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REPORT OF INVESTIGATIONS/1994

Self-Contained Self-Rescuer Field Evaluation: Fourth-Phase Results

By Nicholas Kyriazi and John P. Shubilla

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

U.S. Department of the Interior
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	L/min	liter per minute
h	hour	min	minute
kg	kilogram	mm H_2O	millimeter of water (pressure)
L	liter	pct	percent

SELF-CONTAINED SELF-RESCUER FIELD EVALUATION: FOURTH-PHASE RESULTS

By Nicholas Kyriazi[1] and John P. Shubilla[2]

ABSTRACT

A joint effort by the U.S. Bureau of Mines (USBM) and the U.S. Mine Safety and Health Administration (MSHA) was undertaken to determine how well self-contained self-rescuers (SCSR's), deployed in accordance with Federal regulations (30 CFR 75.1714), held up in the underground environment with regard to both physical damage and aging. This report presents findings regarding laboratory-tested SCSR's in the fourth phase of testing from 1989 to 1993. The SCSR's were tested on human subjects and on a breathing and metabolic simulator (BMS). These results indicate that most of the apparatus, if they pass their inspection criteria, perform as expected except units with manufacturing defects. However, when the apparatus are carried in and out of the mine daily and stored at the working section, they may suffer abuse. Physical signs of abuse, unless extremely obvious, are frequently not detected by the miners or mine operators. In addition, some apparatus collected for this study had not been returned to the manufacturer in a recall effort for correction of a manufacturing defect. In both cases, the apparatus would have presented problems in emergency use. Recommendations include improved training in inspection procedures and better enforcement of recall notices.

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INTRODUCTION

On June 21, 1981, coal mine operators in the United States were required to make available to each underground coal miner a self-contained self-rescuer (SCSR). The regulations (30 CFR 75.1714) require that each person in an underground coal mine wear, carry, or have immediate access to a device that provides respiratory protection with an O_2 source for at least 1 h, as rated by the certifying agencies, the National Institute for Occupational Safety and Health (NIOSH) and MSHA. The USBM is involved with MSHA in a long-term, in-mine evaluation of SCSR's now deployed in underground coal mines. In this study, MSHA's responsibility is to identify the participating mines and to procure from those mines the SCSR's to be tested. The USBM replaces those SCSR's with new apparatus and tests the SCSR's in its laboratories. The objective of this long-term program is to evaluate the in-mine, operational durability of SCSR's. Of utmost concern is the successful performance of any SCSR that passes its manufacturer's inspection criteria. The USBM is interested only in apparatus that pass their inspection criteria. Such apparatus are relied upon to function successfully in an emergency. Apparatus that fail inspection criteria are expected to be removed from service.

ACKNOWLEDGMENTS

The authors thank Don Peiffer, physical scientist, Approval and Certification Center, Mine Safety and Health Administration, Triadelphia, WV for soliciting participation in this study amongst commercial underground coal mines.

EXPERIMENTAL PROCEDURE

This program involves testing approximately 100 SCSR's in each phase of the study. This report describes findings in the fourth phase of testing occurring from late 1989 through early 1993. Testing was conducted using a BMS and human subjects on a treadmill.

The SCSR's tested were manufactured by CSE Corp., Draegerwerk AG, Mine Safety Appliances Co., Inc. (MSA), and Ocenco, Inc. and were sampled according to estimated market share (table 1). The sampling was modified to ensure that at least 10 SCSR's from each manufacturer were sampled for each phase of the program, 90 pct using the BMS and 10 pct with human subjects.

Table 1.—Self-contained self-rescuers received for evaluation

Apparatus	Quantity inspected	Quantity tested
CSE AU-9A1	20	19
Draeger OXY-SR 60B	26	26
MSA 60-min SCSR	12	12
Ocenco EBA 6.5	45	45
Total	103	102

Some apparatus were not tested because of failure to pass inspection criteria or because of a manufacturing defect preventing testing.

The O_2 constant-flow rate is checked on compressed-O_2 apparatus; the NIOSH-required flow is 1.5 L/min at ambient temperature and pressure, dry (ATPD).

All apparatus are checked for leak-tightness after opening. The leak test used is that recommended for the CSE AU-9A1 by the manufacturer; this test is identical to the one required by Draeger for the BG-174 rescue breathing apparatus. The test is performed to determine the leak-tightness of the breathing circuit; i.e., how well the apparatus isolates the user from the assumed-toxic environment. Passing the test is not a requirement of the regulations. The test was required by CSE to be performed by the user after field refurbishment of the AU-9A1; however, field service is no longer authorized.

MSHA selected the participating mines with regard to type of mining operation, coalbed height, and SCSR deployment mode to obtain a representative cross section of U.S. mines.

The BMS test consisted of the average metabolic work rate exhibited by the 50th-percentile miner weighing 87 kg while performing the 1-h man test 4 from 30 CFR 11. The metabolic workload (volumes at standard pressure and temperature, dry (STPD)) is given in table 2. In the treadmill testing, the subjects walked at whatever speed and grade resulted in an O_2 consumption rate of 1.35 L/min (STPD). The other parameters of the

workload cannot be controlled in human test subjects, but are listed in table 3, all volumes at STPD.

Table 2.—BMS metabolic workload

O_2 consumption rate	L/min	1.35
CO_2 production rate	L/min	1.10
Ventilation rate	L/min	30.0
Tidal volume	L per breath	1.68
Respiratory frequency	breaths per min	17.9
Peak respiratory flow rate:		
Inhalation	L/min	89
Exhalation	L/min	71

Table 3.—Human subject workloads in treadmill tests

Subject	$\dot{V}CO_2$, L/min	$\dot{V}_e$, L/min	RF, breaths per min
A	1.20	35	25
B	1.25	26	25
C	1.35	25	10

RF Respiratory frequency.

$\dot{V}CO_2$ CO_2 production rate.

$\dot{V}_e$ Ventilation rate.

The parameters monitored were inhaled levels of CO_2 and O_2, inhalation wet- and dry-bulb temperatures, and inhalation and exhalation breathing pressures in both the BMS and treadmill testing. In the BMS testing, however, average inhaled levels of gas concentration were measured as opposed to minimum values of CO_2 and maximum values of O_2 in the treadmill testing. Average inhaled gas levels include the effect of apparatus dead space, whereas minimum values of CO_2, for example, are only the lowest level of gas concentration during inhalation. The BMS measures average inhaled values by electronically summing all the CO_2 and O_2 of each inhalation cycle, weighted by the instantaneous flow rate. The BMS also measures minimum inhaled CO_2 levels. End-of-breath, dry- and wet-bulb temperatures, and peak inhalation and exhalation breathing pressures were measured.

Tests on the BMS were terminated upon exhaustion of the O_2 supply as indicated by large negative pressures coinciding with an empty breathing bag. Treadmill tests were terminated in the same manner or if inhaled minimum CO_2 levels reached 4 pct, maximum O_2 levels fell below 15 pct, at which points negative physiological symptoms begin to occur, or if the test subject stopped because of subjectively high breathing pressures or temperatures.

RESULTS AND DISCUSSION

Experience with each brand of apparatus is discussed separately. The values of the monitored parameters were averaged over the entire test duration and are presented graphically (figs. 1-4) for each apparatus by parameter. The values for deployed units tested on the BMS can be compared with the values for new units tested on the BMS, and to some extent, with deployed units tested on human subjects on a treadmill, which are plotted afterward. Because human subjects may differ from each other and from the BMS in terms of VCO_2, V_e, and respiratory frequency, all of which will affect apparatus duration as well as all of the monitored parameters, these tests cannot be considered necessarily equivalent to the BMS tests even though the O_2 consumption rate is the same. Missing data points are indicative of equipment malfunction or other anomaly that invalidated the data.

The Wilcoxon rank-sum test was performed for each monitored parameter to determine whether or not the deployed units behaved differently from new units. It tests the hypothesis that the two samples are from populations with the same mean. The values from both samples are ranked in ascending order of magnitude. If the sum of the ranks of the smaller sample (T) (in this case, new units) falls within the acceptable range for the given sample sizes, then there is not sufficient evidence at the specified probability level (P=0.05, two-sided) to say that the means of the two samples differ. The rank-sum test does not rely upon the assumptions that either the new- or deployed-unit data are normal distributions or that they have identical variances, as does the t-test for two populations of independent samples. One limitation of the Wilcoxon rank-sum test is that it does not distinguish between large and small differences in values. The results of the two-sided, P=0.05, Wilcoxon rank-sum tests are presented in table 4. The probability of T, the rank sum of the new units, falling outside the given range is 0.05 if the populations have the same mean.

Table 4.—Wilcoxon rank-sum test results

Apparatus	Duration		Av inhaled CO_2		Av inhaled O_2		Wet-bulb temp		Dry-bulb temp		Inhalation pressure		Exhalation pressure	
	Range	T	Range	T	Range	T	Range	T	Range	T	Range	T	Range	T
CSE	22-66	40	22-66	43	13-50	46	13-50	53	13-50	52	20-60	44	20-60	42
Draeger	16-68	43	16-68	66	16-68	34	15-63	43	16-68	23	16-68	43	16-68	39
MSA	16-44	34	16-44	26	16-44	34	15-41	45	16-44	41	16-44	19	16-44	41
Ocenco	15-60	22	14-58	32	15-60	40	14-58	16	14-58	34	14-58	37	14-58	36

T Sum of the ranks of the smaller sample (new units).

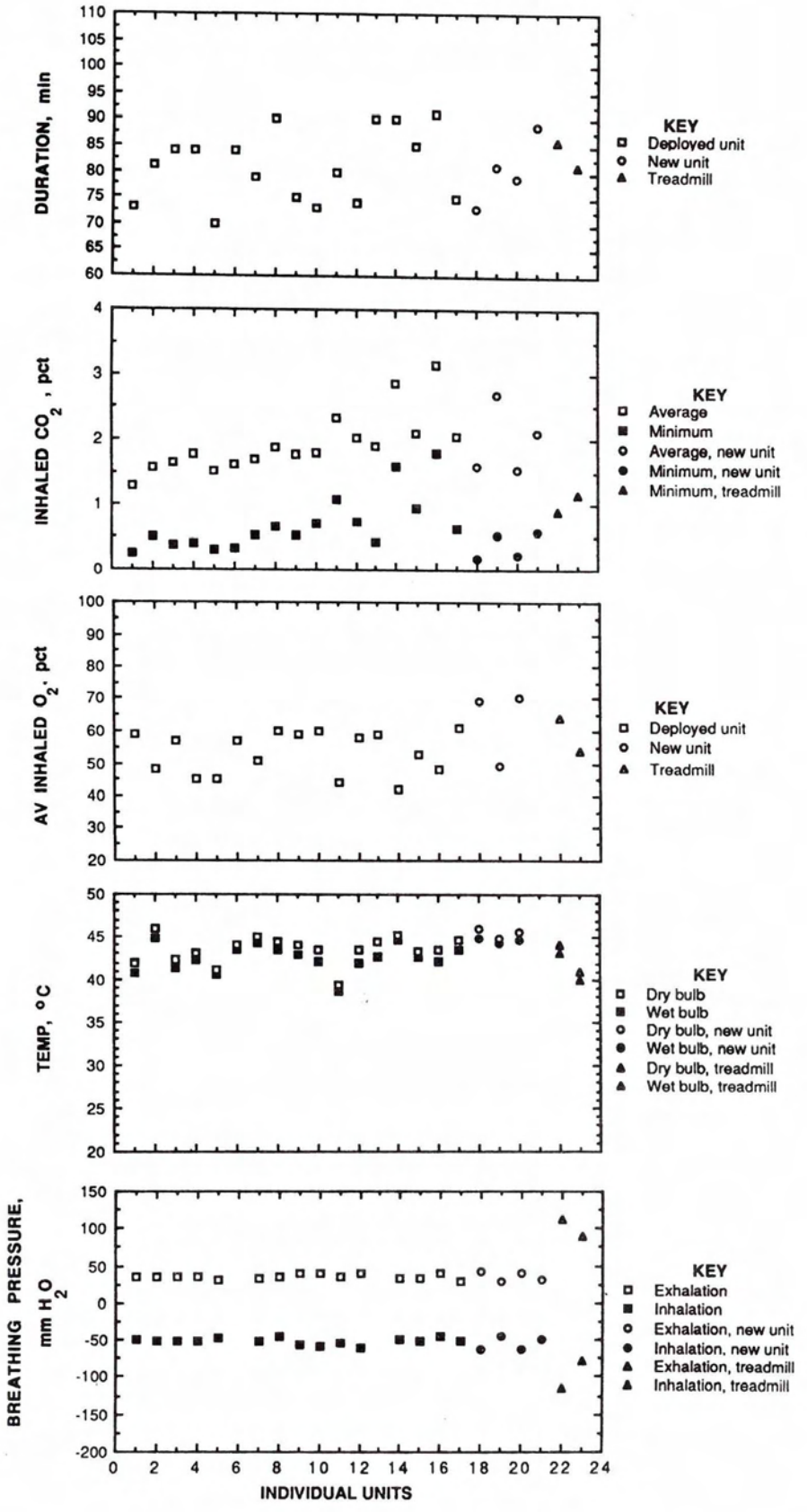

Figure 1.—CSE units.

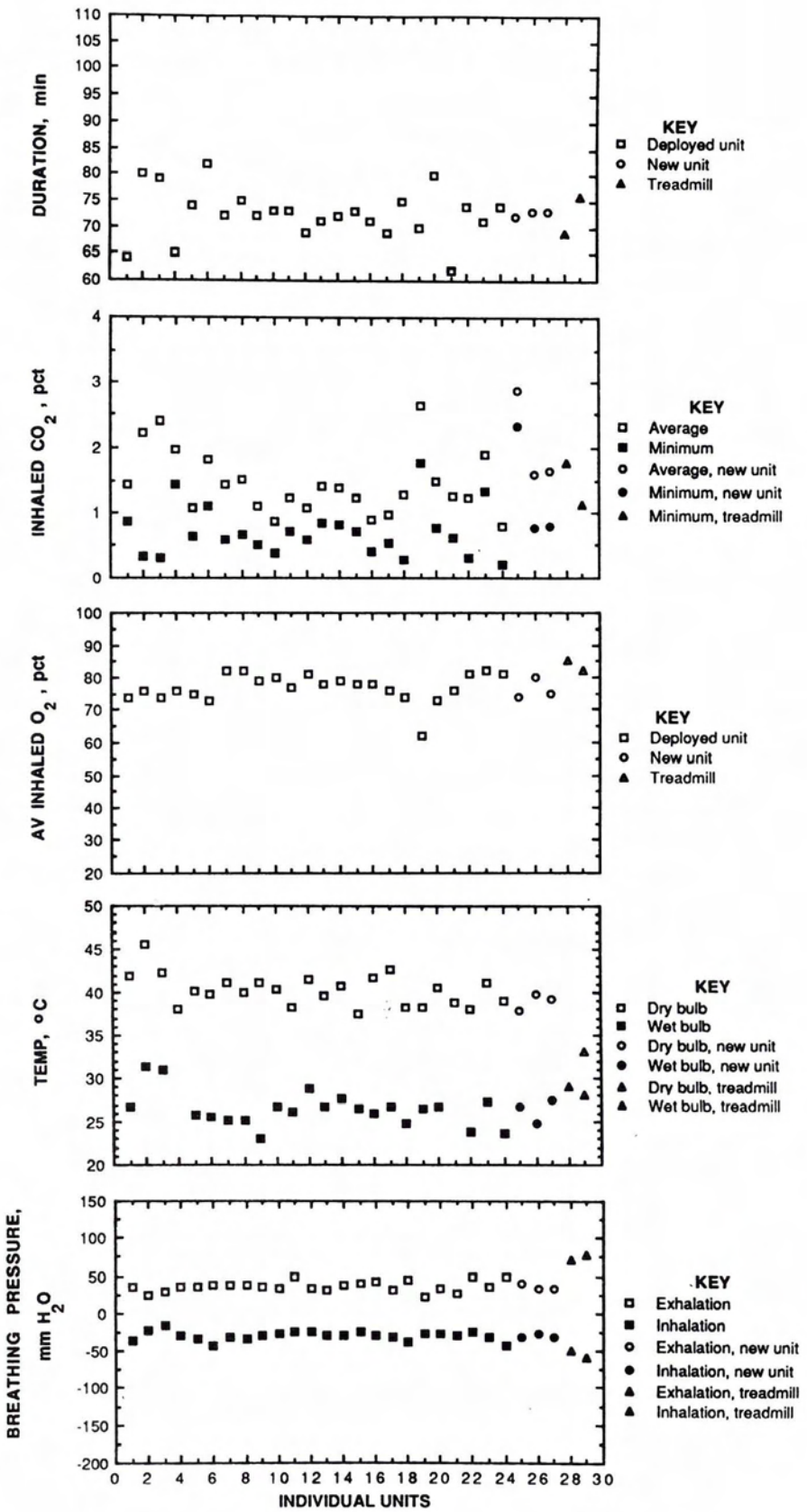

Figure 2.—Draeger units.

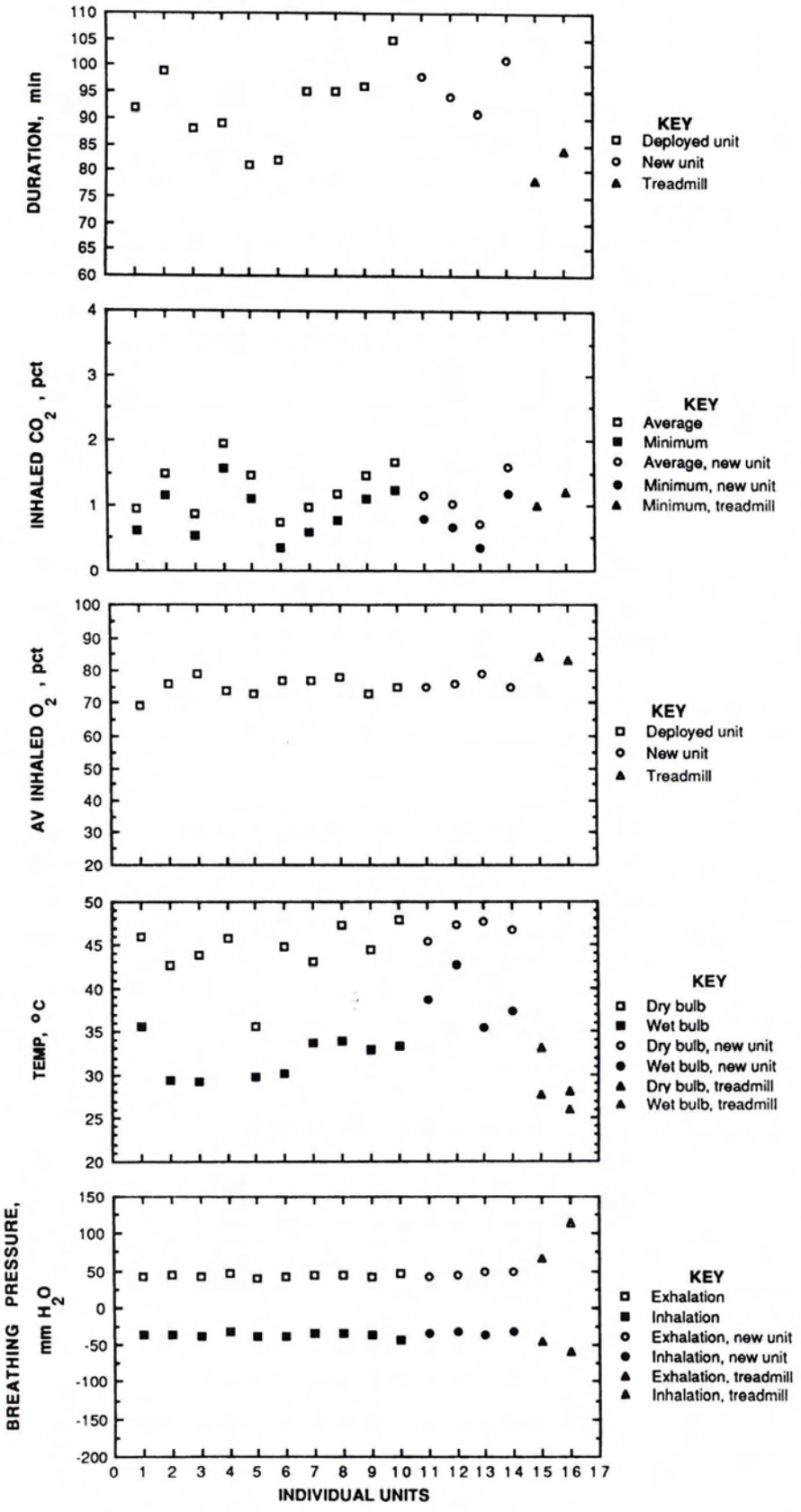

Figure 3.—MSA units.

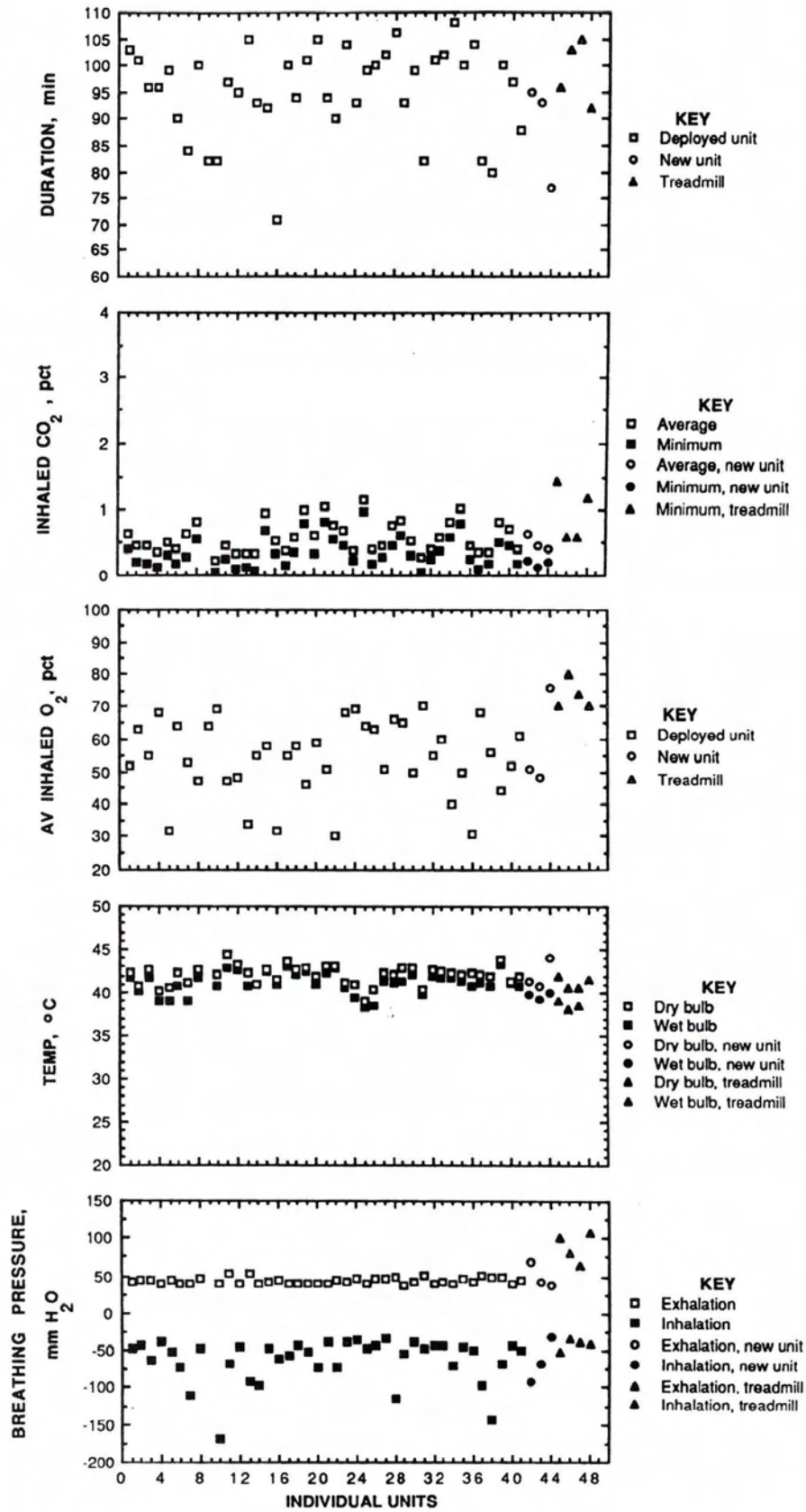

Figure 4.—Ocenco units.

CSE

Five of the twenty apparatus sampled were found to have their original, unmodified O_2 regulators. Because the original regulators have the potential to burst apart with great force upon opening of the cylinder valve, making the unit unusable and possibly injuring the user or persons nearby, the apparatus were recalled in 1986 to have their regulators modified. The regulator of one unit did burst upon opening prior to starting a BMS test. Normally, the damaged regulator would be replaced with a new one and then the unit tested. This was not done, however, since other components were damaged by the burst. The cylinder on the unit had been opened once before to check its constant flow rate with no problem, illustrating the random nature of the occurrence. The problem of end-users not complying with the manufacturer's request for recall was reported to MSHA.

The modified regulators of two other units malfunctioned without bursting, but vented large quantities of stored O_2 before being turned off. They functioned properly after reopening and were tested without further incident. Other than being frightening, the only negative impact is a loss of stored O_2 and consequently, some apparatus duration.

Eight of the apparatus failed the leak-tightness test. One apparatus had an empty O_2 cylinder. This unit was refilled and tested. Several units had loose or disconnected CO_2 canisters and O_2 cylinder straps. One unit had its relief valve disconnected from the breathing bag. The red seal was broken on the O_2 cylinder of one unit indicating that the valve had been opened and closed, although still registering full. The belt strap of one unit was caught in the case seal. All these occurrences imply that the units were either not refurbished properly or developed the problems over the time that they were deployed underground.

The Wilcoxon rank-sum tests for the wet- and dry-bulb temperatures showed higher values for new than deployed units. As can be seen from figure 1, however, the new-unit values are only slightly higher than the deployed values; if deployment causes the apparatus to run cooler, that is no cause for alarm. It has been found that the temperature of the laboratory and the use of the exhaust fan significantly affect the inhalation temperature of the apparatus being tested. The higher new-unit temperatures may be attributed to coincidentally high laboratory temperatures. Real or coincidental, the finding is of little concern for this study.

The higher breathing pressures in the human subject versus the BMS testing are directly related to higher ventilation rates by the human test subjects, possibly due to human reaction to super-ambient, average inhaled CO_2 levels. The BMS does not react to high CO_2 by increasing ventilation.

Six deployed units tested on the BMS and one unit tested on a human subject reached 4 pct CO_2 (breakthrough) before the O_2 supply was expended. The BMS tests were permitted to continue until the O_2 supply was expended while the treadmill test was terminated at that time. One new unit tested on the BMS also experienced CO_2 breakthrough. Table 5 illustrates the situation.

Table 5.—CSE CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
BMS:		
Deployed	87	90
	74	80
	70	90
	80	85
	73	75
	68	91
New	75	81
Human on treadmill:		
Deployed	86	86

BMS Breathing and metabolic simulator.

The second treadmill-tested unit was removed at 81 min after the subject complained of high breathing pressures, which reached +150 and -150 mm H_2O. The minimum inhaled CO_2 level at that time was 3.4 pct. Human reaction to high CO_2 is to increase ventilation rate. This results in higher breathing pressures that eventually limit ventilation rate, and, finally, O_2 consumption rate, which limits work rate.

DRAEGER

One unit, SN 282, in BMS testing, exhibited high average inhaled CO_2 levels with low levels of minimum inhaled CO_2. A large spread between average and minimum inhaled CO_2 is usually indicative of large dead space—breathing circuit volume containing exhaled air, uncleansed of CO_2, which will be rebreathed. Since this unit had a much higher spread than other units of this same model—a difference between average and minimum inhaled CO_2 of approximately 2.0 pct versus the usual 0.6 pct—the unit was inspected after testing. It was found that the exhalation check valve was stiff and brittle, preventing it from shutting during inhalation, thus, increasing the volume of dead space. This appears to be caused by aging of the check valve material, natural rubber. The inhalation check valves, made of silicon, were in good condition. A review of past test data revealed that another unit (SN 585) experienced this same wide spread between average and minimum inhaled CO_2, but had already been

disposed of before it could be inspected to confirm a brittle check valve.

This condition would affect a wearer increasingly as work rate and breath volume decrease making the dead space a larger fraction of breath volume. As this happened, average inhaled CO_2 would increase, causing most users to increase their breath volume in an attempt to dilute the CO_2. Some users are not as sensitive to CO_2 and would not increase their breath volume; they would experience higher CO_2 levels. This problem was reported to NIOSH and MSHA. Draeger was already replacing this check valve as part of a recall replacing the breathing hose so no further action was necessary. The breathing hose has been found in recent years to be taking a set in its folded position making it increasingly difficult to open for use.

Six of 25 units failed the leak-tightness test. One unit had a broken nose-clip clamp; it had not been sent back to the manufacturer in the recall program of 1985 for replacement of the clamps.

Two deployed units tested on the BMS and one unit tested on a human subject reached 4 pct CO_2 before the O_2 supply was expended. One of the two deployed BMS units, however, was tested in two sessions separated by 40 days, due to equipment problems. This delay may have resulted in degradation of the bed. One new unit tested on the BMS also experienced CO_2 breakthrough (see table 6).

Table 6.—Draeger CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
BMS:		
Deployed	55	65
	61	70
New	54	72
Human on treadmill:		
Deployed	69	69

BMS Breathing and metabolic simulator.

MSA

All the apparatus tested were carried by MSHA mine inspectors. Two of the 12 units sampled had dislocated shock mounts, presumably due to severe impact. These two were built in 1980 and were part of a group of apparatus sold to MSHA before the apparatus was produced commercially. The commercially available apparatus built later incorporated design changes intended to remedy this tendency. Two of the apparatus failed the leak test.

One of the apparatus with the dislocated shock mounts also experienced a sodium chlorate candle misfire. When it was started manually with multiple exhalations, a fine, white mist was visible coming back out through the mouthpiece. It is presumed that the mist was KO_2 since breathing it was extremely irritating. The unit was then run on the BMS without incident. A user would have needed to further wet down the breathing circuit with more breaths before it could have been worn. Since the defective filter that likely caused this incident is not found in commercially available units, and since MSHA has no more of this type of apparatus, no action was taken.

Wet-bulb temperatures for new units were significantly higher than deployed units, but dry-bulb temperatures were in line with each other (fig. 3). This means that the humidity was higher in the new units than the deployed units. The reason for this is unknown. A review of the data revealed no relation between the wet-bulb temperature and test date or serial number. There may be some physical cause for this phenomenon related to the KO_2 bed condition, but no similar phenomenon was observed in previous phases of this study. In any case, decreased humidity in the breathing air is no great impediment to escape.

Figure 3 shows also that the wet-bulb temperatures in the treadmill tests were slightly lower than in the BMS tests. The dry-bulb temperatures, however, were much lower, a phenomenon also seen in the Draeger tests (fig. 2). Both of these are chemical-O_2 units. In the compressed-O_2 units, the wet- and dry-bulb temperatures are similar for the treadmill and BMS tests. The reason for the difference is, at present, unknown; the BMS closely matches wet- and dry-bulb exhalation temperatures of human subjects breathing similar wet- and dry-bulb gas mixtures. This will be further explored by the USBM.

Five deployed units tested on the BMS reached 4 pct CO_2 before the O_2 supply was expended. Three new units tested on the BMS also experienced CO_2 breakthrough (see table 7).

Table 7.—MSA CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
BMS:		
Deployed	97	99
	82	89
	94	95
	89	96
	98	105
New	92	98
	91	94
	90	101

BMS Breathing and metabolic simulator.

OCENCO

One apparatus, SN 63886, had a low O_2 constant-flow rate (0.67 L/min ATPD instead of the NIOSH-required 1.5 L/min ATPD), and in the BMS test, exhibited low O_2 levels. After testing, closer inspection of the unit revealed a cracked demand valve regulator housing. This permitted some of the gas flow to leak out of the circuit to ambient, and since the O_2 supply rate was now lower than the consumption rate, the demand valve was activated. However, instead of drawing gas from the O_2 cylinder, ambient air was drawn into the circuit through the cracks, thus, lowering the O_2 level. In emergency use, the in-leakage of ambient air would have negatively affected the user. Even if the ambient air were not toxic or hypoxic, the in-leakage would have made the air in the breathing circuit go hypoxic, the extent depending upon the in-leakage rate of 79 pct N_2, ambient air. It is presumed that the demand valve regulator housing was damaged from impact to the outer case. The gas supply hose from the cylinder attaches to the housing in such a manner that it acts as a lever arm, extending outwards and nearly touching the inside of the case. It can crack the housing at its point of attachment if it is deflected by an impact of the case. This problem has been reported to NIOSH and MSHA.

None of the deployed apparatus passed the leak test, although new apparatus don't pass, either. In a short experiment, five of six units checked did pass this noncertification test when their relief valves were capped, implying backflow through the valves. The average leak rate exhibited by the apparatus at a moderate work rate is not believed to present a danger to the user, however.

Four units were found to have damage that was sufficient to require them to be removed from service. One had a crack in the clear, polycarbonate case; a second had its orange, U-channel, case seal pinched, a piece of loose orange rubber in the case, and a dented canister; a third had its U-channel case seal blown out of the case bottom; and the fourth had a small crack in its case and a visible, rusty canister rim. After opening, this unit was found to also have a dented canister and a broken cylinder neck clamp. All the units were able to be tested, however, and performed normally.

The high inhalation pressures exhibited by some of the apparatus on the BMS (fig. 4) were caused by activation of the demand valve, which is relatively stiff. When the demand valve is not required, the inhalation pressures are low, reflecting low system resistance.

Two deployed units tested on the BMS and one on a human subject reached 4 pct CO_2 before or at the time the O_2 supply was expended (see table 8).

Table 8.—Ocenco CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
BMS:		
Deployed	93	99
	96	100
Human on treadmill:		
Deployed	92	92

BMS Breathing and metabolic simulator.

CONCLUSIONS

The results of this study suggest that the large majority of SCSR's that pass their inspection criteria can be relied upon to provide a safe level of life support capability for mine escape purposes. Few problems have arisen involving subtle performance degradation due to the mining environment: the cracked demand valve-regulator housing on the Ocenco EBA 6.5 and possible loosening of internal component connections on the CSE AU-9A1. Some minor problems with materials have been noted due to age: the exhalation check valve and the breathing hose on the Draeger OXY-SR 60B.

Some SCSR's collected during the study were damaged by daily, in-mine use and should have been removed from service. The damage was generally apparent and visible and should have been detected if the SCSR's had been properly inspected. Improved training is recommended.

Problems were found with users not responding to manufacturer recalls. This may result in apparatus not functioning properly in an emergency as in the case of the bursting regulators on the CSE AU-9A1. Improved enforcement of manufacturer recalls is recommended.

The results of this continuing program provided the groundwork and justification for the recently implemented service life plans for SCSR's deployed in underground coal mines. These plans will improve the reliability of SCSR's.