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

Nicholas Kyriazi and John P. Shubilla

Pittsburgh Research Laboratory
National Institute for Occupational Safety and Health
Pittsburgh, PA, USA

Abstract

The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory, has undertaken a study to determine how well self-contained self-rescuers (SCSRs), deployed in accordance with Federal regulations (30 CFR 75.1714), hold up in the underground environment with regard to both physical damage and aging. This report presents findings regarding laboratory-tested SCSRs in the sixth phase of testing from mid-1996 to early 1998. The SCSRs were tested on human subjects and on a breathing and metabolic simulator. These results indicate that most of the apparatus, if they pass their inspection criteria, perform satisfactorily. However, the deployed CSE SR-100s exhibited significantly higher inhaled CO_2 levels than new units, as in the previous phase. This will cause higher ventilation rates in most users, which will, in turn, result in higher breathing pressures, possibly causing users to prematurely remove the apparatus. CSE Corp. has developed a noise test that can identify apparatus suffering from chemical-bed degradation causing the early CO_2 breakthrough. This test was added to the inspection criteria for the SR-100. In addition, several of the MSA Portal-Packs that passed their inspection criteria were found to have KO_2 dust in their mouthpieces. Further investigations by NIOSH and the Mine Safety and Health Administration confirmed these findings, which resulted in the decertification of the apparatus and their removal from service.

Unit of measure abbreviations used in this report.

breaths/min	breaths per minute	L/min	liter(s) per minute
hr	hour(s)	min	minute(s)
kg	kilogram(s)	mL/min	milliliter(s) per minute
L	liter(s)	mm H_2O	millimeter(s) of water (pressure)
L/breath	liter(s) per breath	ppm	parts per million

Introduction

On June 21, 1981, US coal mine operators 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 hr, as rated by the certifying agencies—the National Institute for Occupational Safety and Health (NIOSH) in Morgantown, WV, and the Mine Safety and Health Administration (MSHA). The NIOSH Pittsburgh Research Laboratory (PRL) is conducting a long-term evaluation of SCSRs deployed in underground coal mines. This work is in support of PRL's disaster prevention research program to improve safety for underground mine workers. PRL locates mines willing to participate in the study and trades deployed SCSRs for new ones. PRL then tests the deployed SCSRs. The objective of this long-term program is to evaluate the in-mine operational durability of deployed SCSRs. Of utmost concern is the successful performance of any SCSR that passes its inspection criteria. PRL is interested only in apparatus that pass their inspection criteria. Such apparatus must function successfully to enable a miner to escape safely during a mine emergency. Apparatus that fail inspection criteria are expected to be removed from service. This study involves testing approximately 100 SCSRs in each phase. This report describes findings in the sixth phase of testing occurring from mid-1996 through early 1998. Previous reports describe phases 1 through 5 [Kyriazi *et al.* 1986; Kyriazi and Shubilla 1992, 1994, 1996]. Testing was conducted using a breathing and metabolic simulator (BMS) (Fig. 1) and human subjects on a treadmill.

Experimental Procedure

The SCSRs 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 apparatus are shown in Figs. 2 through 6. Ninety percent of the apparatus were tested on the BMS; 10%, on human subjects.

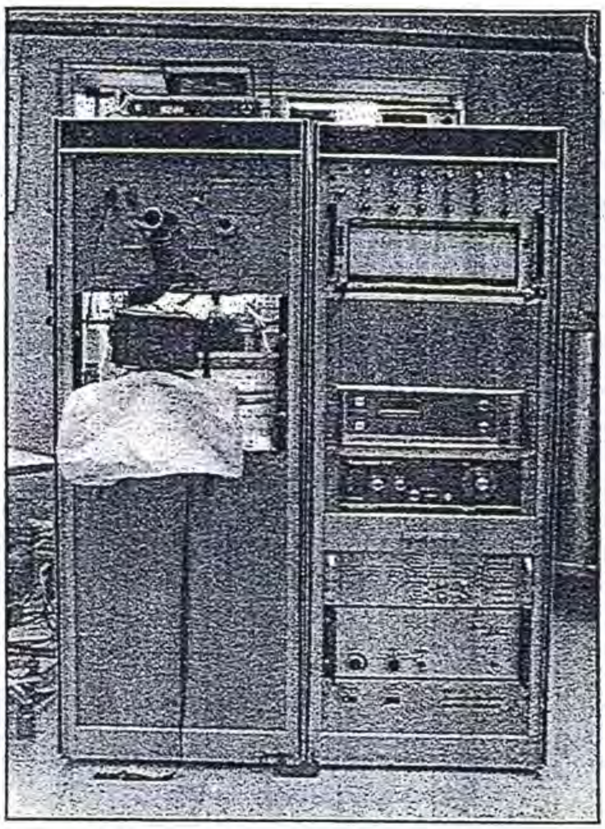

Figure 1. Breathing and metabolic simulator at the NIOSH Pittsburgh Research Laboratory, Bruceton, PA.

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 (at NIOSH in Morgantown, WV), dry (ATPD).

All apparatus are checked for breathing circuit leak tightness after opening. The leak test used is that recommended by Draeger for its BG-174A rescue breathing apparatus. It is performed to determine how well the apparatus isolates the user from the environment, which may be irrespirable in an emergency. Passing the test is not a requirement of the regulations, however. The test permits a decay in breathing circuit pressure from –70 to –60 mm H_2O in 1 min. We have determined that just passing the test is equivalent to a leak rate of approximately 1 mL/min given an internal volume for both the apparatus and test stand of 1 L (all volumes in this report are given at standard temperature and pressure, dry, unless otherwise noted). To give this some perspective, an in-leakage rate of 87 mL/min in a 10% CO atmosphere at a peak inhalation flow rate of 250 L/min would result in an 8-hr threshold limit value (TLV) for CO of 35 ppm. The 250 L/min peak inhalation flow rate is used be-cause this occurs at roughly a 100 L/min ventilation rate, the highest

Table 1. SCSRs received for evaluation.

Apparatus	No. received	No. ~~received~~ tested
CSE SR-100	30	27
Draeger OXY K Plus	10	9
MSA Portal-Pack	10	8
Ocenco EBA 6.5	40	38
Ocenco M-20	10	10
Total	100	92

Figure 2. Cased and uncased CSE SR-100 self-rescuer.

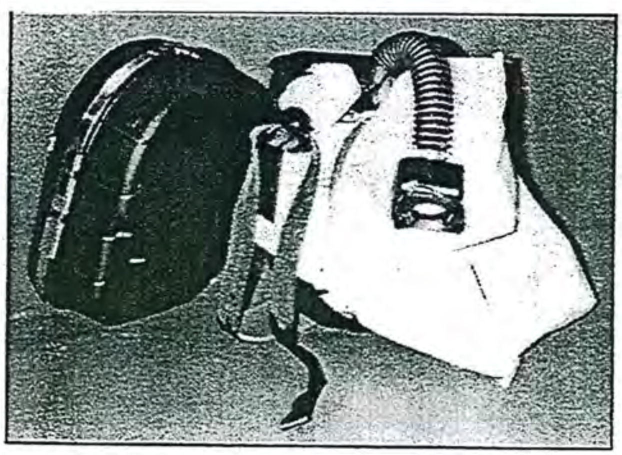

Figure 3. Cased and uncased OXY K Plus self-rescuer.

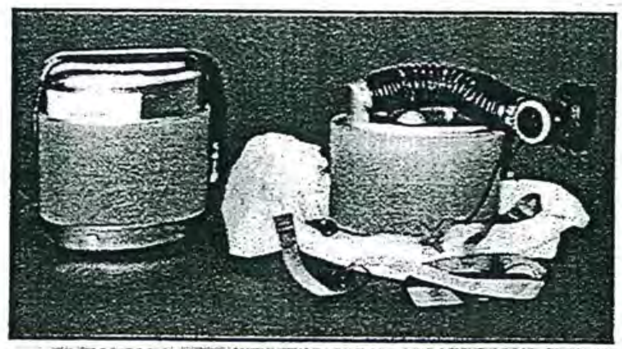

Figure 4. Cased and uncased MSA Portal Pack self-rescuer.

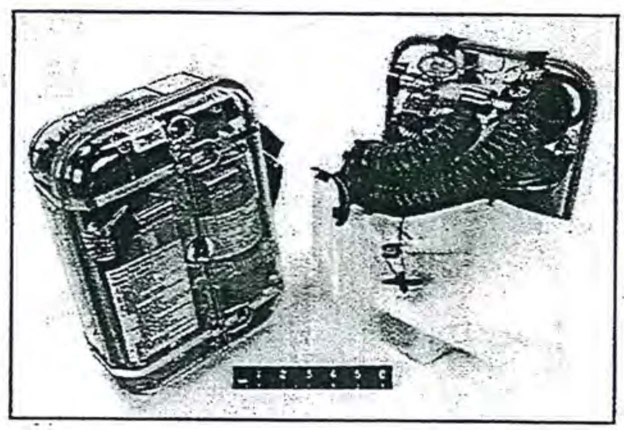

Figure 5. Cased and uncased Ocenco EBA 6.5 self-rescuer.

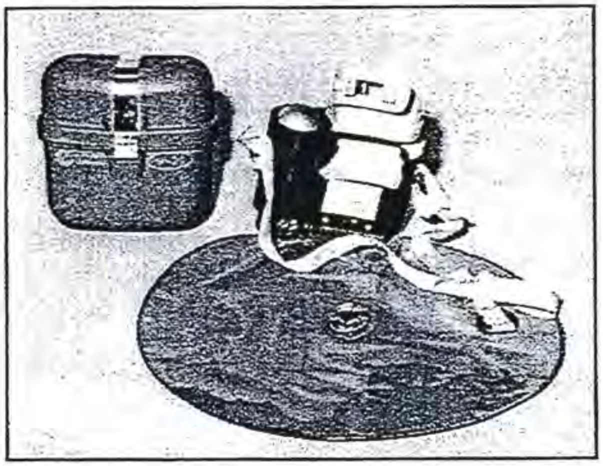

Figure 6. Cased and uncased Ocenco M-20 self-rescuer.

likely rate that can reasonably be expected of a user. At such a maximal work rate, inhalation pressure should not exceed –300 mm H_2O, the highest negative pressure tolerated by 80% of test subjects in a recent study [Hodgson 1993]. At a leak test pressure of –70 mm H_2O, the proportional in-leakage rate resulting in an 8-hr TLV would be 20 mL/min at a peak inhalation flow rate of 58 L/min. The Draeger leak test, therefore, can be considered very conservative.

PRL selected the participating mines with regard to type of mining operation, coalbed height, and SCSR deployment mode in order to obtain a wide range of deployment impact. Deployment modes included permanent storage on the ground, on a mantrip or mining machine, or belt-worn.

The BMS test consisted of the average metabolic work rate exhibited by the 50th-percentile miner weighing 87 kg while performing the 1-hr man test 4 as described in 42 CFR 84. In the treadmill testing, the human subjects walked at whatever speed and grade resulted in an O_2 consumption rate of 1.35 L/min. The CO_2 production rate, ventilation rate, and respiratory frequency varied in the test subjects. The metabolic workloads are given in Table 2.

The parameters monitored were inhaled levels of CO_2 and O_2, end-of-inhalation wet- and dry-bulb temperatures, and inhalation and exhalation peak 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 of the CO_2 and O_2 over each inhalation cycle, weighted by the instantaneous flow rate. The BMS also measures minimum inhaled CO_2 levels.

Tests on the BMS were terminated upon exhaustion of the O_2 supply as indicated by negative pressures reaching –200 mm H_2O, coinciding with an empty breathing bag. Some BMS tests were terminated when average inhaled CO_2 levels reached 10% or O_2 levels went below 15%. Treadmill tests were terminated in the same manner, but using a limit of 4% minimum inhaled CO_2 or if the test subject stopped because of subjectively high breathing pressures or temperatures. Because the BMS is unaffected by high CO_2 levels, in order to gain more information about the performance of an apparatus, tests were continued to the higher CO_2 level in BMS testing.

Table 2. BMS and human-subject metabolic parameters.

Metabolic workload		BMS	Subject A	Subject B	Subject C
O_2 consumption rate	L/min	1.35	1.35	1.35	1.35
CO_2 production rate	L/min	1.30	1.12	1.18	1.15
Ventilation rate	L/min	30.0	27.0	22.0	30.0
Tidal volume	L/breath	1.68	1.59	2.20	3.33
Respiratory frequency	breaths/min	17.9	17.0	10.0	9.0
Peak respiratory flow rate:					
Inhalation	L/min	89.0	(1)	(1)	(1)
Exhalation	L/min	71.0	(1)	(1)	(1)

1 Not measured.

Results and Discussions

Experience with each model of apparatus is discussed separately. The minute average values of the monitored stressors were averaged over the entire test duration and are presented graphically (Figs. 7–11) for each apparatus by stressor. The values for new units tested on the BMS can be compared with those for deployed units tested on the BMS and, to some extent, with those for 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 CO_2 production rate, ventilation rate, and respiratory frequency, all of which affect apparatus duration as well as all of the monitored stressors, these tests cannot be considered equivalent to the BMS tests even though the O_2 consumption rate is the same. Missing data points for wet-bulb temperature indicate equipment malfunction or inability to instrument apparatus.

The Wilcoxon rank-sum test was performed for each monitored stressor to determine whether 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 ($\alpha = .05$, 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, $\alpha = 0.05$, Wilcoxon rank-sum tests are presented in Table 3. 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.

CSE SR-100

Three deployed apparatus tests had instrument problems, and their data were not used. Regarding leak testing, 17 of 25 deployed units passed, and 3 of 4 new apparatus passed.

The Wilcoxon rank-sum test for average inhaled CO_2 showed a significant difference between new and deployed units, with deployed units having higher values than new ones (Table 3). This was also found to be true in the previous phase of this study [Kyriazi and Shubilla 1996].

Table 4 shows that 19 of 24 apparatus tested on the BMS experienced CO_2 breakthrough before expenditure of the O_2 supply; 15 of these occurred before 60 min. Of the new units, two of four experienced premature breakthrough, but only by several minutes and neither before 60 min. The effect of high inhaled levels of CO_2 will be increased ventilation rates in most users. Increased ventilation rates will result in higher breathing pressures experienced by the user, possibly resulting in pre-mature removal of the apparatus. Breathing pressures in the SR-100 increase rapidly toward end-of-life even in new apparatus; elevated CO_2 levels will accelerate this rise.

The termination of one treadmill test (human subject C) at 40 min was for high breathing pressures (–480 to +210 mm H_2O) even though there was sufficient volume in the breathing bag to permit continued use. This occurred with minimum inhaled CO_2 levels of only 0.9%. This unit was dissected at CSE Corp.'s facility and found to have a canister dented on three sides; this damage was not evident from external inspection according to present inspection criteria. As a result of this incident, the manufacturer has added an inspection criterion to closelyinspect the end-cap seals for damage. Another treadmill test was terminated at 60 min when the minimum inhaled CO_2 level reached 4% with unmeasured average inhaled level necessarily higher. This test subject also coughed repeatedly at the start of the test, but was able to continue.

One unit had to be manually started by exhaling several times into the mouthpiece when the starter O_2 cylinder provided no O_2 to the breathing circuit.

Two units had breathing hoses that were stuck together and required some effort to open them for use. One also required some effort to remove the case top and bottom.

Draeger OXY K Plus

All deployed and new units tested failed the leak-tightness test. The Wilcoxon rank-sumtests showed that the durations of the new units were statistically significantly lower than those of the

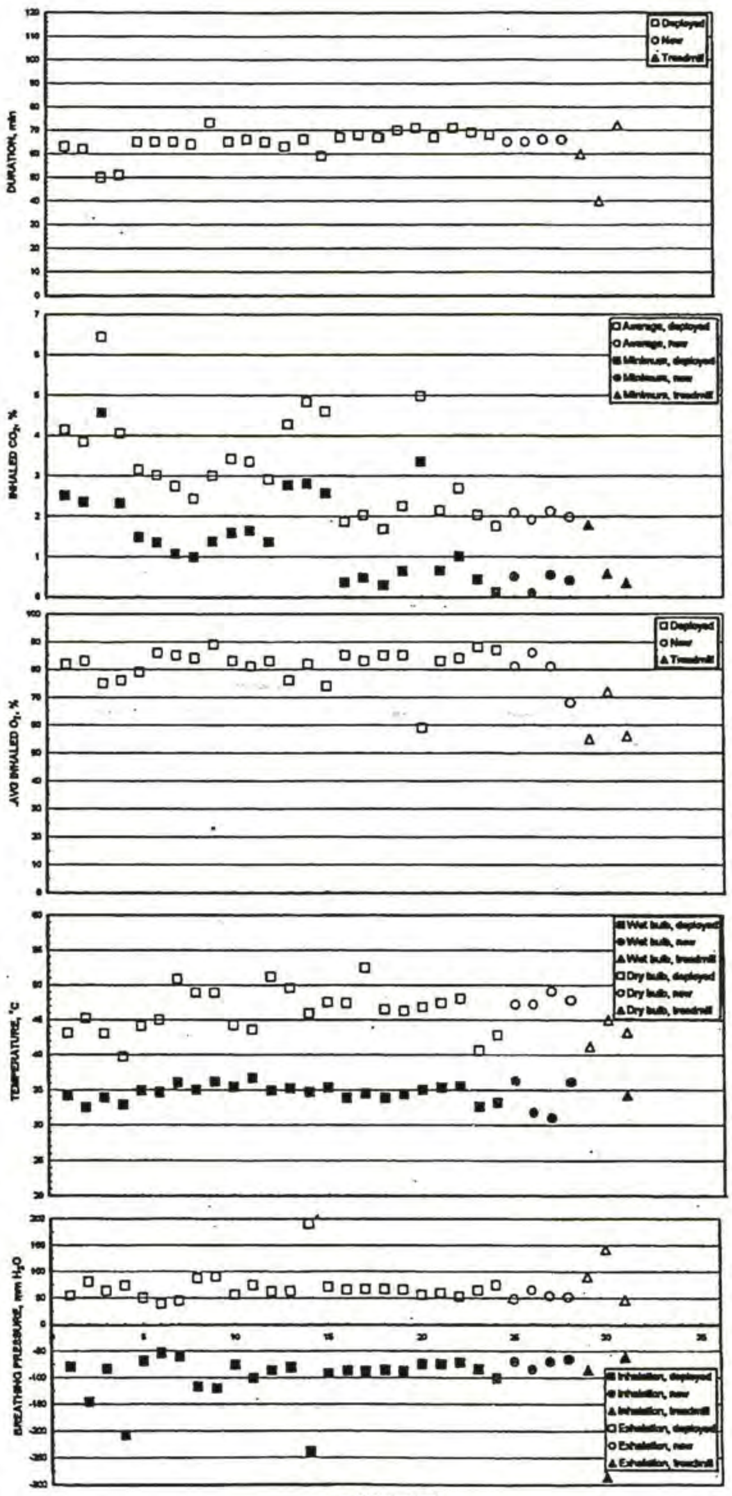

Figure 7. CSE SR-100 test results.

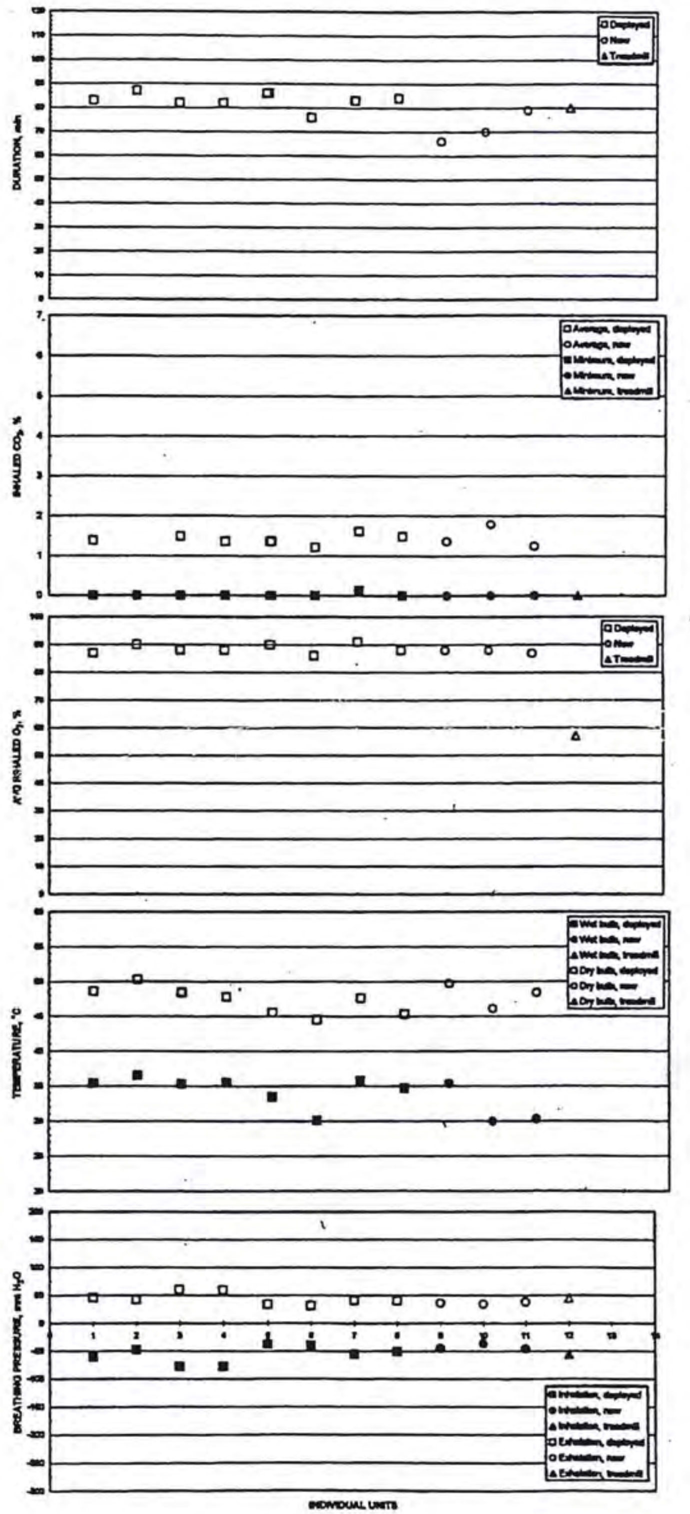

Figure 8. Draeger OXY K Plus test results.

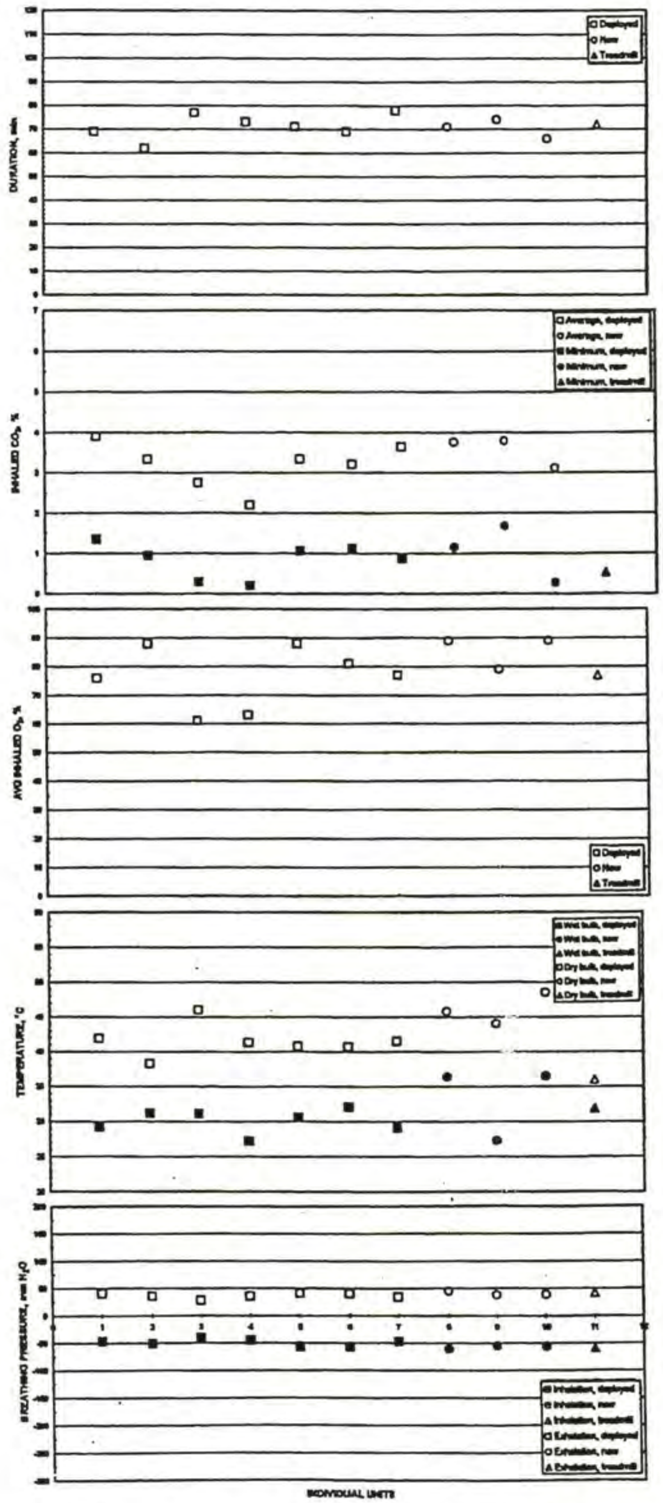

Figure 9. MSA Portal-Pack test results.

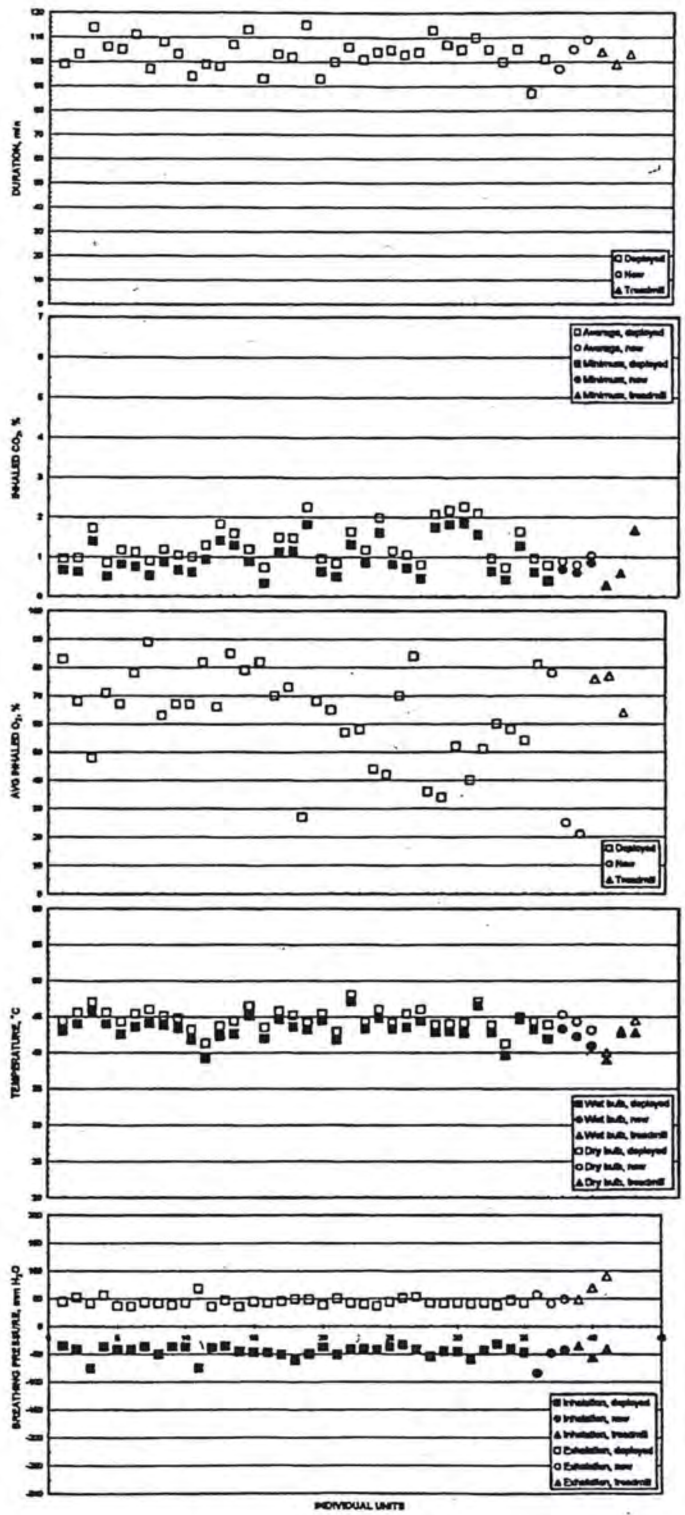

Figure 10. Ocenco EBA 6.5 test results.

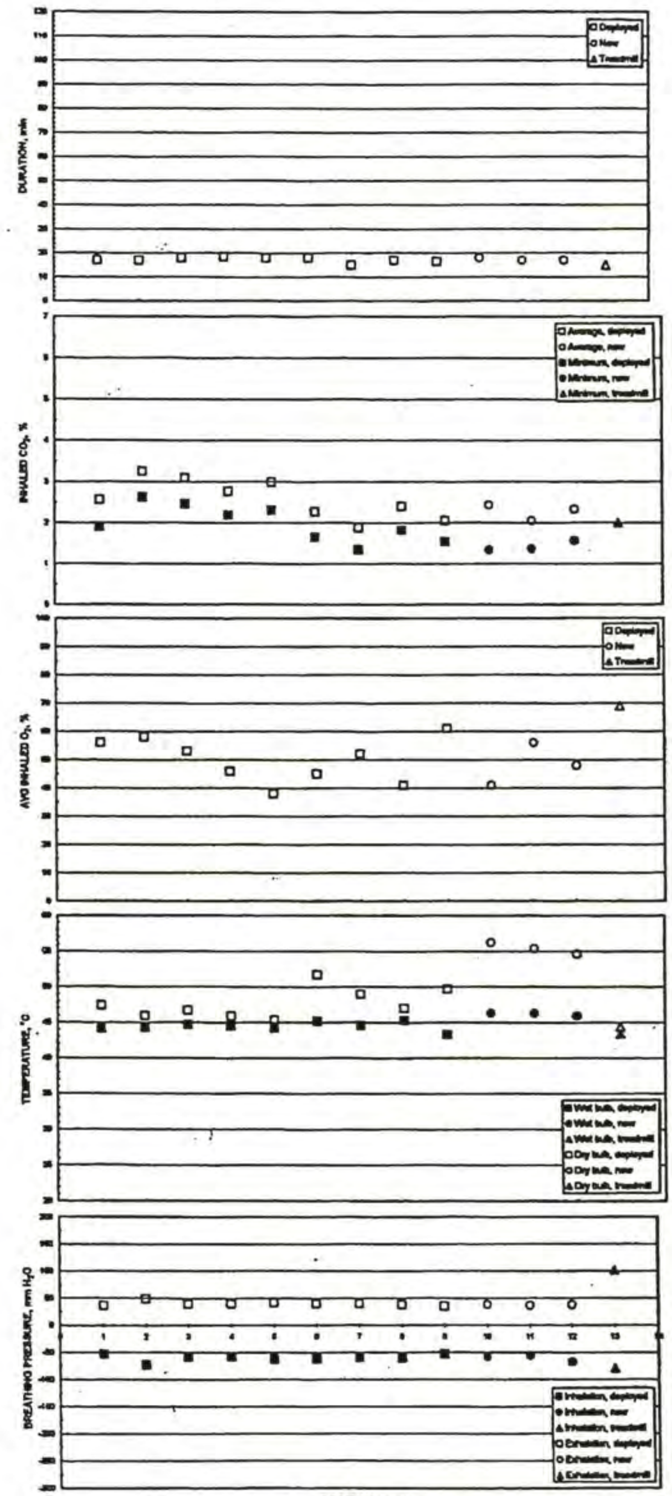

Figure 11. Ocenco M-20 test results.

Table 3. Wilcoxon rank-sum test results.

	Duration		Average inhaled CO_2		Average inhaled O_2		Wet-bulb temperature		Dry-bulb temperature		Inhalation pressure		Exhalation pressure	
Apparatus	Range	T	Range	T	Range	T	Range	T	Range	T	Range	T	Range	T
SR-100	28–88	55	28–88	26	28–88	44	28–88	55	28–88	75	28–88	28	28–88	31
OXY K Plus	8–28	7	7–26	16	8–28	14	8–28	11	8–28	21	8–28	10	8–28	11
Portal-Pack	7–26	15	7–26	20	7–26	24	7–26	21	7–26	25	7–26	23	7–26	21
EBA 6.5	13–53	23	13–53	18	13–53	19	13–53	18	13–53	26	13–53	46	13–53	43
M-20	8–31	19	8–31	14	8–31	18	8–31	33	8–31	33	8–31	18	8–31	12

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

Table 4. CSE SR-100 CO_2 breakthrough times, minutes.

Type of unit and test method	CO_2 breakthrough time	Test duration	Maximum CO_2
Deployed: BMS	29	63	7.9
	42	62	8.1
	12	50	10.2
	32	51	8.5
	55	65	7.3
	56	65	6.5
	59	65	6.1
	57	64	8.0
	60	73	9.9
	46	65	7.3
	49	66	8.6
	57	65	7.0
	37	63	10.6
	34	66	10.3
	34	59	10.5
	69	70	4.8
	29	71	11.9
	66	71	6.0
	69	69	4.3
Deployed: Human subject on treadmill	60	60	4.0
New: BMS	64	65	4.8
	63	66	5.1

CO_2 breakthrough for BMS—4% average inhaled; for treadmill—4% minimum inhaled.

deployed units. If deployment caused the bed chemical to break into smaller particles, resulting in more surface area, this could causebetter chemical utilization, resulting in longer duration. It might also result in higher breathing pressures. Since this was not found to be the case, longer durations on deployed apparatus are not viewed as a problem.

One deployed apparatus reached an average inhaled CO_2 level of 4% at 81 min before exhaustion of the oxygen supply at 83 min (Table 5). No new units experienced CO_2 breakthrough.

MSA Portal-Pack

Three deployed units evidenced potassium superoxide (KO_2) dust in their mouthpieces; two of these were dissected without testing at MSHA's request to inspect for damage. The other unit was tested on the BMS and was found to perform normally. Exhaling 5 to 10 times into the breathing hose of an apparatus found to have fine dust in the mouthpiece wets down the dust, permitting the apparatus to be worn. However, the certification agencies, after inspecting a number of other units, decided that this was too much to expect of a user in an emergency and decertified the apparatus after they could all be replaced with the new MSA Life-Saver 60 or other certified SCSR.

Of seven deployed apparatus tested for leaks, six failed while all of the three new apparatus passed. The Wilcoxon rank-sum tests showed that new units did not perform differently from deployed units in any performance measure.

All deployed and new units tested on the BMS reached 4% CO_2 before the O_2 supply was expended; five of the deployed and two of the new units occurred before 60 min (Table 6).

Activation of the sodium chlorate candle, which provides an initial volume of oxygen, sometimes results in visible white smoke emanating from the mouthpiece. This occurred in the treadmill test, and the test subject did not want to breathe the smoke. Instead, after the smoke stopped, a manual start was performed consisting of exhaling into the mouthpiece eight times and then donning the apparatus. The test subject reported feeling nauseated for the first 10 min of wear and terminated the test at 72 min after feeling light-headed. All measured stressors were within acceptable ranges, although minimum inhaled CO_2 levels were climbing and reached 2.1%

Table 5. Draeger OXY K Plus CO_2 breakthrough times, minutes.

Type of unit and test method	CO_2 breakthrough time	Test duration	Maximum CO_2
Deployed: BMS	81	83	4.4

CO_2 breakthrough for BMS—4% average inhaled; for treadmill—4% minimum inhaled.

Table 6. MSA Portal-Pack CO_2 breakthrough times, minutes.

Type of unit and test method	CO_2 breakthrough time	Test duration	Maximum CO_2
Deployed: BMS	43	69	10.0
	47	62	10.0
	72	77	4.5
	50	71	10.0
	49	69	7.3
	51	78	9.1
New: BMS	49	71	11.5
	54	74	15.8
	61	66	4.6

CO_2 breakthrough for BMS—4% average inhaled; for treadmill—4% minimum inhaled.

by test termination. It should also be noted that, because of large apparatus dead space, average inhaled CO_2 levels would be significantly higher than this. The difference between minimum and average inhaled CO_2 levels with a 1.67-L tidal volume as used in the BMS tests is approximately 2%.

Ocenco EBA 6.5

Ten apparatus were found to have been altered from their original manufacturer's condition. The units had been opened, their service life indicators changed to extend their service lives, some components replaced, and then reassembled without applying new tamper seals. Some of these units exhibited cracks in their cases, dents in their canisters, had lithium hydroxide (LiOH) dust in their mouthpieces and breathing bags and had very high breathing circuit leak rates. Several apparatus were tested on the BMS before we discovered that they had been altered; they performed normally, however. The perpetrator of the unauthorized alterations was discovered and ordered by MSHA to stop.

Two of the thirty-eight deployed apparatus tested for breathing circuit tightness passed the leak test; none of the three new apparatus passed. Many units passed the test when their relief valves were capped, however, implying backflow through the valves.

The Wilcoxon rank-sum tests showed that, in all performance measures, new units could not be distinguished from deployed units.

Twenty-two deployed units tested on the BMS and one on the treadmill reached average inhaled levels of 4% CO_2 before the O_2 supply was expended; none occurred before 60 min (Table 7). No new units experienced this phenomenon.

The large range of average inhaled O_2 level test averages is due to the difference in the apparatus O_2 regulator flow rates, which ranged in this phase from 1.51 to 2.62 L/min ATPD (approximately 1.36 to 2.36 L/min STPD). The O_2 concentration in a breathing circuit will rise if the O_2 supply rate is higher than the O_2 consumption rate.

Ocenco M-20

Of the nine deployed units tested for leak tightness, four passed; of the three new units, one passed. All except one deployed BMS-tested apparatus, all of the new BMS-tested apparatus, and the one treadmill-tested apparatus experienced average inhaled CO_2 levels of 4% before exhaustion of the oxygen supply (Table 8).

The Wilcoxon rank-sum tests revealed that the wet- and dry-bulb temperatures of new units were statistically significantly higher than those of the deployed units. This is not viewed as a problem.

The breathing bag and mouthpiece of one unit had somewhat taken a set in their folded packing orientations, but not to the extent that donning of the apparatus was compromised.

Conclusions

The results of this sixth-phase SCSR test study at PRL suggest that the large majority of SCSRs that pass their inspection criteria can be relied upon to provide a safe level of life support capability to allow miners to escape safely during a mine emergency. However, the mining environment seems to have caused some performance degradation in the CSE SR-100 and the MSA Portal-Pack. Several Portal-Packs were found to have KO_2 dust in their mouthpieces. NIOSH-Morgantown and MSHA, after finding more instances of this problem, decided to decertify the Portal-Pack. CO_2 levels were found to be higher in deployed CSE SR-100s than in new ones (Table 3 and Fig. 7). No statistically significant worsening in any other performance category was detected in the SR-100 or any other apparatus. The SR-100 has been belt-worn longer than any other SCSR. It may be that this type of impact is in store for all belt-worn apparatus and will become evident as other belt-worn apparatus have more field time.

The smoke sometimes emitted from the chlorate candle of the MSA Portal-Pack may suggest that the apparatus is malfunctioning and lead the user to abandon it. Since the apparatus is no longer being used, the point is moot, but should be remembered by manufacturers in future design efforts.

Table 7. Ocenco EBA 6.5 CO_2 breakthrough times, minutes.

Type of unit and test method	CO_2 breakthrough time	Test duration	Maximum CO_2
Deployed: BMS	102	103	4.2
	106	114	5.7
	105	105	4.0
	111	111	4.0
	96	97	4.3
	104	108	5.1
	102	103	4.4
	94	94	4.0
	97	99	4.2
	92	107	7.1
	107	113	5.3
	93	103	6.7
	92	102	7.2
	94	115	8.3
	94	106	7.7
	88	104	9.3
	102	103	4.2
	99	113	5.8
	91	107	5.9
	87	105	6.2
	97	110	5.5
	94	105	8.0
Deployed: Human subject on treadmill	103	103	4.0

CO_2 breakthrough for BMS—4% average inhaled; for treadmill—4% minimum inhaled.

Table 8. Ocenco M-20 CO_2 breakthrough times, minutes.

Type of unit and test method	CO_2 breakthrough time	Test duration	Maximum CO_2
Deployed: BMS	14.5	17	6.6
	13.5	17	6.7
	14.0	18.0	6.9
	15.0	18.5	6.2
	15.0	18.0	5.3
	15.0	18.0	5.7
	15.0	17.0	4.8
	16.0	16.5	5.8
Deployed: Human subject on treadmill	14.0	15.0	4.4
New: BMS	15.5	18.0	6.6
	15.5	17.0	5.2
	15.0	17.0	5.8

CO_2 breakthrough for BMS—4% average inhaled; for treadmill—4% minimum inhaled.

Acknowledgments

Without the cooperation of the coal mines and MSHA field offices, this study would not be possible. The following coal mines and MSHA field offices participated in the sixth phase of this study:

Cooperating mine or MSHA office.

Assisting MSHA office	Mining company	Mine name
MSHA District 2:		
Rosebud Mining Co.	Rosebud No. 3	Kittanning, PA, Field Office
Rosebud Mining Co.	Roaring Run	Kittanning, PA, Field Office.
Dunkard Mining Co.	Dunkard Mine	Waynesburg, PA, Field Office
Canterbury Coal Co.	DiAnne Mine	Indiana, PA, Field Office
Consolidation Coal Co.	Bailey Mine	Washington, PA, Field Office
Consolidation Coal Co.	Enlow Fork Mine	Washington, PA, Field Office
MSHA	Johnstown, PA, Field Office	
MSHA District 4:		
Elk Run Coal Co.	White Knight Mine	Mt. Hope, WV, Field Office
Eastern Associated Coal Corp.	Harris No. 1	Mt. Hope, WV, Field Office
Maple Meadow Mining Co.	Maple Meadow Mine	Mt. Hope, WV, Field Office
Mystic Energy, Inc.	Candice 2 Mine	Madison, WV, Field Office
RWJ Mining, Inc.	Mine No. 7	Princeton, WV, Field Office
DuPaul Resources, Inc.	Mine No. 1	Pineville, WV, Field Office
Terry Eagle Coal Co.	Bald Eagle No. 1 Mine	Summerville, WV, Field Office

MSHA District 5:		
Crystal Bay Corp.	Mine No. 2	Richlands, VA, Field Office
Island Creek Coal Co.	Virginia Pocahontas No. 3	Richlands, VA, Field Office
Lebo Mining, Inc.	Mine No. 5	Norton, VA, Field Office
MSHA District 9:		
Twentymile Coal Co.	Foidel Creek Mine	Price, UT, Field Office
MSHA District 11:		
U.S. Steel Mining Co.	Oak Grove Mine	Hueytown, AL, Field Office

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Review of Recent Research on Respiration While Wearing a Respirator
A. T. Johnson

Review of Recent Research on Communications While Wearing a Respirator
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