaly⁹¹ provide examples of how subjective responses of subjects can be used to quantify the comfort or discomfort of SCBA use, while Vercruyssen⁹² provides a chronology of the research on psychological reactions to wearing respirators. Raven has pointed out⁹³ that future respirator research should focus on the human-respirator interface.

The present certification procedures attempt to evaluate "undue discomfort," but as pointed out by Held and Richards³ the term "undue discomfort because of airflow restriction or other physical or chemical changes. . . is vague and poorly defined." Only by considering the suggestions of these investigators can this aspect of respirator use and testing be improved.

Summary

Based on this extensive review of literature dealing with the evaluation and testing of SCBA, the following conclusions are made:

(1) Current man test criteria and procedures used in the U.S. for testing SCBA are outdated and in need of revision. This suggests a need to examine test procedures in various countries to determine if they are adequate for evaluating SCBA performance. Proposed revisions should reflect the technological advances that have occurred over the past few decades as well as the growing variety of environments and work tasks for which such devices are employed. Continuous monitoring of the physiological responses of the test subject would provide a much more valid indication of how the SCBA affects performance of various tasks and how safe and effective the unit truly is. The literature reviewed suggests that test methods, whereby the subject is monitored intermit-

tently, are no longer acceptable. The literature also suggests that at this time there is no consensus as to what acceptable criteria should be employed. There is also inadequate literature examining criteria when stressors are seen in combination.

(2) Many factors will affect the SCBA's efficacy and must be considered in developing or proposing any SCBA certification or performance requirements. These factors include, but are not limited to: metabolic requirements, breathing resistances and temperatures, oxygen and carbon dioxide concentrations, apparatus weight, wearer comfort, and psychological factors.

In closing, the concerns raised in the literature underscore the need for modification of current SCBA "Use Test" procedures and performance criteria.

Disclaimer

Mention of a company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH).

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