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Evaluation of Proposed Methods to Update Human Testing of Self-Contained Breathing Apparatus

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The current Man Test protocols used by the National Institute for Occupational Safety and Health for the certification testing of self-contained breathing apparatus (SCBA) do not provide continuous real-time information on the performance of these devices during actual use. In addition, current protocols do not test human subjects at the same absolute work rates but at rates that vary according to the subjects' body weights. This study was conducted to evaluate revised "Use Test" protocols proposed by the U.S. Bureau of Mines, which are normalized to subjects' body weights. No differences in duration were observed among the three body weight categories for the multiple work rate Use Test 2. It was concluded that the proposed Use Test protocols could form the basis for eventual recommendations to revise the current Man Tests for SCBA performance evaluation.

APPLIED STUDIES

The purpose of this study is to demonstrate the feasibility of using updated test methods and protocols for the human testing of self-contained breathing apparatus (SCBA). There is general agreement among respirator researchers, users, and manufacturers that the current Man Tests described in 30 CFR, Part 11,[1] are in need of revision.[2–7] The stated purposes of the current Man Tests are 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.[1]

The current protocols for Man Tests 1–4 do not adequately fulfill purposes 3 and 4. Real-time monitoring was not technically feasible when these standards were written; consequently, monitoring currently occurs only during specified 2-min periods of inactivity. During these periods of inactivity, all the measured physiological variables (respiration rate, mouth pressure, temperature, and inspired CO_2 concentration) decrease significantly. Research by Bernard et al.[3] indicates that within 30 sec of termination of moderate-intensity exercise, minute ventilation decreases 30% and pressure at the mouth drops 50%. Therefore, the continuous monitoring technique used in this study was of benefit to the participants, by monitoring their safety, and to the investigators, by providing continuous real-time information on respirator performance.

In addition to a lack of continuous monitoring, current Man Test protocols do not consistently test subjects at the same absolute work loads. The proposed Use Test protocols prescribe different treadmill settings for several ranges of body weights, providing for consistent absolute work loads regardless of body weight.

A previous literature review[8] omitted several recent experimental and demographic studies[9–12] that are relevant to the currently proposed Use Test protocols. These studies fall into two distinct categories: physical characteristics of SCBA users and metabolic rates of SCBA users. Each is discussed separately.

PHYSICAL CHARACTERISTICS OF SCBA USERS

Metabolic rate, as measured by oxygen consumption ($\dot{V}O_2$), has been shown by Kamon et al.[2] to vary by as much as 30% between 50th and 95th percentile miners. It is apparent that SCBA performance during the

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current National Institute for Occupational Safety and Health (NIOSH) Man Tests[1] is dependent on the body weight of the subject chosen to perform the test. To decrease the intersubject variability in oxygen consumption and SCBA performance, the same absolute metabolic rate must be attained by all test subjects. The most accurate way to achieve this is to adjust the treadmill protocol individually to each subject; however, this is not practical for certification testing. Therefore, three treadmill protocols that correspond to three ranges of body weights were developed. In this way, the Use Test protocols in this proposal take the body weight of the test subject into account; test subjects were placed in one of three body weight categories, based on the results reported from two large studies[9,10] of firefighters and miners, which are summarized along with results from an earlier study[2] in Table I.

The first study examined the physical fitness status of 193 male and female firefighters (both civilian and military) assigned to four U.S. Air Force bases between 1980 and 1983.[9] Data were divided into three age groups with different sample sizes, and the weighted mean body weight for the combined age groups was 80.6 kg. Mean standard deviation (SD) in body weight across age groups was approximately 11 kg, and the 95th percentile, calculated as the mean plus 1.65 times the SD, was 98.8 kg. The weighted mean maximum oxygen consumption ($\dot{V}O_2max$) across age groups was approximately 3.1 L/min and the mean SD was approximately 0.56 L/min, which results in a calculated 95th percentile for $\dot{V}O_2max$ of 4.0 L/min.

A series of two large studies examined the biomechanical and physical fitness characteristics of male underground and low coal miners (N = 305) between 1979 and 1984.[10] The weighted mean body weight for the combined age and mining groups was approximately 80.9 kg. The mean SD was approximately 13 kg, making the 95th percentile 102.4 kg. [These results are in contrast to an earlier study by Kamon et al.,[2,10] where the mean body weight of approximately 54 miners was found to be 87 kg (SD = 11 kg).] The weighted mean was $\dot{V}O_2max$ approximately 3.0 L/min. The mean SD was approximately 0.64 L/min, making the 95th percentile for $\dot{V}O_2max$ 4.1 L/min.

Based on the two more recent studies[9,10] of firefighters and miners with a combined sample size of 498 and using a weighted average SD of 12 kg, the following body weight categories were used to group Use Test subjects for testing: 50th to 70th percentile: 80.0–86.5 kg; 70th to 85th percentile: 86.5–92.5 kg; and 85th to 95th percentile: 92.5–100.0 kg.

TABLE I. Studies of the Physical Characteristics of SCBA Users

Author (year published)	Sample Size	Mean Body Weight (SD) (kg)	Mean $\dot{V}O_2max$ (SD) (L/min)
Myhre et al.[9] (1986)	193	80.6 (11.0)	3.1 (0.6)
Ayoub et al.[10] (1984)	305	80.9 (13.0)	3.0 (0.6)
Kamon et al.[2] (1975)	54	87.0 (11.0)	—

—, $\dot{V}O_2max$ was not reported

Metabolic Rates of SCBA Users

The oxygen cost of fire fighting has been estimated to be very high. In a recent study by Louhevaara et al.,[11] nine firemen (mean body weight 79.5 ± 9.3 kg, mean $\dot{V}O_2max$ 3.6 ± 0.3 L/min) were monitored during simulated firefighting while wearing an SCBA (N = 3, T_{amb} = 110–120°C) and repair and rescue tasks (N = 6, T_{amb} = 2–3°C). The range of mean recorded heart rates was 142–160 beats/min. Mean estimated $\dot{V}O_2$ during work (based on heart rate) was 2.3 ± 0.4 L/min and estimated maximum $\dot{V}O_2$ during work was 2.9 ± 0.5 L/min. Estimated mean minute ventilation ranged from 45 to 70 L/min.

These results are in close agreement with those of Lemon and Hermiston,[12] who tested 20 firefighters (mean body weight 84.5 kg, mean $\dot{V}O_2max$ 3.5 L/min) while they performed four simulated fire fighting tasks. Mean $\dot{V}O_2$ was 2.4 L/min (aerial ladder climb), 2.53 L/min (victim rescue), 2.55 L/min (hose dragging), or 2.30 L/min (ladder raise).

If the mean metabolic cost of firefighting is approximately 2.5 L/min, the metabolic cost for the 95th percentile firefighter (100 kg) would be 3.0 L/min. To protect the 95th percentile firefighter adequately, work intensities of 3.0 L/min should be included in a multiple work rate Use Test protocol.

Proposed SCBA Use Test Protocols

The currently proposed Use Test protocols are based on research performed and sponsored by NIOSH and the U.S. Bureau of Mines.[7] Test 1 allows the apparatus to be tested at a continuous work rate, recommended by the manufacturer, so that the quantity of consumable oxygen and duration of the apparatus can be determined. Test 2 is designed to assess the response of an apparatus to changes in work rate. The two proposed test protocols are further described below.

Table II shows the absolute steady-state work rates, expressed as $\dot{V}O_2$, which would be selected by the manufacturer for Use Test 1. The purpose of Use Test 1 is to determine the duration and/or volume of breathing gas available for a constant work rate. The work rate selected would approximate the average oxygen consumption for the intended use of the SCBA. The moderate work rate, 1.35 L/min, represents the average $\dot{V}O_2$ for the 50th percentile miner during the NIOSH 1-hr Man Test 4.[2]

The purpose of Use Test 2 is to assess the performance of SCBA during the dynamic situation of going from a very high, to a high, to a low metabolic work rate (Table III). The metabolic work rates are performed in descending order because this represents a worst-case scenario for and places the most demand on the

TABLE II. Work Rates to be Used for Steady-State Use Test 1

Work Rate	$\dot{V}O_2$ (L/min)	Estimated $\dot{V}_E$[A] (L/min)
Moderate	1.35	30.0
High	2.00	44.0
Very high	3.00	65.0

[A]Minute ventilation (STPD, based on recent exercise testing data from this laboratory)

TABLE III. Work Rates and Minutes for Use Test 2

Work Rate	$\dot{V}O_2$ (L/min)	Service Time in Minutes 3	5	10	15	30	60	120[A]	180[A]	240[A]
Very high	3.0	2	2	2	2	5	5	5	5	5
High	2.0	1	2	2	2	15	15	15	15	15
Low	0.5	—	1	2	2	10	10	10	10	10
Very high	3.0	—	—	2	2	—	5	5	5	5
High	2.0	—	—	2	2	—	15	15	15	15
Low	0.5	—	—	—	2	—	10	10	10	10
Very high	3.0	—	—	—	2	—	—	5	5	5
High	2.0	—	—	—	1	—	—	15	15	15
Low	0.5	—	—	—	—	—	—	10[B]	10[C]	10[D]

[A]Average $\dot{V}O_2$ reduced 10%
[B]Repeat the 30-min test one more time
[C]Repeat the 30-min test three more times
[D]Repeat the 30-min test five more times

apparatus. The duration and/or volume of delivered breathing gas would not be rated during this test. For tests longer than 60 min in duration, average $\dot{V}O_2$ would be reduced by 10%, as currently occurs in the Man Tests.

EXPERIMENTAL METHODS

The subjects for this study were seven male nonsmoking volunteers between the ages of 18 and 35 yr. Subjects were professional and volunteer firefighters, safety personnel, and exercise physiology and occupational safety students.

Before inclusion in the study, all subjects signed a consent form, completed a medical history questionnaire, and received a resting 12-lead electrocardiograph and spirometry. Each subject also completed a graded exercise test on a treadmill using a modified Balke protocol.[13] Maximum aerobic capacity was determined by measuring $\dot{V}O_2$max using an MMC Horizon, Advanced Exercise System 5, metabolic cart (SensorMedics, Yorba Linda, Calif.). After these screening procedures, subjects were placed into one of three body weight categories. Subject categories and characteristics are shown in Table IV.

The SCBA selected for this study consisted of four different manufacturers' 60-min closed circuit self-contained self-rescuers (Models A–D) and one 4-hr closed-circuit rescue apparatus (Model E). Relevant closed-circuit SCBA performance variables were continuously monitored; data were sampled at 60 Hz and logged by a Hewlett-Packard Vectra QS-20 IBM-compatible computer. Inspired dry bulb temperatures were measured using a fast-response Type T copper-constantan thermocouple. Inspired and expired pressures were measured using a Validyne differential pressure transducer and carrier demodulator (Northridge, Calif.). Tidal volumes and flow rates were measured and calculated, respectively, using a Sensormedics Ventilation Measurements Module turbine (Yorba Linda, Calif.). Inspired CO_2 and O_2 concentrations were measured by Ametek CD-3 and S-3A/II analyzers, respectively (Pittsburgh, Pa.). All exercise was performed on a Quinton 645 programmable treadmill (Seattle, Wash.).

Instrumentation of each NIOSH-certified SCBA was accomplished by punching small holes in the breathing hose, starting approximately 4 cm from the SCBA mouthpiece. The gas sampling line was closest to the mouthpiece, followed by the pressure, temperature, and gas return lines; the lines were placed 2 cm apart. For respirator Model D, the pressure line was inserted into the mouthpiece. The turbine volume transducer was inserted into the breathing hose at the point where the mouthpiece attached to the hose. The dead space of the turbine was approximately 75 mL, and the diameter of the turbine casing (2.5 cm) was identical to that of the breathing hose for each SCBA.

There are three distinct measurements of inspired gas concentration that can be made during the human subject testing of respirators: minimum inspired, maximum inspired, and average inspired concentration. The measurement of the first two concentrations is relatively simple, requiring only a gas sample line and a pressure sample line to be attached to the mouth–apparatus interface. However, measurement of these two quantities does not reveal the actual concentration inhaled by the user because it fails to take into account apparatus dead space. The measurement of average inspired gas concentration does take apparatus dead space into account but requires more instrumentation and modification to the apparatus being tested. Instantaneous inspired flow rates are required for the accurate measurement of flow-weighted average inspired gas concentrations and may only be obtained through insertion of a flow measurement device into the breathing line of the SCBA. Both flow-weighted and time-weighted average inspired CO_2 concentrations were measured in the current study; however, the flow-weighted concentrations were found to be inaccurate because of respirator-induced variations in turbine response time.

Subjects performed three tests wearing five different closed-circuit respirators. Test 1 was performed at a $\dot{V}O_2$ of 1.35 for 1 hr using respirator Models A and B. Test 2 was performed for 1 hr for four of the five respirators tested; Test 2 was performed by four subjects for 4 hr for the remaining respirator. Subjects also performed Test 2 for 1 hr without wearing a respirator while physiological variables were monitored using the metabolic cart.

Data were collected using custom software that phased the various signals into a

TABLE IV. Mean and SD of Subject Characteristics (N = 7)

Weight Group (percentile)	Age (yr)	Height (cm)	Weight (kg)	$\dot{V}O_2$max (mL/kg/min)	FVC[A] (L)
50th to 70th (N = 3)	27 ± 4.4	178.0 ± 3.0	81.9 ± 2.4	43.0 ± 7.9	5.57 ± 1.04
70th to 85th (N = 2)	20 ± 1.4	184.0 ± 5.7	90.0 ± 1.4	45.2 ± 0.5	5.92 ± 0.01
85th to 95th (N = 2)	26 ± 7.1	188.0 ± 4.2	99.8 ± 1.6	38.6 ± 1.6	6.72 ± 0.84

[A]Forced vital capacity (BTPS)

APPLIED STUDIES

TABLE V. Control Data for Use Test 2 by Weight Group (N=7)

Target $\dot{V}O_2$ (L/min)	Observed $\dot{V}O_2$ (L/min)	$\dot{V}CO_2$^A (L/min)	$\dot{V}_E$^B (L/min)	f^C	PF_E^D
Weight Group 1 (N = 3)					
0.5	0.8 ± 0.2	0.7 ± 0.1	18.7 ± 1.6	24.2 ± 2.4	113.9 ± 21.3
2.0	1.9 ± 0.1	1.6 ± 0.1	36.6 ± 3.0	28.9 ± 1.7	187.0 ± 20.6
3.0	2.7 ± 0.1	2.8 ± 0.1	58.5 ± 5.8	31.3 ± 2.9	212.5 ± 12.8
Weight Group 2 (N = 2)					
0.5	0.9 ± 0.1	0.8 ± 0.1	19.3 ± 2.1	23.0 ± 2.3	117.3 ± 28.4
2.0	1.9 ± 0.1	1.8 ± 0.1	38.1 ± 2.2	28.6 ± 0.5	166.6 ± 16.4
3.0	2.8 ± 0.1	2.9 ± 0.2	57.1 ± 7.0	29.1 ± 4.2	244.8 ± 22.2
Weight Group 3 (N = 2)					
0.5	0.9 ± 0.1	0.8 ± 0.1	19.7 ± 2.4	20.9 ± 3.0	124.9 ± 25.2
2.0	1.9 ± 0.2	1.8 ± 0.2	38.4 ± 4.1	27.1 ± 4.4	181.0 ± 75.7
3.0	2.9 ± 0.1	3.0 ± 0.2	62.3 ± 7.3	26.5 ± 9.8	234.6 ± 50.5

Values are means ± SD
^A CO_2 production (STPD)
^B Minute ventilation (STPD)
^C Breathing frequency (breaths per minute)
^D Peak expiratory flow rate (STPD)

breathing waveform, located minimum and maximum values, and calculated average inspired gas concentrations by integration versus flow rates. Five to 15 breaths were obtained for each minute, and minute averages were calculated and stored. Raw data were also stored and were displayed on the computer monitor in real time.

RESULTS

Data from the control tests (no SCBA) using the protocol for Use Test 2 were combined for the three body weight categories. Means and SD for $\dot{V}O_2$, CO_2 production ($\dot{V}CO_2$, minute ventilation, breathing frequency, or peak expiratory flow rate) are shown in Table V. Observed mean $\dot{V}O_2$ was very close to the target $\dot{V}O_2$ for each work load.

Data from the three body weight categories were combined for all further analysis. Table VI shows the end-of-test values observed during Use Test 1 for respirator Models A and B. These respirators are rated for 60 min and were therefore tested at a continuous moderate work rate of 1.35 L/min. None of the tests on respirator Model A was stopped because of elevated CO_2 concentration; however, three of six tests performed on Model B were stopped at less than 60 min when minimum inspired CO_2 ($F_ICO_2$min) exceeded 3%. No other variables exceeded current limits for failure[1] during Use Test 1.

TABLE VI. End-of-Test Observed Values for Use Test 1 Respirator Tests

Variable	Respirator Model A (n=7)	Respirator Model B (n=6)
Number of Tests Lasting 60 min	7	3
Duration (min)^A	59.9 ± 0.4	53.6 ± 8.4
$F_ICO_2$min (%)^B	0.6 ± 0.5	2.5 ± 0.7
$F_IO_2$max (%)^C	66.0 ± 5.0	52.9 ± 7.1
P_E (cmH_2O)^D	6.4 ± 1.5	7.7 ± 4.2
P_I (cmH_2O)^E	−3.3 ± 0.4	−5.5 ± 2.8
T_{Idb} (°C)^F	37.6 ± 4.0	41.1 ± 3.3

Values are means ± SD
^A Means include tests terminated at 60 min
^B Minimum inspired CO_2 concentration
^C Maximum inspired O_2 concentration
^D Peak expiratory pressure
^E Peak inspiratory pressure
^F Peak inspiratory dry bulb temperature

The results of respirator tests using the proposed Use Test 2 protocol are presented in Table VII. For the 60-min tests, the maximum observed values (minimum observed O_2 values) shown are the peak values observed for each variable at any time during the test, regardless of the work rate or minute. These peaks most often occurred at minute 35, 50, or 60 for all variables except maximum inspired O_2, for which minimums were observed at minutes 20 and 60. Tests were allowed to continue until subjects requested to stop because of high breathing resistance (61% of tests lasting less than 60 minutes) or temperature (28%) or until research staff observed that $F_ICO_2$min exceeded 3% (33%). Elevated $F_ICO_2$min (greater than 1%) was the reason for terminating all 4-hr tests, and subjects consistently reported fatigue upon termination of this test.

Data collected continuously over the course of Use Test 2 respirator tests are presented in Figures 1–4. Figure 1 shows minimum (Models A–D) and average (Models A–C; average values for Model D were very similar to minimums) inspired CO_2 concentrations. The average CO_2 concentrations shown are time-weighted averages obtained from high-speed chart recordings. Computer averages calculated by integration of instantaneous CO_2 concentration versus flow were not included in any data summaries; because of respirator-induced variations in turbine response time, these averages were not consistently accurate. Figures 2, 3, and 4 show $F_IO_2$max, maximum expiratory and inspiratory pressures, and maximum inspired dry bulb temperatures, respectively. No Model C respirator lasted longer than 35 min during Use Test 2; for Models A, B, and D, N was reduced to five by minute 35 and to three by minute 55. No significant differences in duration ($p < 0.05$) were observed among the three body weight categories when respirator models were combined.

DISCUSSION

The proposed test protocols and methods evaluated in this study represent an attempt to provide continuous information on the performance of an SCBA during human activities consisting of relevant quantified metabolic work rates. An additional goal was

TABLE VII. Maximum[A] Observed Values for Use Test 2 Respirator Tests

Variable	Respirator Model A (N = 7)	B (N = 7)	C (N = 7)	D (N = 6)	E (4-hr)[B] (N = 4)
Number of Tests Lasting 60 min	3	2	0	4	0
Duration (min)[C]	49.4 ± 10.5	47.3 ± 12.2	28.3 ± 11.2	51.2 ± 13.7	184.3 ± 14.4
$F_ICO_2$min (%)[D]	1.9 ± 0.6	2.9 ± 1.0	3.1 ± 1.8	1.7 ± 1.1	1.7 ± 1.0
$F_IO_2$max (%)[E]	55.4 ± 9.9	50.5 ± 11.0	44.8 ± 11.8	30.3 ± 10.5	
P_E (cmH_2O)[F]	11.1 ± 2.0	11.1 ± 2.3	14.4 ± 3.5	12.1 ± 1.0	
P_I (cmH_2O)[G]	−8.1 ± 2.4	−16.2 ± 10.5	−17.5 ± 4.6	−14.3 ± 3.9	
T_{Idb} (°C)[H]	42.3 ± 5.8	44.3 ± 3.7	46.8 ± 1.4	48.9 ± 1.4	

Values are means ± SD
[A]Minimum observed test values for $F_IO_2$max
[B]Only CO_2 data were obtained for the 4-hr unit
[C]Means include tests terminated at 60 min
[D]Minimum inspired CO_2 concentration
[E]Maximum inspired O_2 concentration
[F]Peak expiratory pressure
[G]Peak inspiratory pressure
[H]Peak inspiratory dry bulb temperature

ers and firefighters show mean $\dot{V}O_2$max to be between 3.0 and 3.5 L/min and simulated work task $\dot{V}O_2$ to be approximately 2.5 L/min. A mean $\dot{V}O_2$ of 1.67 L/min would therefore seem to be reasonable for a multiple work rate test such as Use Test 2.

to provide the ability to test apparatus at consistent absolute work rates regardless of the body weight of the human subject. Variation in such physiological variables as $\dot{V}O_2$ was successfully controlled by separating subjects above the 50th percentile (greater than 80 kg) in body weight into three body weight categories and prescribing different treadmill grades for each category. During Use Test 2 control tests, SDs for $\dot{V}O_2$ and $\dot{V}CO_2$ were reduced to 3–5% of the means for the high and very high work rates (Table V).

In addition to providing consistent absolute work rates, the protocol for Use Test 2 would provide added protection to SCBA users of higher body weights by testing apparatus at a mean $\dot{V}O_2$ of 1.67 L/min for 60 min. The mean $\dot{V}O_2$ for the current Man Test 4 (60 min) is 1.35 L/min for the 50th percentile miner and 1.75 L/min for the 95th percentile miner.[2] Demographic data on min-

The proposed Use Tests do not necessarily impose greater demands than current NIOSH tests on subjects or apparatus. Without continuous monitoring, it is impossible to compare results from the Man Tests in 30 CFR, Part 11,[1] to the current test results. Because sampling occurs during rest periods in 30 CFR, Part 11, Man Tests, current performance criteria may have to be modified to accommodate the proposed continuous monitoring of respirator variables. New performance criteria should be established based on further testing and on recent physiology and respirator research such as that supported by the U.S. Bureau of Mines[14,15] and NIOSH.[8,16] Data from the present study demonstrate that for apparatus performing the full 60 min during Use Test 2 (N = 9), maximum inspiratory dry bulb temperature averaged approximately 46.0°C. Maximum expiratory pressure averaged around 11.5 cmH_2O and maximum inspiratory pressure averaged −13.5 cmH_2O. These values for resistance are higher than the current machine test limits for closed-circuit apparatus[1] and reflect the rigors of continuous monitoring. $F_ICO_2$min was allowed to reach 3% to obtain the most information possible on overall apparatus performance. The current upper limit for average F_ICO_2 is 0.5% during human testing and 2.0% for dead space during machine testing of a 1-hr

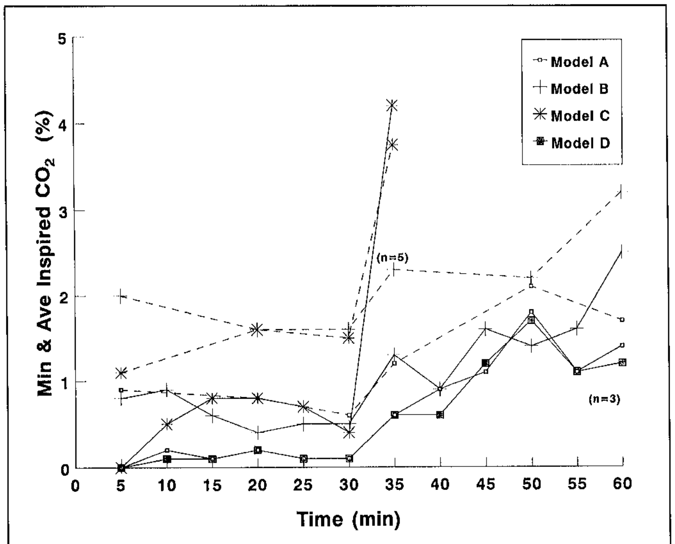

FIGURE 1. Minimum (——, respirator Models A–D) and average (- - -, Models A–C) inspired CO_2 concentrations for Use Test 2 respirator tests

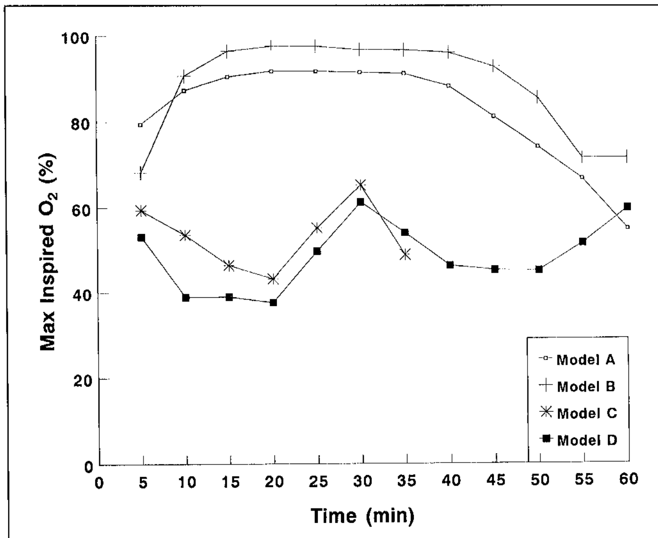

FIGURE 2. Maximum inspired O_2 concentration for Use Test 2 respirator tests

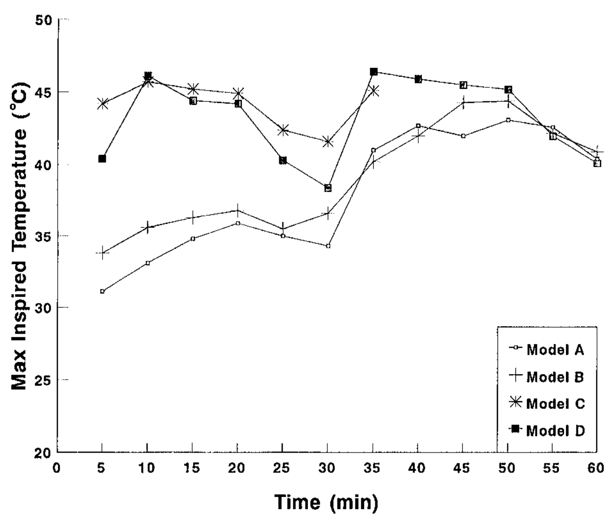

FIGURE 3. Maximum inspired air temperature for Use Test 2 respirator tests

apparatus. For apparatus lasting the full 60 min during Use Test 2, $F_ICO_2$min was approximately 2.0% and average F_ICO_2 was between 2.5 and 3.0%.

Further research is needed before recommendations can be made for updating the present human testing protocols and methods for SCBA performance evaluation. This study examined several proposed test protocols that provide continuous monitoring of relevant variables and consist of metabolic work rates, based on quantified rates of oxygen consumption, which are consistent regardless of the body weight of the test subject. Neither Use Test 1 nor 2 is equivalent to the present 30 CFR, Part 11, Man Test 4 because of the differences in test protocol and sampling methods. Side-by-side human subject and metabolic simulator testing using these protocols would provide additional information on their efficacy.

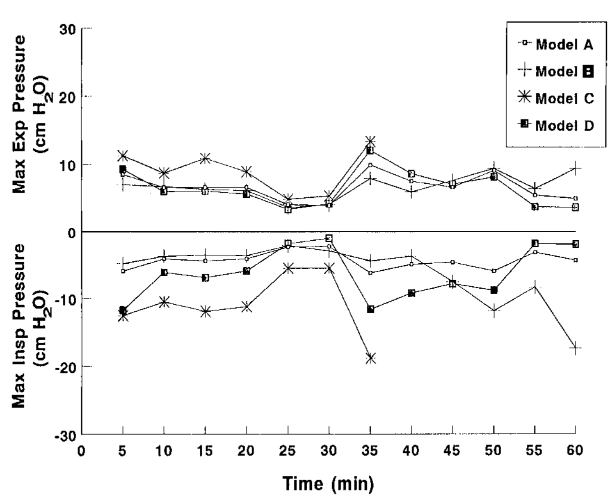

FIGURE 4. Maximum inspired and expired pressure for Use Test 2 respirator tests

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