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Bureau of Mines Report of Investigations/1983

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
William P. Clark, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Laboratory testing of compressed-oxygen self-rescuers for ruggedness and reliability.

(Report of investigations / United States Department of the Interior, Bureau of Mines ; 8839)

Bibliography: p. 17.

Supt. of Docs. no.: I 28.23:8839.

1. Mine rescue work—Equipment and supplies—Testing. 2. Respirators—Testing. 3. Oxygen. I. Kyriazi, Nicholas. II. Series: Report of investigations (United States. Bureau of Mines) ; 8839.

TN23.U43 [TN297] 622s [622'.8] 83-18972

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	lb	pound
cm	centimeter	L/min	liter per minute
ft	foot	m	meter
ft/s	foot per second	mm	millimeter
g	acceleration of gravity	mph	mile per hour
h	hour	min	minute
Hz	hertz	pct	percent
kg	kilogram	s	second
L	liter	$\dot{V}_{O_2}$	volume of O_2 per minute

LABORATORY TESTING OF COMPRESSED-OXYGEN SELF-RESCUERS FOR RUGGEDNESS AND RELIABILITY

By Nicholas Kyriazi,[1] John Kovac,[2] Wayne Duerr,[3] and John Shubilla[4]

ABSTRACT

The Bureau of Mines subjected three commercial compressed-oxygen self-contained self-rescuers to a series of laboratory treatments designed to simulate various environmental conditions in underground coal mines. The environmental treatments consisted of extremes of temperature and of shock and vibration. The tests were designed to predict the ability of the self-rescuers to withstand those environmental stresses without causing a decrease in wearer protection. A critical concern was internal damage to an apparatus that would cause it to malfunction or seriously degrade its performance without any obvious external signs.

The Bureau has previously tested chemical oxygen self-contained self-rescuers in a similar research program. Although the three compressed-oxygen units are not as sturdy as the chemical oxygen self-rescuers tested previously, they performed reliably after treatments on treadmill tests with human subjects and on machine tests using a breathing and metabolic simulator. Serious damage was caused by both the heat treatment of 71° C (venting of the O_2 bottle in most cases), and in the shock treatment (breaking open of the case and dislodging of the components). When physical damage is obvious, a complete refurbishing of the damaged self-rescuer is recommended.

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[2] Supervisory mechanical engineer.
[3] General biological scientist.
[4] Engineering technician.
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INTRODUCTION

On June 21, 1981, coal mine operators were required to make a self-contained self-rescuer (SCSR) available to each person who goes into an underground coal mine in the United States. The regulations (30 CFR 75.1714) require that each person in an underground coal mine wear, carry, or have immediate access to an SCSR that provides an O_2 source. The SCSR will replace the filter self-rescuer (FSR) as primary escape equipment. FSR's protect only against low levels of CO.

Five models of SCSR units are commercially available (fig. 1); they can be characterized as follows:

Chemical oxygen breathing apparatus--Draeger OXY-SR 60B and MSA 60-min SSR.

Compressed oxygen breathing apparatus--CSE AU-9A1, Ocenco EBA 6.5, and PASS 700.

The chemical oxygen units underwent Bureau testing for mine-worthiness in a program begun in late 1980 (5).[5] When compressed oxygen self-rescuers became available, the Bureau included them in a similar program.

There is no implication that either the National Institute for Occupational Safety and Health (NIOSH, U.S. Department of Health and Human Services), the Mine Safety and Health Administration (MSHA, U.S. Department of Labor), or the manufacturers have conducted less than thorough testing of these devices. On the contrary, as the NIOSH-MSHA approval indicates, these SCSR's have successfully demonstrated the adequacy of their designs and manufacture, and they are considered to be dependable. However, the gradual deterioration that all equipment and materials undergo necessitates a study of environmental effects, which can help in the estimation of equipment lifetime. The rate of deterioration will certainly vary depending upon use: apparatus that are stored will fare better than those that are mounted on vibrating machinery or those that are worn or carried in and out of the mine everyday.

Actual experience will determine how well we have simulated in-mine use. The Bureau is currently planning a long-term field evaluation to obtain this experience. In the meantime, the laboratory tests offer the following benefits: (1) If the test is severe enough, one can directly observe the failure mode for a particular environmental assault on the equipment, and (2) the laboratory test results can be used as indicators of areas where attention should be focused during the field evaluations.

Of major concern are situations where the unit exhibits no external damage but where internal damage has occurred that markedly degrades the performance of the apparatus and possibly makes it inoperable. Obvious external damage which mandates removal from service and refurbishing is of no concern from a safety viewpoint but was reported for informational purposes.

ACKNOWLEDGMENTS

The authors would like to thank MSHA mine inspectors George G. Hazuza, Charles W. Pogue, and Timothy Thompson for their voluntary participation in the treadmill testing in this study.

DESCRIPTION OF SELF-RESCUERS

In basic terms, a closed-circuit, self-contained breathing apparatus of any type is composed of (1) a mouthpiece or facepiece and breathing hose, (2) an O_2 source, (3) a CO_2 absorbent, and (4) a breathing bag. All three of the compressed oxygen self-rescuers tested here contain these components but differ from each other in a number of ways.

[5]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

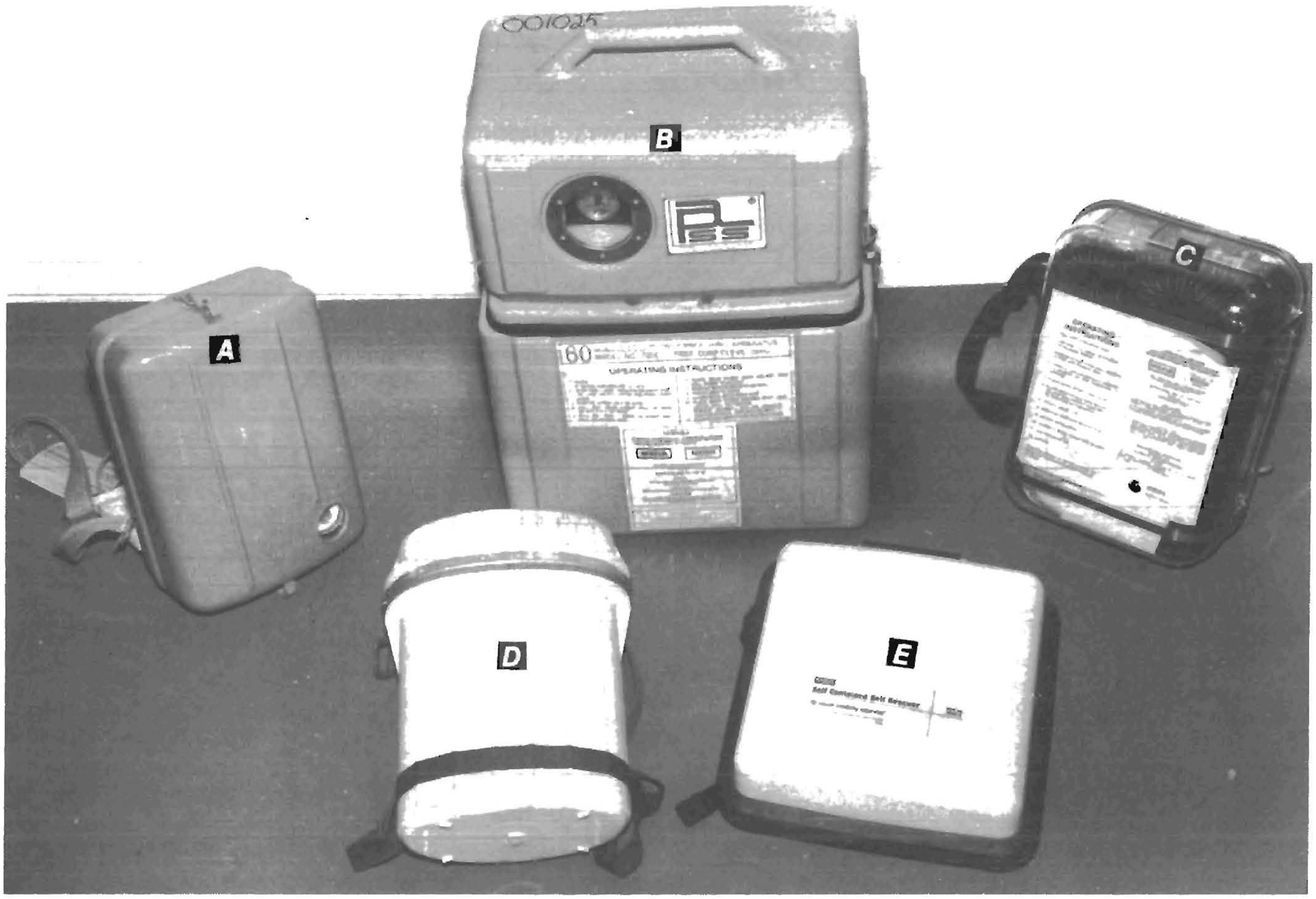

FIGURE 1. - Commercially available oxygen self-rescuers. *A*, CSE AU-9A1; *B*, PASS 700; *C*, Ocenco EBA 6.5; *D*, Draeger OXY-SR 60B; *E*, MSA 60-min SSR.

The CSE AU-9A1 is a pendulum-type apparatus that utilizes a bidirectional flow path with no check valves (fig. 2). It has a constant flow of O_2 of at least 1.5 L/min plus a demand valve for times when O_2 consumption is higher than that provided by the constant flow regulator. The steel oxygen bottle contains 130 L of O_2; the CO_2 absorbent is lithium hydroxide (LiOH), a solid chemical.

The Ocenco EBA 6.5 is a circle-type apparatus that provides for a unidirectional flow path with two check valves at the mouthpiece to regulate flow direction (fig. 3). It also has a constant flow of oxygen of at least 1.5 L/min plus a demand valve. The fiberglass-wrapped aluminum bottle contains 157 L of O_2; the CO_2 absorbent is LiOH.

The PASS 700 is a circle-type apparatus through the CO_2-absorbent bed and the breathing bag, but it has bidirectional flow in the breathing hose (fig. 4). The apparatus features an enclosed breathing bag, similar to rescue breathing apparatus. It provides a constant flow of oxygen of at least 3 L/min with no demand valve. The aluminum O_2 bottle contains 240 L of O_2; the CO_2 absorbent is soda lime, a solid chemical.

EXPERIMENTAL DESIGN AND TEST METHODS

Laboratory testing consisted of (1) environmentally treating the SCSR's and (2) measuring the effects of the treatments on operational performance. The treatments considered were temperature extremes (71° C for 48 h (7), and -45° C

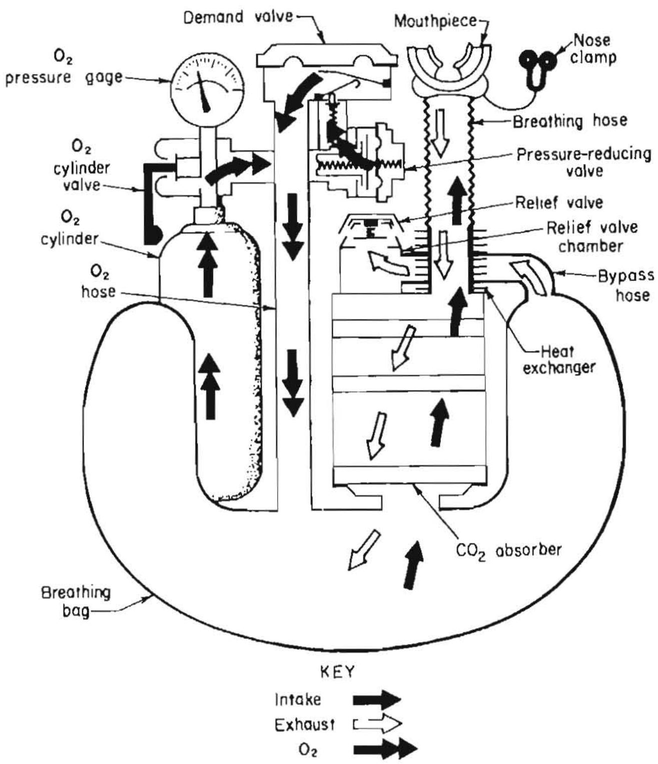

FIGURE 2. - CSE AU-9A1 schematic.

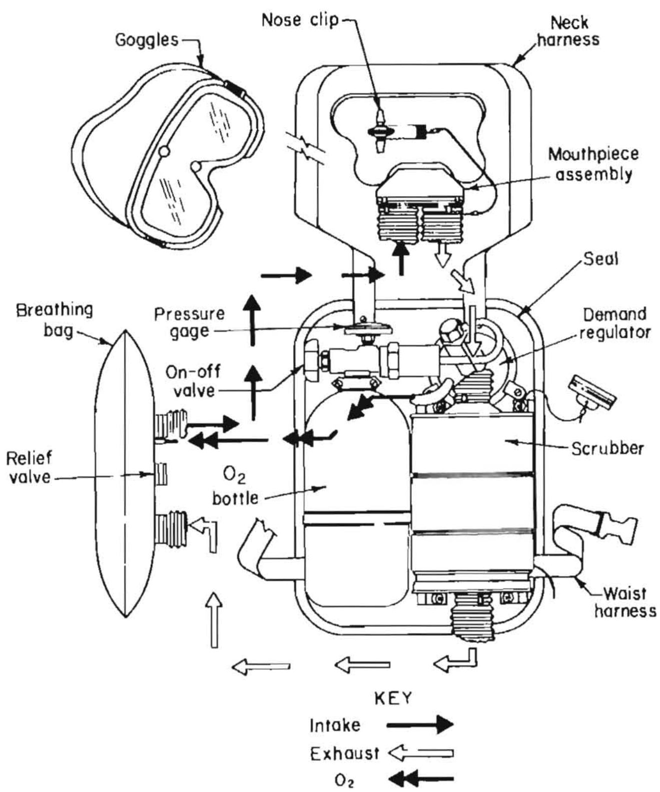

FIGURE 3. - Ocenco EBA 6.5 schematic.

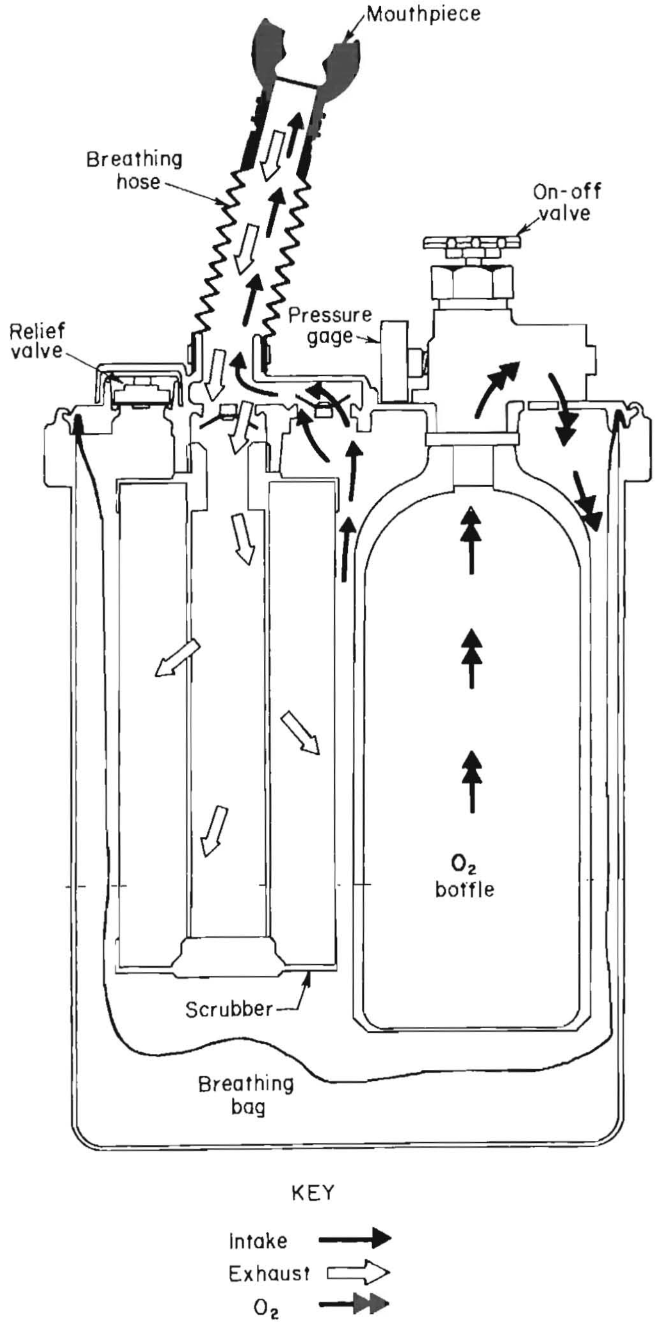

FIGURE 4. - PASS 700 schematic.

for 16 h) and shock and vibration. Both human-subject tests on a treadmill and machine tests using a breathing and metabolic simulator (BMS) were used to measure the effects of the environmental treatments on SCSR performance. Human-subject testing provided relevant human-factor information; the BMS tests provided a more reproducible method for quantifying the duration of respiratory protection and performance parameters.

Duration of respiratory protection is necessarily a function of workload during testing. The BMS, unlike a human subject, can be programmed to precisely reproduce a given demand (workload) from test to test.

An apparatus could fail in two ways: Measured parameters could exceed predefined limits, or the apparatus could cease to support life. In other words, even though an apparatus may be very hard to breathe through, for example, and may exceed the predefined limits, it could still be used in a life-or-death situation to escape from an irrespirable atmosphere.

TREADMILL TESTING

The human-subject test used was the treadmill equivalent of NIOSH man-test 4 for 60 min (table 1). The treadmill simulation of the test was based on the published studies of Kamon (4). Treadmill testing permitted continuous monitoring of CO_2, O_2, temperature, and pressure measured in the mouthpiece. At the end of 60 min, a constant speed of 6 mph was maintained until apparatus failure or test-subject exhaustion. Three human subjects (weighing 78, 91, and 96 kg) were used for the treadmill testing (fig. 5). Characteristics of untreated, new SCSR's were measured during human-subject and machine tests in order to establish the normal range of performance. These tests were used as controls for comparison with the treated SCSR's. Duration was defined by the termination time. Factors determining termination were (1) inhaled gas concentrations of CO_2 greater than 4.0 or of O_2 less than 15 pct, (2) inadequate gas volume, and (3) any subjective intolerable discomfort, such as breathing resistance or high temperature of inhaled gas or of apparatus surface.

BMS TESTING

A prototype BMS built by a private firm was used in the machine testing part of the study (fig. 6). The metabolic state used in the machine testing represented the average work rate that would be exhibited by a 50th percentile miner (87 kg) performing man-test 4 for 60 min (4).

TABLE 1. - NIOSH 1-hour man-test 4[1] and treadmill equivalent

Time, min	Activity	Treadmill equivalent
2	Sampling and reading	Stand.
2	Walk at 3 mph	Walk at 3 mph.
1	Climb vertical treadmill (1 ft/s)	Walk at 4.5 mph at 15 pct grade.
2	Walk at 3 mph	Walk at 3 mph.
5	Pull 45-lb weight to 5 ft (60 times in 5 min)	Walk at 4.2 mph.
3	Walk at 3 mph	Walk at 3 mph.
8	Carry 50-lb weight over overcast (4 times in 8 min).	Walk at 2.7 mph.
2	Sampling and reading	Stand.
4	Walk at 3 mph	Walk at 3 mph.
1	Run at 6 mph	Run at 6 mph.
9	Carry 50-lb weight over overcast (6 times in 9 min).	Walk at 3.6 mph.
3	Pull 45-lb weight to 5 ft (36 times in 3 min)	Walk at 4.2 mph.
2	Sampling and reading	Stand.
6	Walk at 3 mph	Walk at 3 mph.
5	Pull 45-lb weight to 5 ft (60 times in 5 min)	Walk at 4.2 mph.
3	Carry 45-lb weight and walk at 3 mph	Walk at 4.2 mph.
2	Sampling and reading	Stand.

[1] 30 CFR 11-H (8).

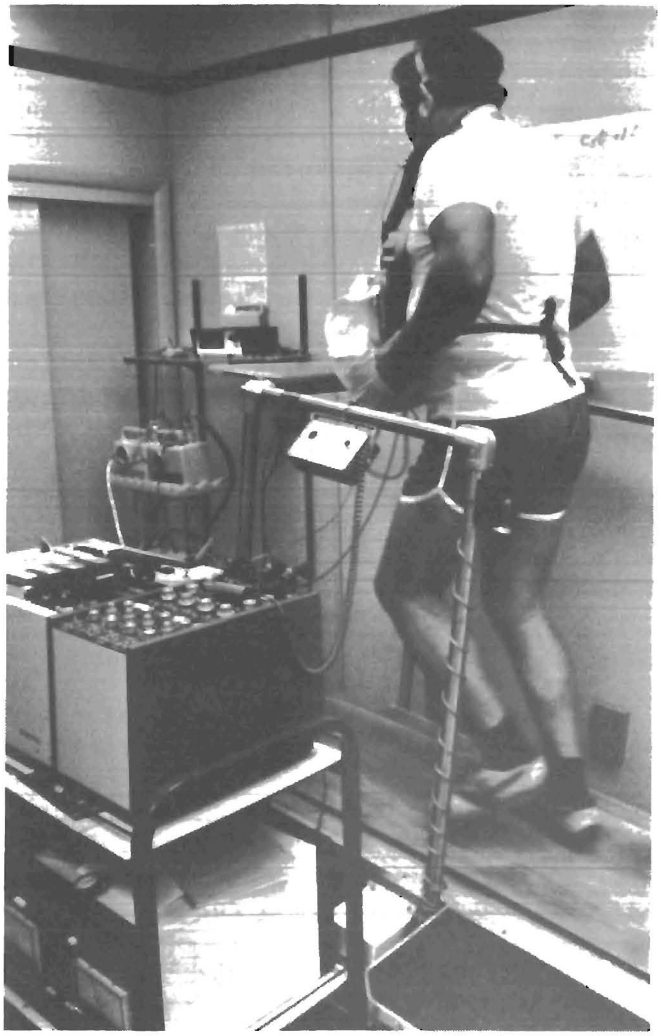

FIGURE 5. - Human-subject treadmill testing.

The physiological parameters at standard temperature and pressure, dry, follow:

V_{O_2}--Oxygen consumption--1.35 L/min.

V_{CO_2}--Carbon dioxide production--1.30 L/min.

V_E--Ventilation--31.89 L/min.

V_T--Tidal volume--1.21 liters per breath.

RF--Respiratory frequency--26.5 breaths per minute.

Termination factors were inhaled gas concentrations with more than 4 pct CO_2, or less than 15 pct O_2, or inadequate gas volume. In our study of chemical oxygen self-rescuers (5), values of 1.5 pct CO_2 and 21 pct O_2 were used. We now feel that those values are conservative and that the new values are more physiologically justified. As a result, the durations in this study should not be compared with those of the previous study. The focus should be on performance differences between treated and untreated apparatus. For a treatment to be considered to have had no impact on an apparatus, there must be no significant degradation in the various measured parameters compared with the control tests. A discussion of the various environmental treatments and methods follows.

SHOCK AND VIBRATION TREATMENT

There is no specific NIOSH or MSHA requirement in the Code of Federal Regulations for shock or vibration testing of breathing apparatus. Currently, however, NIOSH requires that self-rescuers survive 40 h of shock and vibration on a rotap sieve shaker. The SCSR's tested by the Bureau have successfully passed this test during NIOSH-MSHA approval testing.

The rotap machine subjects the SCSR's to vibration from rotary motion and an impact from hammer blow (2.5 impacts per second). The SCSR is rigidly mounted to avoid excessive acceleration levels and monitored to maintain acceleration levels to within 15 g's, peak to peak, for the entire test period. The test originates from experience with FSR's and simulates the extent of damage suffered in worst-case tests of harsh mining environments, as well as carrying and mounting on machines for 1 yr. The rotap test itself, however, does not simulate vibration spectra and types likely to be seen on mining machinery. To resolve this problem, we devised a composite test based on the reported vibration levels experienced on portable equipment, on underground mining machines (longwall, continuous) measured on the frame, and on underground and surface haulage vehicles (6).

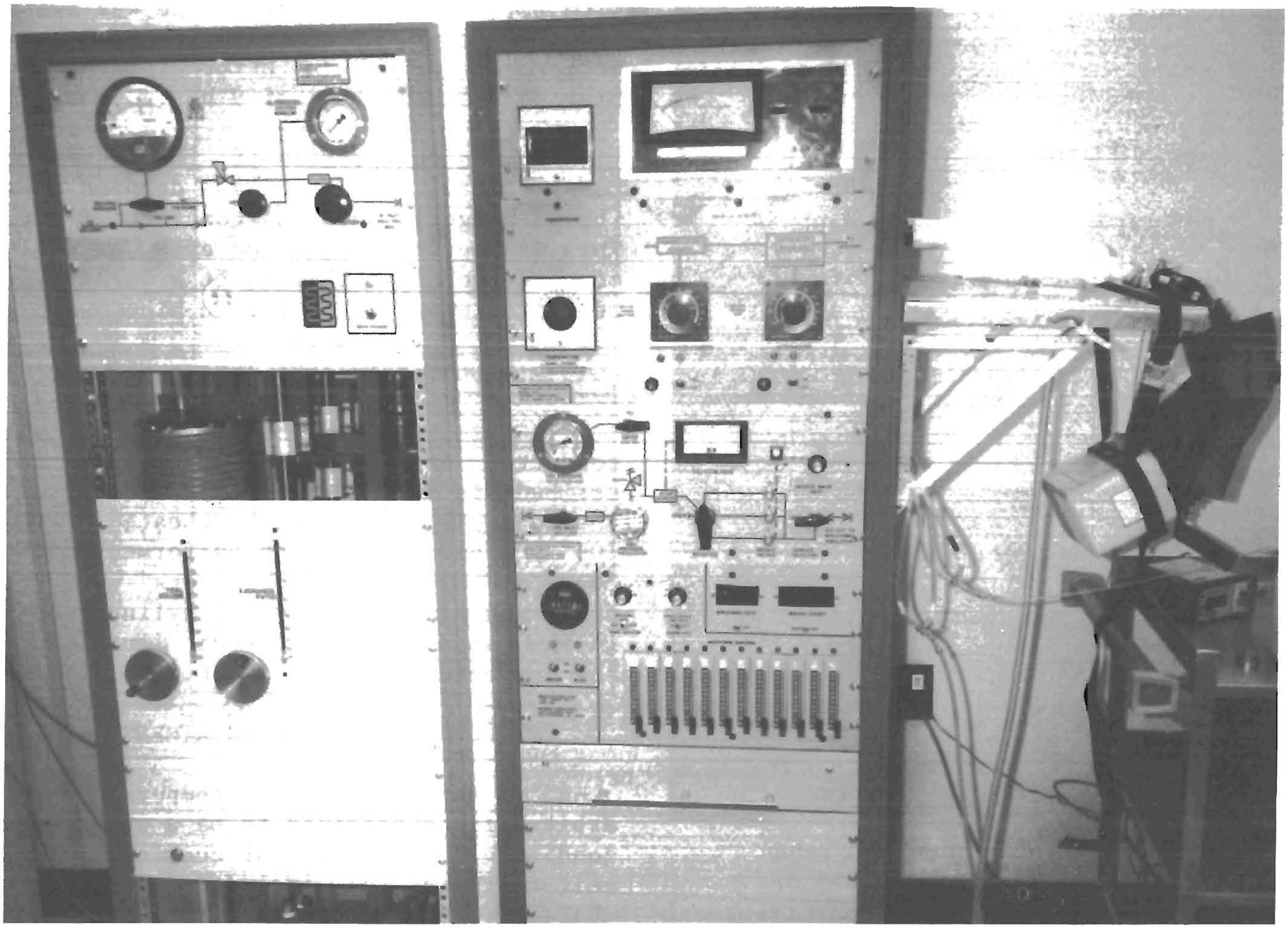

FIGURE 6. - Breathing and metabolic simulator (BMS).

A shaker table of the types used in military standard (MIL-STD) vibration tests was used in the vibration treatment with motion along the vertical (Z) axis only (fig. 7). The test conditions were as follows:

Frequency, Hz	Acceleration, g (±peak)
5- 92	2.5
92- 500	3.5
500-2,000	1.5

There is no consensus as to what constitutes an appropriate vibration treatment simulating the mining environment. MIL-STD-810B, which specifies a frequency range of 9 to 500 Hz at an acceleration of 4 g (±peak), has been recommended (1), but others recommend MIL-STD-810C (2), which specifies 1.5 g (±peak) from 5.5 to 30 Hz, increasing to 4.2 g (±peak) at 5 to 500 Hz, as being a more appropriate test.

One procedural variation in this study on the vibration tests was to vibrate the SCSR's loose rather than to strap them down as is usually done. We believe that, based on European experience (1), the self-rescuers will not be strapped tightly to machines, but will be simply placed in unpadded holders if not just thrown on the floor or other surface, unrestrained. We restricted their lateral motion (±1 cm) with pegs, which were screwed into the 1.3-cm aluminum table. Although at first inspection it would seem that the bouncing of the apparatus at lower frequencies would make individual treatments vastly different in terms of vibration and shock insult, we believe that the cumulative effect of the

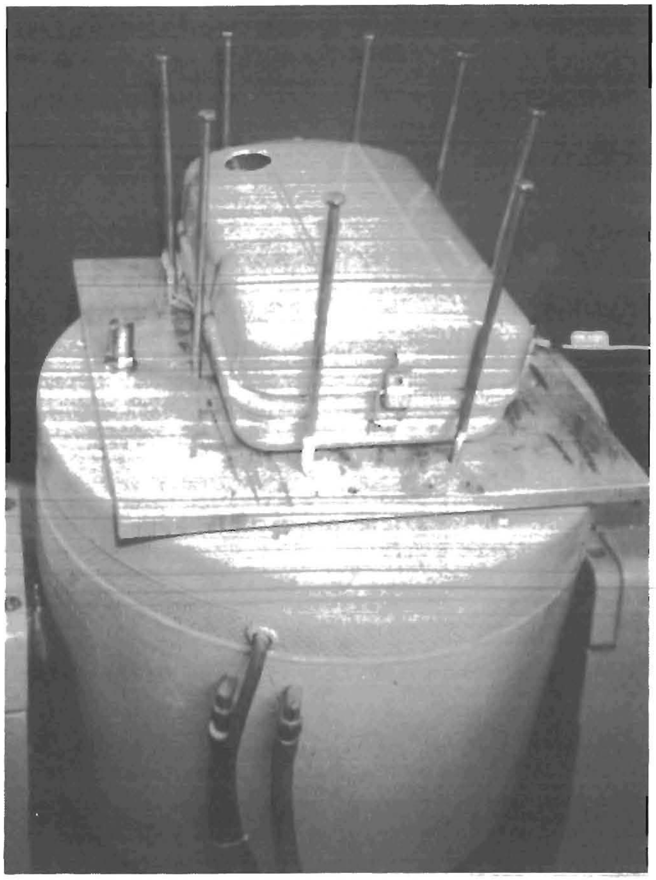

FIGURE 7. - Vibration table setup.

unclamped-apparatus vibration treatment over an entire test is similar and reproducible.

The control accelerometer was screw-mounted on the table as close to the SCSR as possible without any danger of contact with it. The frequency range was swept every 20 min for 3 h. This procedure was performed for each axis for a total vibration test duration of 9 h.

In the shock portion of the treatment (drop test), the SCSR was dropped 1 m (belt height) onto a concrete floor. This was performed once on each axis also. We consider this to be a worst-case realistic expectation for in-mine use.

HIGH-TEMPERATURE TREATMENT

71° C for 48 h.--This treatment was conducted according to procedures described in MIL-STD-810C (7) except that the convection oven was preheated. The 100° C treatment for 4 h performed on the chemical oxygen self-rescuers was not performed since any oxygen cylinder used in the apparatus would vent long before the apparatus reached 100° C.

LOW-TEMPERATURE TREATMENT

-45° C for 16 h.--This temperature was arbitrarily determined to be a worst-case condition. The study of chemical oxygen self-rescuers (5) included efforts to characterize performance of the KO_2 beds with regard to time required for chemical beds to reach approved operating temperatures. Similar efforts were not attempted with regard to the CO_2-absorption beds since previous work in this area has been published (3).

RESULTS AND DISCUSSION

Six sets of bar charts are presented showing how each of the three apparatus tested performed on each of the treatments (baseline, 71° C, -45° C, and shock and vibration) with regard to duration, inhaled temperature, percent O_2 and CO_2, and inhalation and exhalation pressure (breathing resistance) (figs. 8-13). These bar charts present data from the tests on the BMS and the treadmill separately, since the human-subject testing did not lend itself to direct comparison in the categories of inhaled gas concentrations and duration. This is because in the treadmill tests, gas was measured at the mouthpiece, and only peaks were measured. In the BMS tests, average inhaled gas concentration was measured. With regard to duration, in most cases, the human subjects could not continue long enough at 6 mph to achieve a termination point (high CO_2, low O_2, or empty O_2 bottle). The BMS tests were continued until the apparatus did reach a point of termination. Also, the 6-mph run was not attempted in some cases due to fatigue of the test subjects. Each bar on the chart represents the average of three tests. The shaded area represents 1 standard deviation around the mean of the three

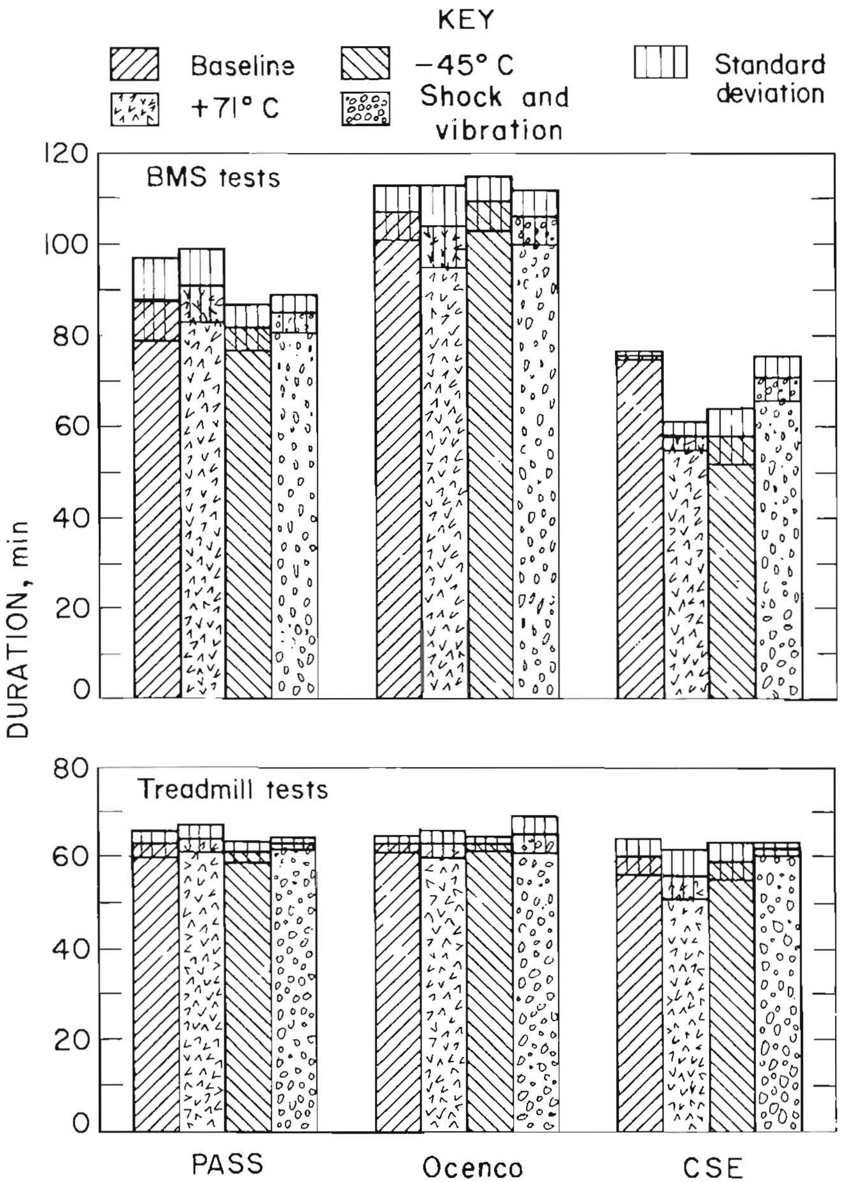

FIGURE 8. - Average duration and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

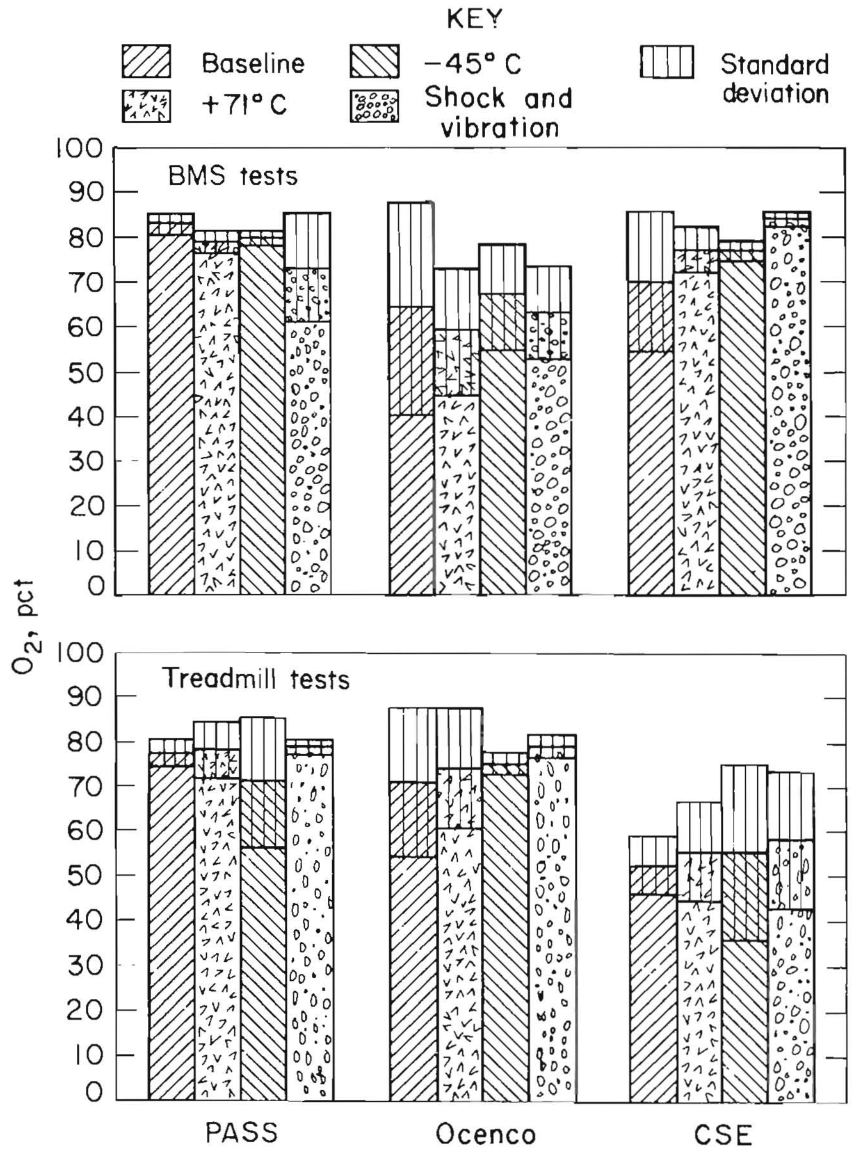

FIGURE 9. - Average O_2 concentration and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

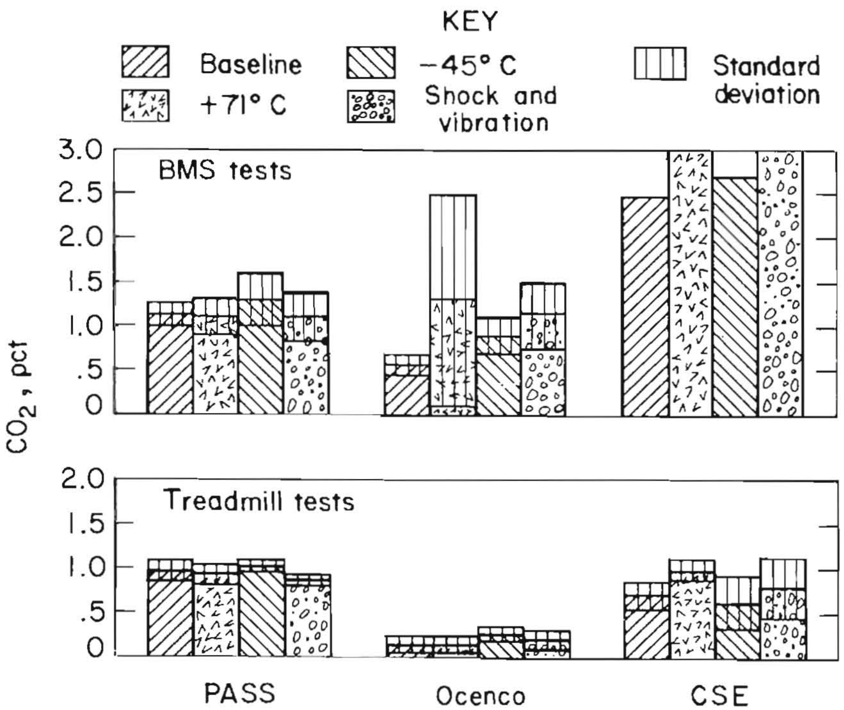

FIGURE 10. - Average CO_2 concentration and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

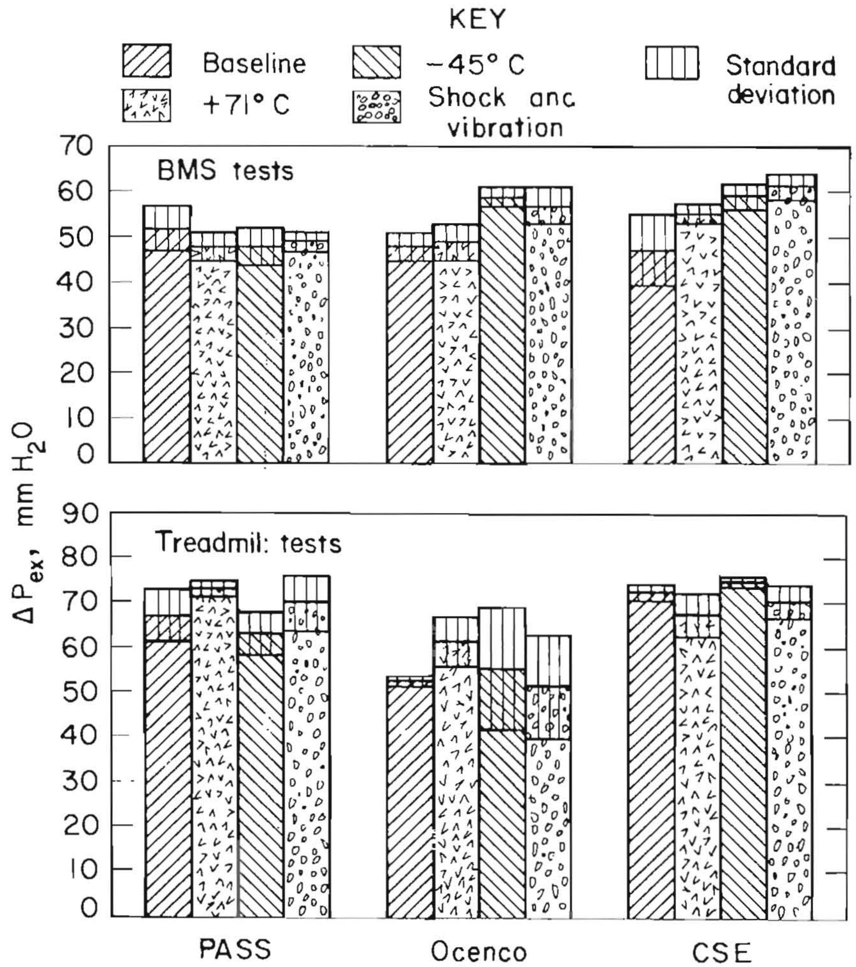

FIGURE 11. - Average exhalation resistance and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

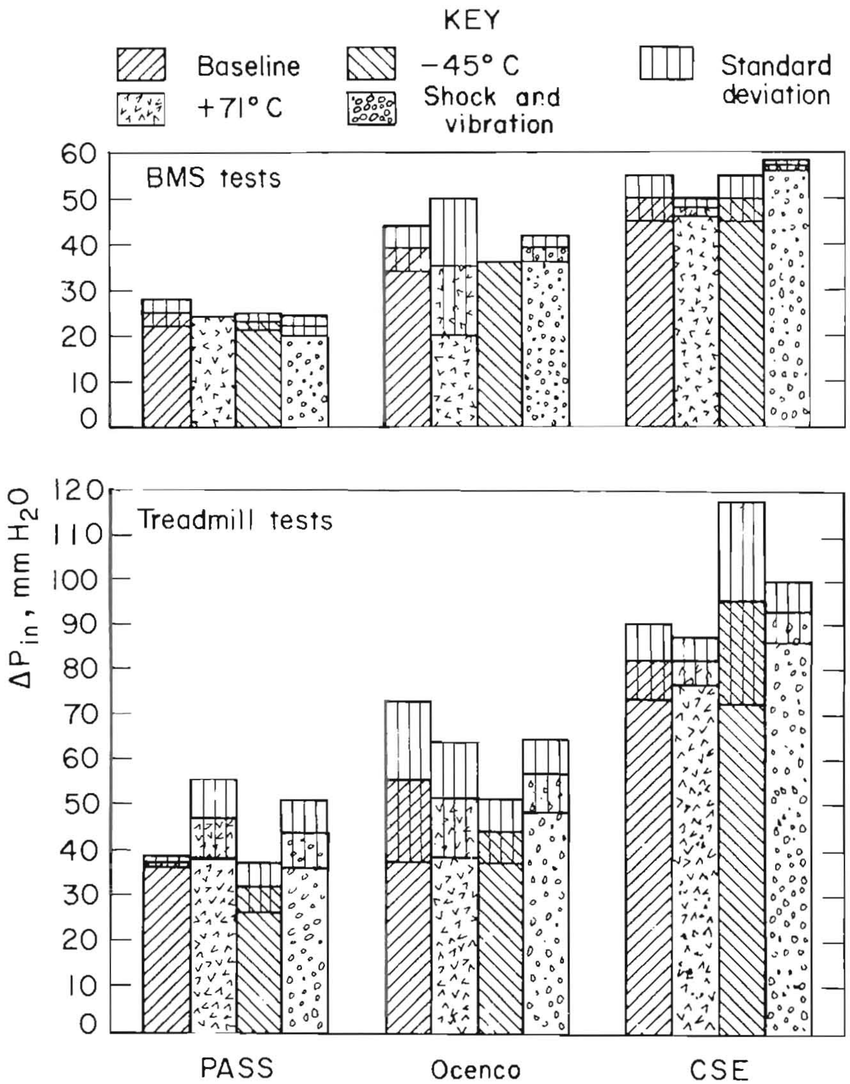

FIGURE 12. - Average inhalation resistance and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

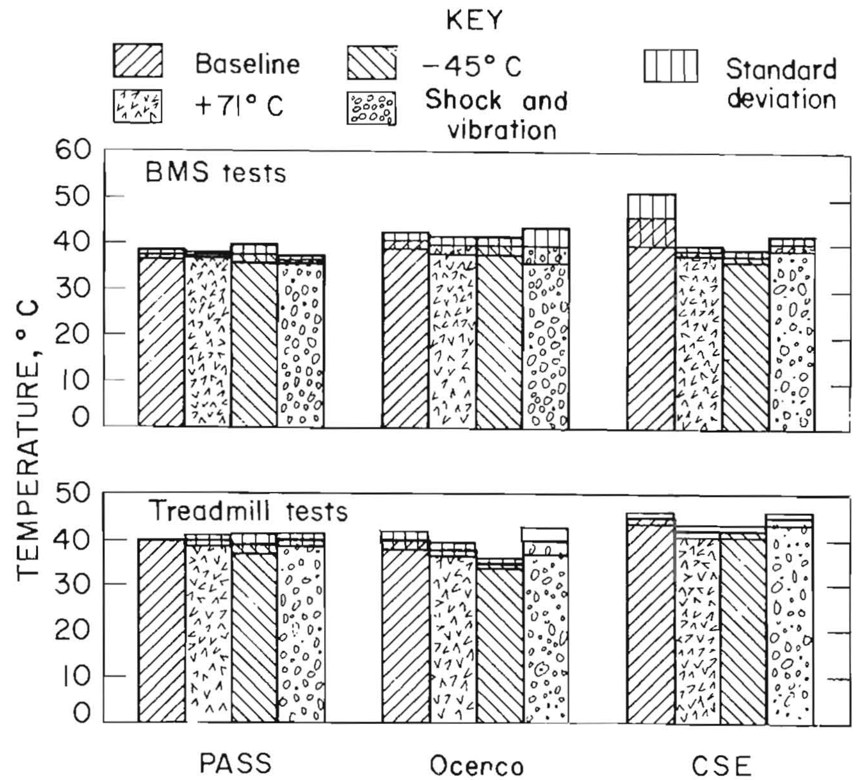

FIGURE 13. - Average inhalation temperature and standard deviation of three BMS tests and three treadmill tests for each treatment and type of self-rescuer.

tests. Standard deviation on the treadmill tests includes the variation between the test subjects. Only gross trends can be detected using such a small sample size.

Results tabulated from the BMS will not necessarily be equal, or even similar, to the results from the treadmill tests for a number of reasons. With regard to duration, the lack of similarity is because at the end of the 60-min treadmill test, the test subjects run at 6 mph, at which point the overall metabolic demand on the apparatus begins to increasingly diverge from that of the BMS. Thus, one would expect that the apparatus would expire sooner in the treadmill test. With regard to the other parameters measured, percent O_2 and CO_2, temperature, and breathing resistance, the possible differences between BMS testing and treadmill testing arise from the fact that the BMS puts a constant metabolic load on the apparatus, whereas man-test 4 contains a number of widely differing metabolic loads. What this means is that variations between the results of the BMS and the treadmill testing are not important in this study. The important differences, if any, are to be found between treated and untreated apparatus within the categories of either the BMS or the treadmill.

Tables 2 and 3 show treadmill and BMS test durations, respectively, and reasons for termination. Discussion of the results will be divided up by type of treatment including comments on both BMS and human-subject testing.

BASELINE (CONTROL) TESTS

During the treadmill testing of the CSE and Ocenco, the test subjects could not continue at various times during the test schedule. This occurred in four tests of the CSE (three baseline and one shock and vibration), due to reported high breathing resistance, and complaints of "not getting enough air." It occurred twice in the Ocenco tests (both times in the vibrated and dropped units) due to difficulty in operating the demand valve. There were consistent complaints about effort required to operate the Ocenco demand valve in all tests. In most instances, however, the test subjects were able to cope with it. The test subjects

TABLE 2. - Treadmill test durations

Apparatus and treatment	Test 1, 78-kg subject		Test 2, 91-kg subject		Test 3, 96-kg subject	
	Time, min	Reason for termination	Time, min	Reason for termination	Time, min	Reason for termination
CSE:						
Baseline......	63	Tired........	62	High CO_2......	56	High CO_2.
71° C.........	54	High CO_2.....	61	...do.........	52	Do.
-45° C........	10	Low O_2.......	62	...do.........	56	Do.
Shock and vibration.	62	Tired........	63	...do.........	61	Do.
Ocenco:						
Baseline......	63	Tired........	65	Tired.........	62	Tired.
71° C.........	63	...do........	67	...do.........	63	Do.
-45° C........	63	...do........	65	...do.........	62	Do.
Shock and vibration.	63	...do........	69	...do.........	63	Do.
PASS:						
Baseline......	64	Tired........	65	Bag bottoming.	60	Tired.
71° C.........	64	High CO_2.....	66	Bag bottoming. and high CO_2.	61	Do.
-45° C........	64	Tired........	60	Tired.........	60	Do.
Shock and vibration.	64	...do........	64	...do.........	62	High CO_2.

TABLE 3. - BMS test durations

Apparatus and treatment	Test 1		Test 2		Test 3	
	Time, min	Reason for termination	Time, min	Reason for termination	Time, min	Reason for termination
CSE:						
Baseline...........	76	High CO_2....	75	High CO_2....	74	High CO_2.
71° C..............	55	...do.......	60	...do.......	60	Do.
-45° C.............	56	...do.......	52	...do.......	65	Do.
Shock and vibration	73	...do.......	75	...do.......	65	Empty bottle.
Ocenco:						
Baseline...........	111	Empty bottle	108	Empty bottle	99	Do.
71° C..............	115	...do.......	100	...do.......	98	Do.
-45° C.............	116	...do.......	105	...do.......	106	Do.
Shock and vibration	111	...do.......	100	...do.......	108	Do.
PASS:						
Baseline...........	79	...do.......	89	...do.......	97	Do.
71° C..............	82	...do.......	93	...do.......	97	Do.
-45° C.............	77	...do.......	86	...do.......	84	Do.
Shock and vibration	88	...do.......	82	...do.......	85	Do.

were mine inspectors and rescue team members experienced with rescue breathing apparatus although they were not appreciably experienced with these particular apparatus. It should be pointed out that the rigid test schedule did not permit slowing down, as one would ordinarily do in any normal situation where breathing difficulties might be encountered. There were no cases of intermittent test stoppages with the PASS self-rescuer. This may be due to the apparatus itself or its testing placement after all the other tests with the CSE and the Ocenco had been completed when the test subjects were accustomed to resistance breathing. Human-subject testing is a very subjective method of apparatus appraisal, as might be expected.

Two PASS tests were terminated at 65 and 66 min, after 5 and 6 min of running at 6 mph, respectively, due to bottoming of the bag. This indicates that the test subject's $\dot{V}_{O_2}$ was greater than the constant flow rate. In two out of three CSE baseline tests, high CO_2 was the cause for test termination. These are cases where the user is limited by the capabilities of the apparatus. Among rescue team members, this is a recognized and accepted possibility. The resolution of this problem is user recognition: one merely slows down when one senses the limits of the apparatus being approached.

SHOCK AND VIBRATION TREATMENT

The shock and vibration treatment had minor effects on the Ocenco and CSE units. In the BMS tests, the CSE apparatus showed a slight increase in breathing resistance on both inhalation and exhalation. The vibration treatment may have powdered some of the LiOH, thus inhibiting ease of flow (figs. 11-12). Increased breathing resistance was not encountered in the treadmill tests, and no complaints were voiced. One of the test subjects, did, however, cough at the beginning of a test, which may have been caused by some LiOH escaping the filtering system. No other coughing occurred during any of the other CSE tests.

The needle of the oxygen pressure gage broke off on one CSE unit during the vibration treatment. Another CSE broke open and spilled its components in a drop test. In another drop test, a CSE unit vented its oxygen charge. All of these involved obvious damage, which is of no concern in this study.

The Ocenco apparatus showed nothing startling in the BMS tests. In the human-subject tests, however, one person coughed at the beginning of the test, possibly due to LiOH powder in the system. Also, two of the test subjects stopped in the middle of the test complaining of being tired due to high breathing resistance. This happened in no other tests of the Ocenco apparatus. In a real-life situation, a person would merely slow down if breathing resistance were too high.

In one drop test, an Ocenco unit opened at one end of the case, breaking the seal. The metal closure straps remained intact.

The PASS apparatus showed no apparent effects of the shock and vibration treatment. This is probably due to its oversize case with thick foam padding.

HIGH-TEMPERATURE TREATMENT

Venting of the O_2 bottles was a problem with all of the apparatus. Five of six heated CSE units vented their O_2 through the burst disc. All seven of the heated Ocenco units vented, and four of the seven PASS units vented. This caused no undue concern since this condition was easily visible and could be detected upon inspection (an O_2 reading of zero or a blown-open case). Vented CSE units were quite obvious with the two halves of the case coming open, shearing the enclosure latch rivets off in the process. Venting in the Ocenco units blew out the sealing gasket on the ends of the case and, in some cases, the cloth neck and waist straps, too. The two halves of the plastic case remained together, however. The PASS units showed no obvious signs other than the gage registering empty. One PASS unit that vented could not hold a charge of O_2 even after the burst disc was replaced. The manufacturer has suggested that the O_2 gage may have suffered damage during the heat treatment and may be the source of the leak. Concerned that such apparatus might be refilled without further inspection, the investigators refilled or replaced the O_2 bottles and ran the units anyway in order to determine if any damage had been inflicted that was not as easily visible as a vented O_2 bottle. The only effect noted was a possible decrease in scrubber efficiency in the CSE units, which was indicated by a 24-pct reduction in duration in the three BMS tests, with termination due to high CO_2. We discussed this problem with the manufacturer of the LiOH used by CSE and Ocenco. Although the manufacturer was not surprised at the findings, it was unable to offer a positive explanation as to what actually happened to the chemical. It was suggested that maybe the heat drove off the moisture in the chemical. It is known that the percentage of water in the LiOH and the breathing loop can dramatically affect performance, but it is not known why this is so. In the treadmill tests, a slight effect was also noted. The Ocenco unit, having a larger scrubber bed, would be less likely to show this effect. The average percent CO_2 level in the Ocenco units in the BMS tests, however, was slightly higher in the heated units. The PASS unit uses soda lime, rather than LiOH. Tests using two of the three PASS units were terminated due to high CO_2; the third test subject ran for only 1 min at 6 mph before tiring.

LOW-TEMPERATURE TREATMENT

The low-temperature treatment seems to affect CSE units. The durations for the cold-treated units in the BMS tests were decreased as they were for the heated units. In one treadmill test, a CSE unit exhibited low O_2 concentation and the test was terminated at 10 min. Although the O_2 flow rate was later measured at 1.41 L/min at ambient conditions, which is lower than NIOSH specifications, the low-temperature treatment was not believed to have caused this problem, since an untreated CSE had an O_2 flow rate of 1.44 L/min. This is not inherently dangerous. The low O_2 level was probably caused by an excessive amount of N_2 initially exhaled into the apparatus and made more significant by the low O_2 flow rate.

One of the cold-treated PASS units had a problem with its O_2 flow rate, causing O_2 concentration to fall over the first 5 min to about 16 pct. We then stopped the test and had the test subject remove the mouthpiece. After approximately 1.5 min, the O_2 level rose to 60 pct, and the unit was donned again. Over the next 5 min, O_2 fell to about 24 pct, then rose to normal levels for the remainder of the test. The O_2 flow rate was measured to be 3.07 L/min ATPD (ambient temperature and pressure, dry) after the test. PASS Inc. took the apparatus back to the plant and found no problem with the unit. The problem would seem to have rectified itself. In an actual emergency, an escaping miner would have experienced symptoms of low O_2 concentration and have been forced to slow down. It is not known if this problem was caused by the cold treatment.

GENERAL OBSERVATIONS

In 9 of 12 instances with the CSE, human-subject tests were terminated due to high levels of inhaled CO_2 (4 pct). This is another situation where the person is limited by the capabilities of the apparatus, which is usually acceptable. In the nine PASS tests where a 6-mph posttest run was attempted, two were terminated due to high CO_2, one was due to the bag bottoming, and one was due to both high CO_2 and bag bottoming. The other five were ended due to the exhaustion of the test subject.

Two points need to be made here: First of all, termination occurred in all cases near the physical capacity of the human test subject. The import of this point is that the wearer has to seriously stress the unit to make it fail. Based on a review of past disaster situations, this would seldom occur. Second, as long as the wearer has some indication that the apparatus is nearing its limits, he or she can make a conscious decision to slow down. In the case of the Ocenco unit, the stiff demand valve would tire the wearer before the apparatus would reach its limits. With regard to the PASS unit, bag bottoming can be easily determined by the wearer. High CO_2 levels in the PASS and the CSE units would not be as obvious to the wearer. Slight symptoms of high CO_2 inhalation might be ignored; however, eventually physiological limitations would force the wearer to slow down. This is in the unlikely case that any miner could keep up such a pace, and that mining conditions would permit such an all-out effort.

It is believed that none of the apparatus were affected in their factory-set regulator flow rates by any of the treatments.

There was some concern that the apparatus would suffer some loosening of internal connections during the vibration and shock testing. In order to measure tightness of the breathing system, CSE provides a test stand that can pressurize the apparatus or pull a negative pressure on it; the time the apparatus can hold a certain pressure, positive or negative, is an indication of tightness and, consequently, how much protection is afforded from the hazardous environment. The CSE test stand is for field service of CSE units. Ocenco and PASS provide no such measurement of apparatus functional performance nor permit field service.

It is not known how the CSE system leak-test standard, which is equivalent to that of the Draeger BG-174A rescue breathing apparatus, correlates with overall protection from toxic environments or quantitative protection factors. This was not a problem in our case since only a relative measure of system tightness was required to measure and compare treated and untreated units. To meet the CSE standard, the apparatus breathing system must be pressurized to 70 mm H_2O, both positive and negative, and not decay to 60 mm in less than 60 sec. Future Bureau research will be undertaken to correlate this standard to that of the NIOSH isoamyl acetate test and to some indication of quantitative protection factors.

We were not able to determine if system leakage increased due to treatments on the Ocenco apparatus since pressure in the breathing system dropped so rapidly (approximately 4 sec in most cases) that accurate measurement was not possible.

Tightness measurements were performed on the CSE and PASS units. The PASS apparatus underwent no change in system tightness. The average time to rise from -70 to -60 mm H_2O was 17 sec. However, the investigators did notice a trend in the CSE apparatus. Using the CSE standard, failures increased from 15 pct of the baseline untreated units, 17 pct of the cold-treated units, 34 pct for the heat-treated units, to 50 pct of the vibrated and shocked units. This was not unexpected. The PASS units had the benefits of much padding, contributing to their large size, but the CSE units had no such protection. Industry experience has shown that whenever rescue breathing apparatus are transported, various parts must be tightened upon arrival at the final destination. Escape breathing apparatus would not be expected to be any different. It should be noted that the CSE apparatus that failed the leak test had drop times of just under 60 sec in all cases. Thus, the loosening that occurred did not decrease significantly the protection offered by the apparatus. Although the purpose of this testing program was to determine the effects of various simulated environmental conditions, some comparisons are unavoidable. Based on this system leak test, it would seem that the CSE units were the tightest units. As was mentioned, it is not known how this relates quantitatively to protection factors.

Some PASS units were defective. One unit had a relief valve stuck open; another was missing a check valve; and another could not hold an oxygen charge, as was previously mentioned. The latter problem was obvious and not viewed as serious. The other two constitute cause for alarm since both apparatus could not have supported life for very long: the stuck valve would cause inhalation of external air, and the lack of a check valve would allow inhalation of exhaled air. Better quality control seems to be the remedy for these types of problems. According to PASS Inc., these quality control problems have been corrected.

CONCLUSIONS

This investigation found that confidence can be placed in a compressed-oxygen self-rescuer that appears to be functional and passes its inspection criteria. The self-rescuers studied are expected to suffer slight degradation due to exposure to the mining environment. In most instances, the damage suffered is very obvious (venting of the oxygen bottles; breaking open or denting of the cases) and of no serious concern. Such obvious damage would necessitate renovation of the entire apparatus. Where damage is less obvious (early CO_2 breakthrough), physiological limitations will prevent injury to an escaping miner.

It has been shown that the apparatus studied will limit activity in some cases of high physical stress. High breathing resistance and CO_2 concentration may force a wearer to slow his or her pace. A wearer could overbreathe a strictly constant-flow-type apparatus. As shown here, the damage inflicted by the environment to the apparatus may further limit physical activity. The training programs should alert the trainees about the limitations of their particular apparatus (CSE--high CO_2; Ocenco--extreme pressure required to activate demand valve; PASS--high CO_2 and bag bottoming).

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☆U.S. GOVERNMENT PRINTING OFFICE: 1983-705-020/99

INT.-BU.OF MINES,PGH.,PA. 27274