

Machine Testing of Self-Contained Breathing Apparatus at a High Work Rate Typical of Firefighting*

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Abstract

We tested fourteen self-contained breathing apparatus (SCBA) on a breathing machine that simulated high work rates associated with firefighting. We investigated reports of suspected loss of wearer protection due to facepiece pressures not remaining positive throughout the entire inhalation-exhalation cycle. We also evaluated the current generation of SCBA equipment according to the National Fire Protection Association (NFPA) proposed high-work-rate machine test. On the basis of pressure measurements on the facepieces, we concluded that losses of pressure are occurring, thereby reducing individual protection. This is particularly true during strenuous work rates as the compressed gas-supply pressures approach the low-level alarm point. We concluded that the proposed NFPA test is reasonably achievable as evidenced by the fact that one SCBA met the required level of performance.

Introduction

Research on self-contained breathing apparatus (SCBA) performance has identified the need for improvement in withstanding firefighting environments. The American National Standard Institute (ANSI 88.9 Committee) and, more recently, the National Fire Protection Association (NFPA 1981 Committee) in the U.S. have been actively developing test standards for SCBA in recognition of the critical needs of firefighters.

Held et al. (1979, 1980, 1983), Raven et al. (1982), and Myhre et al. (1979) in the U.S. and Dahlback in Sweden (1983) have recently suggested that SCBA approved by National Institute of Occupational Safety & Health (NIOSH) do not maintain positive pressure at work rates experienced by firefighters. We conducted the following breathing machine tests to investigate SCBA facepiece pressures (i.e., protection) at work rates more typical of firefighting activities.

Human performance of work principally affects three respiratory parameters of significance to machine tests: respiratory rate (RR) in breaths per minute (B/min), tidal volume (TV) in liters per breath (L/B), and minute volume ($\dot{V}_E$) in liters per minute (L/min):

$$\dot{V}_E = RR \times TV$$

For example, present NIOSH machine-testing is done at work rates corresponding to a $\dot{V}_E$ of 40 L/min, a RR of 24 B/min, and a TV equal to 1.7 L/min (Title 30 CFR, 1972). A $\dot{V}_E$ of 40 L/min has been classified as a heavy work rate (Pritchard, 1976). Burgess, however, in a NIOSH study of firefighters concluded that the median minute volume of firefighters was approximately 60 L/min (1976). Further interpretation of that data has indicated that firefighters are capable of work rates corresponding to 100 L/min, and that such a level encompasses nearly all firefighters. The researchers mentioned previously found some firefighters capable of minute volumes beyond

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100 L/min. Minute volumes of 100 L/min are classified as exhaustive in that they can be sustained only for short periods—a good qualitative description of firefighters' activities (Pritchard, 1976).

Literature Review

We reviewed the literature to determine which respiratory physiology parameters would be appropriate to a high-work-rate, breathing-machine test. Results of that review are listed and referenced in Table 1. Based largely on this information, we chose the following set of parameters: $\dot{V}_E = 100$ L/min, RR = 42 B/min, and TV =

2.4 L. Of interest here is that physiologists reported peak flows in a range of $3.0\text{--}4.3 \times \dot{V}_E$ at these higher work rates. Peak or instantaneous flow rates are thought to be significant because of the severe stress they impose on the demand valve, which must rapidly turn on and off the air supply in order to deliver the required average flow rate. If the regulator is not capable of meeting the requirements of a user at hard work, instantaneous loss of positive facepiece pressure and increased inhalation resistance can result. This loss of positive pressure in the facepiece results in a significant reduction in the protection factor.

Methods

We tested a total of fourteen NIOSH-MSHA-certified SCBA (including one closed-circuit apparatus) and two unapproved SCBA commercially available in other countries (Table 2). Because

only one new or nearly new unit of each design was tested, the data are best considered as a survey which indicated overall performance, rather than precisely depicting the performance of each

Table 1. Comparison of reported respiratory physiology parameters.

Reference	$\dot{V}_E$ (L/min)	Resp. rate (B/min)	Tidal vol. (L)
Raven et al. (1982)	70	28	2.5
Silverman et al. (1951)	90.3	42	2.15
Myhre et al. (1979)	96	35.4	2.72
Bernard et al. (1978)	100	44	2.26
Raven (1982)	100	30	3.0

Table 2. Positive-pressure SCBA tested.

Manufacturers	Model	Remarks ^a
AGA	Spiromatic	Nose cup, facepiece-mounted demand valve , not NIOSH-MSHA approved at time of testing
Bendix	Air 30-LW	Nose cup , facepiece demand valve
Draeger	PA-80	Nose cup, facepiece demand valve
ISI	Ranger	Nose cup
Kawasaki	Life Gem	Nose cup, not NIOSH-MSHA approved
Globe	Guardman	
MSA	401	
Rexnord	BioPak 60P	Nose cup, closed circuit
Scott	Air Pak	
	Air Pak II	
	Air Pak 2.2	Facepiece mounted demand valve
Siebe-Gorman	Air Chief	Nose cup
Survivair	MK I	Nose cup
	MK II	

^a All open-circuit SCBA unless otherwise noted.

model. For that reason, SCBA are not identified. Calibration of pressure recording equipment was performed before and after each test. All tests were repeated and data was taken for a minimum of ten breaths. SCBA were pretested at the NIOSH test rate of 40 L/min to ensure proper operation as evidenced by the pressure tracing before testing at 100 L/min.

Rather than use the typical cardioid-shape cam to generate the breath waveform, a circular cam was fabricated to produce a sine waveform and a maximum tidal volume. Especially at high work rates, the sine wave is considered a physiologically correct breath waveform approximation (Cooper, 1960). It also simplifies the modification of existing breathing machines, thus making the test easier to do.

Figure 1 depicts schematically the equipment we used. The breathing machine is based on a

U.S. Bureau of Mines design and consists of two pistons which together produce a TV of 2.06 L. Because this was less than that needed to produce a $\dot{V}_E$ of 100 L/min, the RR was increased from 42 to 49 B/min. Although not physiologically correct, this approximation caused more severe transient pressure fluctuations and peak pressures, thus producing a "worst case" test.

Output from a Validyne (Model No. P24) pressure transducer was recorded by a Hewlett Packard (Model No. 680) strip-chart recorder and was calibrated to ± 0.1 inch (0.25 cm) H₂O pressure. The pressure-sensing orifice was located midline between the upper lip and nose of a Sierra anthropometric head form. The facepiece was attached and the SCBA operated according to the manufacturer's recommended instructions, after first verifying that the SCBA was functional.

Results and Discussion

We felt that the location of the pressure-sensing orifice required some validation because the pressure at the outer sealing surfaces of the facepiece could be different than those in the breathing zone. Pressure-mapping was done with three facepieces, two of which had nose cups that isolated the breathing-zone air from the rest of the facepiece (Fig. 2). No detectable differences (± 0.1 inch H₂O) were noted for a total of eight locations per facepiece. This may indicate that the response of the pressure recording system is not very sensitive.

Our predictions for the outcome of these tests were pessimistic, due to the severity of the work rate—the average ventilation rate of the test is 2-1/2 times greater than that required to pass NIOSH testing (Fig. 3). Of particular concern was

the SCBA's ability to maintain positive pressure down to the low-level alarm point and not cause excessive breathing resistances.

Ten of fourteen SCBA we tested maintained positive pressure initially at full cylinder pressure (Fig. 4). Four of those 10 SCBA produced excessive breathing resistances (defined as greater than 4 inches or 10 cm of H₂O pressure) upon exhalation at full cylinder pressure. Four of the 10 SCBA maintained exhalation resistances within the maximum 3.5 inches (8.8 cm) of H₂O pressure permitted by NIOSH.

Only 6 of the 10 SCBA which maintained positive pressure at full cylinder pressure were available for retesting at low-level alarm points. Of those 6 tested, only 1 was capable of maintaining positive facepiece pressure at a $\dot{V}_E$ of 100 L/

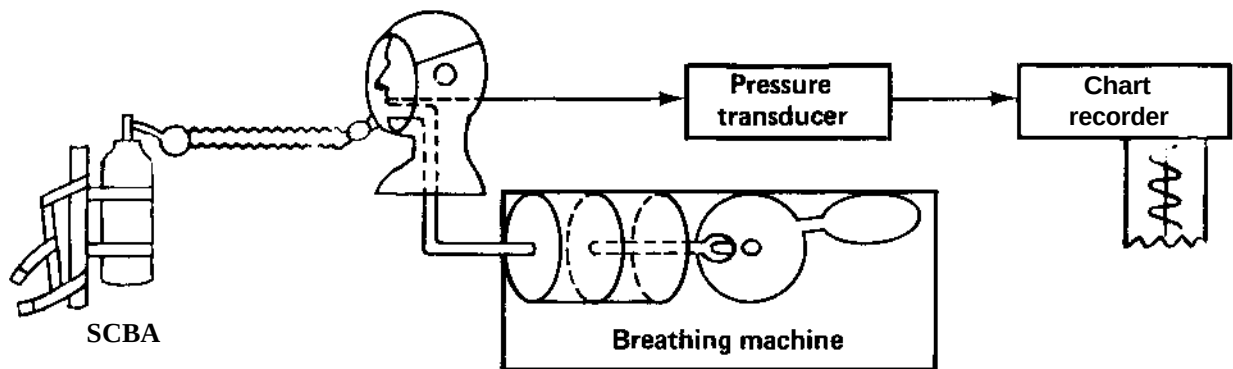


Figure 1. Diagram of SCBA testing apparatus.

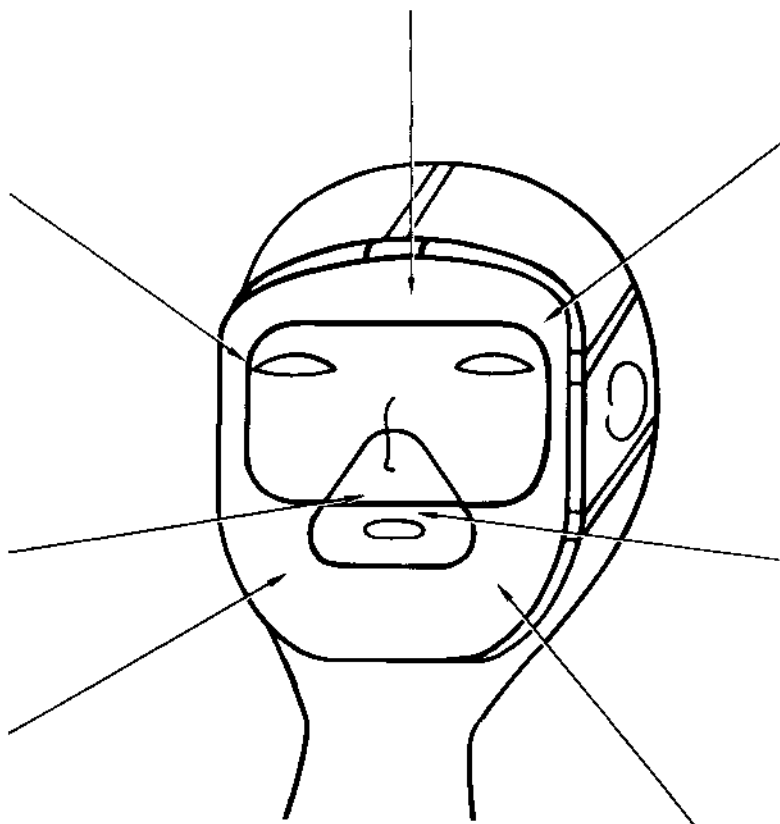


Figure 2. Pressure mapping of various test locations within facepiece.

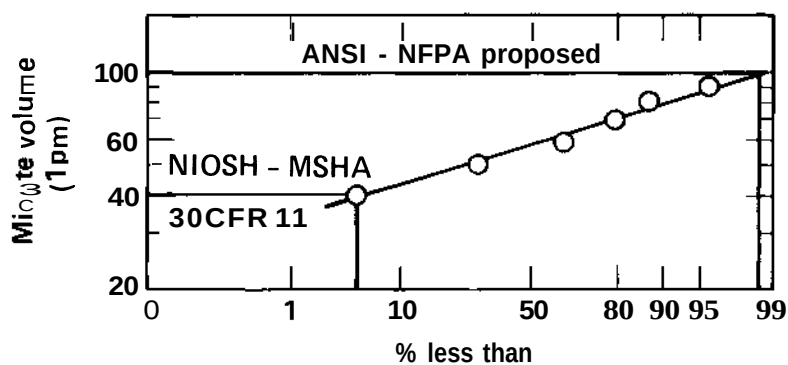


Figure 3. Comparison of firefighters' physiology data with current and proposed machine testing levels.

min (Fig. 5). Some SCBA that failed to maintain positive pressure at full cylinder pressures also produced prohibitively high exhalation resistances 7-9 inches or 17.5-22.5 cm of H_2O pressure) at the low-level alarm point (Fig. 6). It may be that simple readjustment of current regulators would allow most SCBA to pass the test. If small differences in regulator adjustment produce large differences in performance at high work rates,

quality control during this aspect of manufacturing and maintenance would become even more critical.

Considering the new or nearly new condition of the SCBA subjected only to laboratory testing, there were an alarming number of malfunctions. This indicates that frequent malfunctions could also be expected in field use. Although most were minor (e.g., a stuck pressure gauge), some were

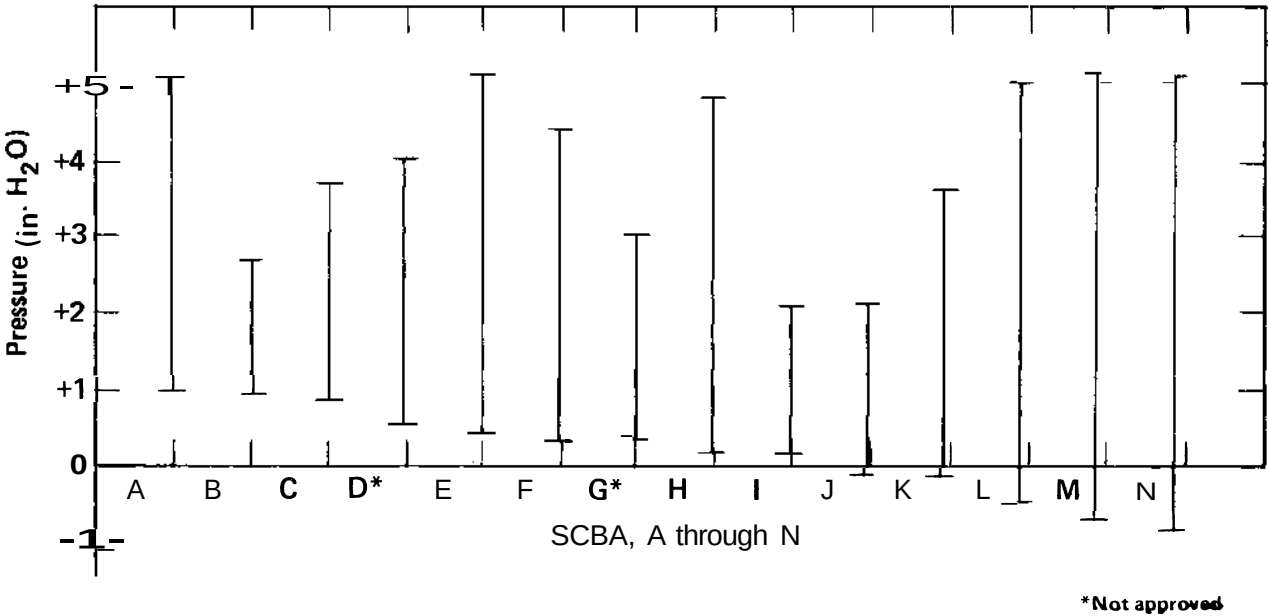


Figure 4. Machine test data: SCBA performance at a high work rate and full cylinder pressure.

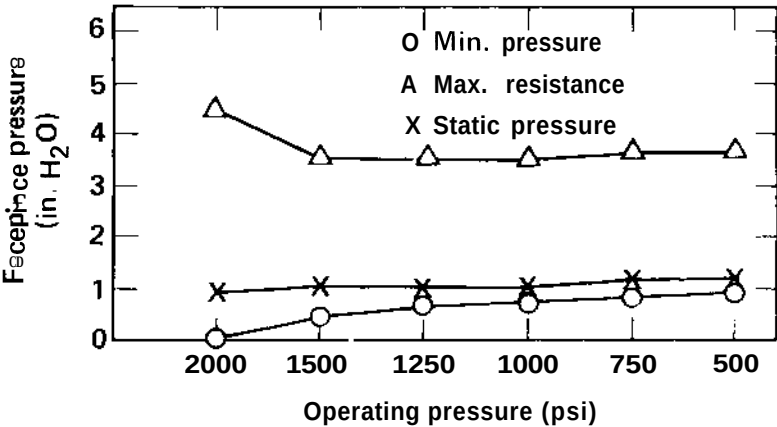


Figure 5. Machine test data: positive facepiece pressure as a function of a compressed-air, cylinder-operating pressure ($\dot{V}_E = 100 \text{ L/min}$).

significant. One demand regulator leaked and one high-pressure regulator failed during testing such that the air supply was continuously and rapidly

discharged through the facepiece. The latter failure could have caused a dangerous loss of air supply within a few minutes.

Conclusions

The proposed NFPA positive-pressure test, directly related to increased protection, is severe but achievable. NIOSH-MSHA-approved SCBA appear to be designed beyond the minimum re-

quirement ($\dot{V}_E$ of 40 L/min), and some are able to maintain positive facepiece pressures at high work rates typical of firefighting. However, a loss of protection for firefighters at high work rates

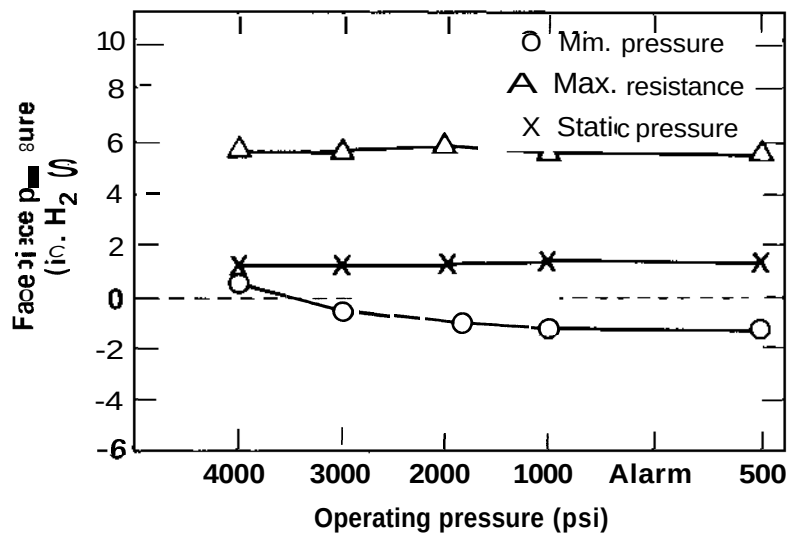


Figure 6. Machine test data: negative facepiece pressure as a function of a compressed-air, cylinder-operating pressure ($\dot{V}_E = 100$ L/min).

may be occurring in most SCBA, in that negative facepiece pressures are developed as compressed gas-supply pressures approach the low-level alarm point. Although nearly all SCBA tested would require adjustment or redesign to pass the high-work-rate test, this level of performance was achieved by one NIOSH-MSHA-approved SCBA during these tests. Breathing resistances at high work rates are generally comfortable and at or near those presently required for NIOSH tests at 40 L/min.

Increased confidence in testing results could be gained by testing all available SCBA designs (more than one of each), and by using a breathing machine capable of the exact, physiologically correct parameters. We also recommend use of more sensitive pressure instrumentation capable of rapid response. SCBA manufacturers are urged to take this approach in evaluating performance of their products using the high-work-rate test.

References

- Bernard, T. E., E. Kamon, and R. L. Stein (1978), "Respiratory Responses of Coal Miners for Use with Mechanical Simulators," *Am. Ind. Hyg.* 39:425-429.
- Burgess, W. H. (1976), *Design Specifications for Respiratory Breathing Devices for Firefighters*, Dept. of Health, Education, and Welfare (NIOSH), HEW Publication No. 76-121.
- Cooper, E. A. (1960), "A Comparison of the Respiratory Work Done Against an External Resistance by Man and by a Sine-Wave Pump," *Quarterly Journal of Experimental Physiology* 45:179-191.
- Dahlback, G. O. and L. Novak (1983), "Do Pressure-Demand Breathing Systems Safeguard Against Inward Leakage?" *Am. Ind. Hyg. Assoc. J.* 44(5):336-340.
- Harder, C. A., B. J. Held, and G. J. Cardenas (1979), "Operation of Self-Contained Breathing Apparatus Exposed to High Air Temperatures," *International Fire Chief* 45(12).
- Held, B. J., N. J. Alvares, D. G. Beason, C. A. Harder, and J. W. Stengel (1980), "Fire Tests on Closed-Circuit Oxygen Breathing Apparatus," *International Fire Chief* 46(11).
- Held, B. J. and C. A. Harder (1983), "Effectiveness of Self-Contained Breathing Apparatus in a Fire Environment," *Journal of the ISRP* 1(4):9-27.
- Myhre, L. G., R. D. Holden, F. W. Baumgardner, and D. Tucker (1979), *Physiological Limits of Firefighters*, Environmental Sciences Laboratory, Tyndall AFB, Florida, Report No. ESL-TR-79-06 AFESC (June).
- Pritchard, J. A. (1976), *A Guide to Industrial Respiratory Protective*, Dept. of Health, Education, and Welfare, DHEW (NIOSH) Publication No. 76-189.

- Raven, P. B. (1982), Dept. of Physiology, Texas College of Osteopathic Medicine, Fort Worth, Texas, private communication (December 14).
- Raven, P. B., D. Rohm-Young, F. L. McClure, and B. Skaggs (1982), "Physiological Response to 'Pressure-Demand' Respirator Wear," *Am. Ind. Hyg. Assoc. J.* 43(10):773-781.
- Silverman, L. D., G. Lee, T. Plotkin, L. A. Sawyers, and A. R. Nancey (1951), "Airflow Measurements on Human Subjects with and without Respiratory Resistance at Several Work Rates," *Archives of Industrial Hygiene and Occupational Medicine* 3:461-478.
- Title 30 Code of Federal Regulations (1972), Part II H, *Respiratory Protective Devices; Tests for Permissibility Fees*.