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REPORT OF INVESTIGATIONS/1996

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

By Nicholas Kyriazi and John P. Shubilla

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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

h	hour	mL/min	milliliter per minute
kg	kilogram	mm H_2O	millimeter of water (pressure)
L	liter	ppm	part per million
L/min	liter per minute	psi	pound (force) per square inch
min	minute	%	percent
mg/m^3	milligram per cubic meter		

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

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

ABSTRACT

A joint effort by the Pittsburgh Research Center (PRC)[3] and the 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 fifth phase of testing from mid-1993 to early 1996. The SCSR's were tested on human subjects and on a breathing and metabolic simulator (BMS) at PRC. These results indicate that most of the apparatus, if they pass their inspection criteria, perform satisfactorily.

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[3]This work originated under the U.S. Bureau of Mines prior to transferring to the U.S. Department of Energy on April 4, 1996.

INTRODUCTION

On June 21, 1981, U.S. coal mine operators were required by Federal law to make available to each underground coal miner a self-contained self-rescuer (SCSR). The regulations at 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 the Mine Safety and Health Administration (MSHA). The Pittsburgh Research Center (PRC) is working jointly with MSHA in a long-term evaluation of SCSR's now deployed in U.S. underground coal mines. This work is in support of PRC's Disaster Prevention research program to improve safety for underground mine workers. In this joint study, MSHA's responsibility is to locate mines willing to participate and to procure from those mines the SCSR's to be tested. PRC replaces those SCSR's with new apparatus and tests the deployed SCSR's in its laboratories. The objective of this long-term project is to evaluate the in-mine operational durability of SCSR's. Of utmost concern is the successful performance of any SCSR that passes its inspection criteria. PRC 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 SCSR's in each phase. This report describes findings in the fifth phase of testing occurring from mid-1993 to early 1996. Previous reports describe phases 1 through 4 (*1-3*).[4] Testing was con- ducted using a breathing and metabolic simulator (BMS) (figure 1) and human subjects on a treadmill.

Figure 1.—Breathing and metabolic simulator (BMS) at the Pittsburgh Research Center, Bruceton, PA.

EXPERIMENTAL PROCEDURE

The SCSR's tested were manufactured by CSE Corp. (AU-9A1 and SR-100), Draegerwerk AG (OXY-SR 60B), Mine Safety Appliances Co., Inc. (MSA), (Portal-Pack) and Ocenco, Inc. (EBA 6.5). The SCSR's were sampled according to estimated market share (table 1). These devices are pictured in figures 2 through 6. Some of the first-generation SCSR's are no longer being used underground (MSA 60-min SCSR and PASS 700); others are being phased out (CSE AU-9A1 and Draeger OXY-SR 60B). The service life of the CSE AU-9A1 expired during this phase, so that we were able to obtain only part of our target number of units for testing. We included apparatus being phased out because information that we ob- tain about these 15-year-old apparatus may help the manufacturers in the design of new apparatus. Ninety percent of the apparatus were tested on the BMS; 10%, on human subjects. One MSA Portal-Pack test was discarded because of instrument problems.

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

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

Apparatus	Quantity tested
CSE AU-9A1	7
CSE SR-100	20
Draeger OXY-SR 60B	20
MSA Portal-Pack	10
Ocenco EBA 6.5	40
Total	97

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 recom-mended for the CSE AU-9A1 by the manufacturer; this test is identical to that required by Draeger for its BG-174 rescue breathing apparatus. It is performed to determine how well the apparatus isolates the user from the environment, which is assumed to be irrespirable. Passing the test, however, is not a requirement of the regulations. The test permits a decay in breathing circuit pressure from −70 to −60 mm H_2O in 1 min. This is equivalent to a leak rate of approximately 1 mL/min (all volumes at standard temperature and pressure, dry, unless otherwise stated) given an internal volume for both the apparatus and test stand of 1 L. To give this some perspective, an in-leakage rate of 1 mL/min in a 10% CO atmosphere during a peak inhalation flow rate of 89 L/min, which occurs in the BMS workload, would result in a 1-ppm concentration of CO in the inhalation gas stream. The 8-h threshold limit value for CO is 50 ppm. The Draeger/CSE leak test, therefore, can be considered very conservative.

Figure 2.—Cased and uncased CSE AU-9A1 self-rescuer.

Figure 3.—Cased and uncased CSE SR-100 self-rescuer.

Figure 4.—Cased and uncased Draeger OXY-SR 60B self-rescuer.

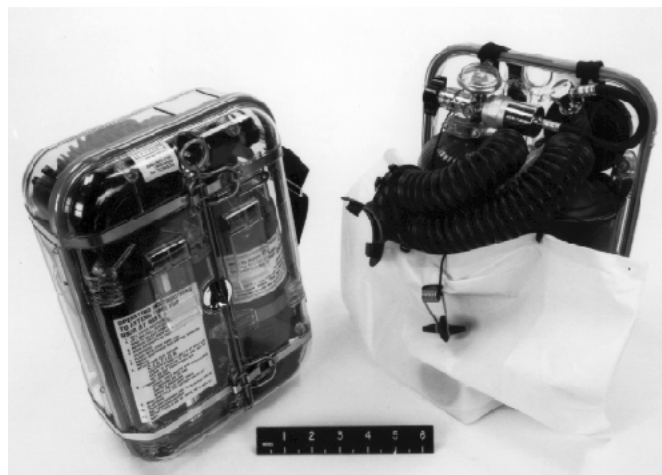

Figure 6.—Cased and uncased Ocenco EBA 6.5 self-rescuer.

Figure 5.—Cased and uncased MSA Portal-Pack self-rescuer.

MSHA selected the participating mines with regard to type of mining operation and SCSR deployment mode in order to obtain a representative cross section of U.S. mines. De-ployment modes sampled were—

- Permanently stored (42%);
- Single-shift, carried and stored (24%);
- Stored on a mining machine (rubber-tired coal shuttle, locomotive, or man-trip) (21%); and
- Single-shift, belt-worn (13%).

Mine types sampled were conventional (28%), continuous (64%), and longwall (8%).

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 as described in 42 CFR 84. The BMS metabolic workload is presented in table 2. The CO_2 production rate was increased to 1.30 L/min from 1.10 L/min in the previous several phases. This was done to reflect the finding that our new set of human test subjects had higher such rates than our previous test subjects. In the treadmill testing, the 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 among human test subjects; these are listed in table 3.

Table 2.—BMS metabolic workload

O_2 consumption rate	L/min	1.35
CO_2 production rate	L/min	1.30
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	89.0
Exhalation	L/min	71.0

The stressors monitored were inhaled levels of CO_2 and O_2, end-of-breath inhalation wet- and dry-bulb temperatures, and inhalation and exhalation peak breathing pressures in both the BMS and treadmill testing. In the treadmill testing, minimum inhaled levels of CO_2 and maximum inhaled levels of O_2 were measured. In the BMS testing, however, average inhaled levels of both CO_2 and O_2 were measured. 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 of 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. Treadmill tests were terminated in the same manner or if inhaled minimum CO_2 levels reached 4%, if maximum O_2 levels fell below 15%, or if the test subject stopped because of subjectively high breathing pressures or temperatures.

Table 3.—Human subject workloads in treadmill tests

Subject	VCO_2, L/min	V_e, L/min	RF, breaths per min
A	1.25	31	26
B	1.18	22	10
C	1.35	25	10
D	1.15	30	9

VCO_2 = CO_2 production rate.
V_e = Ventilation rate.
RF = Respiratory frequency.

TEST RESULTS AND DISCUSSION

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 (figures 7 through 11) for each apparatus by stressor. The values for new units tested on the BMS can be compared with the values for deployed 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 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 equip-ment malfunction.

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 (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

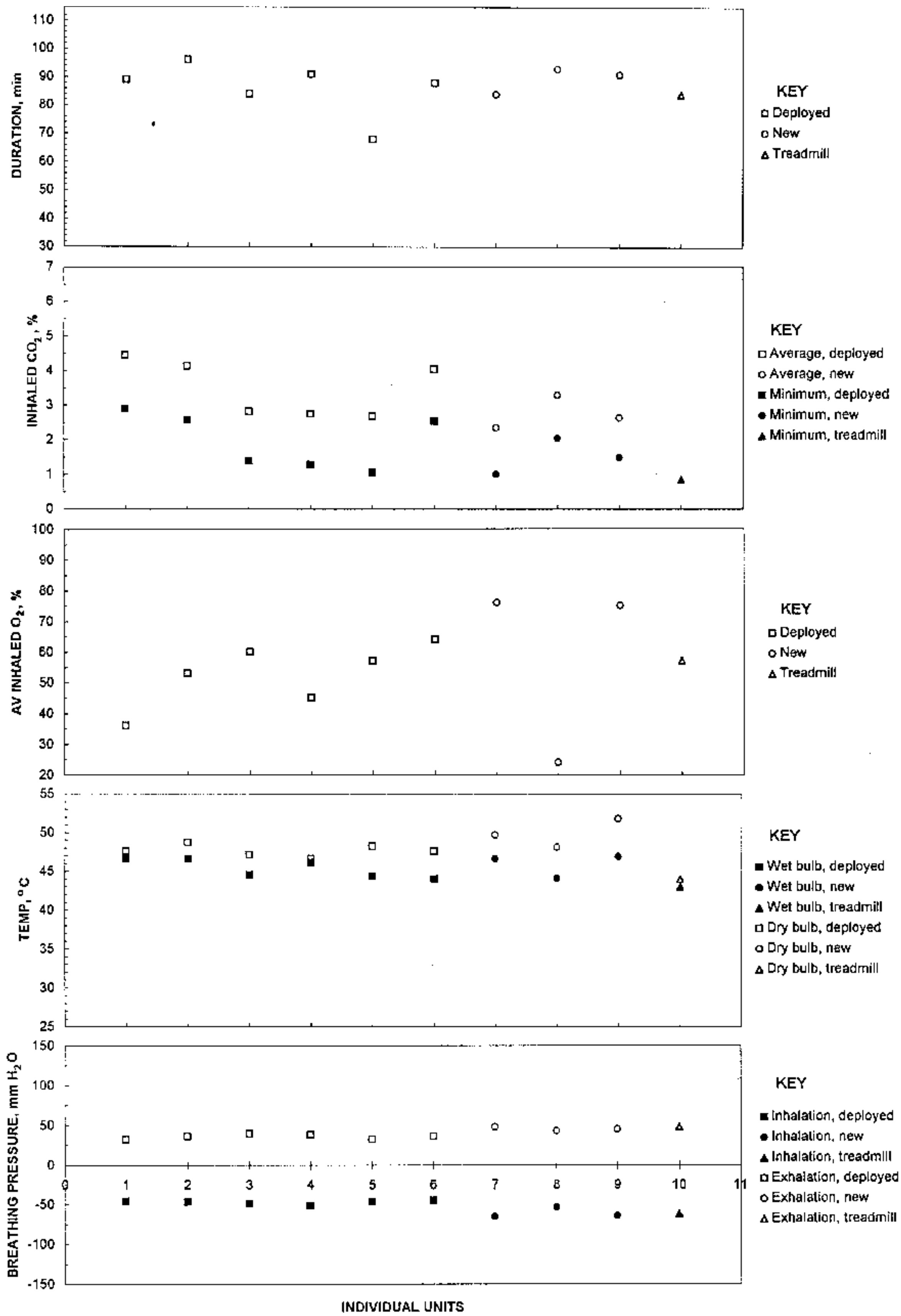

Figure 7.—CSE AU-9A1 test results.

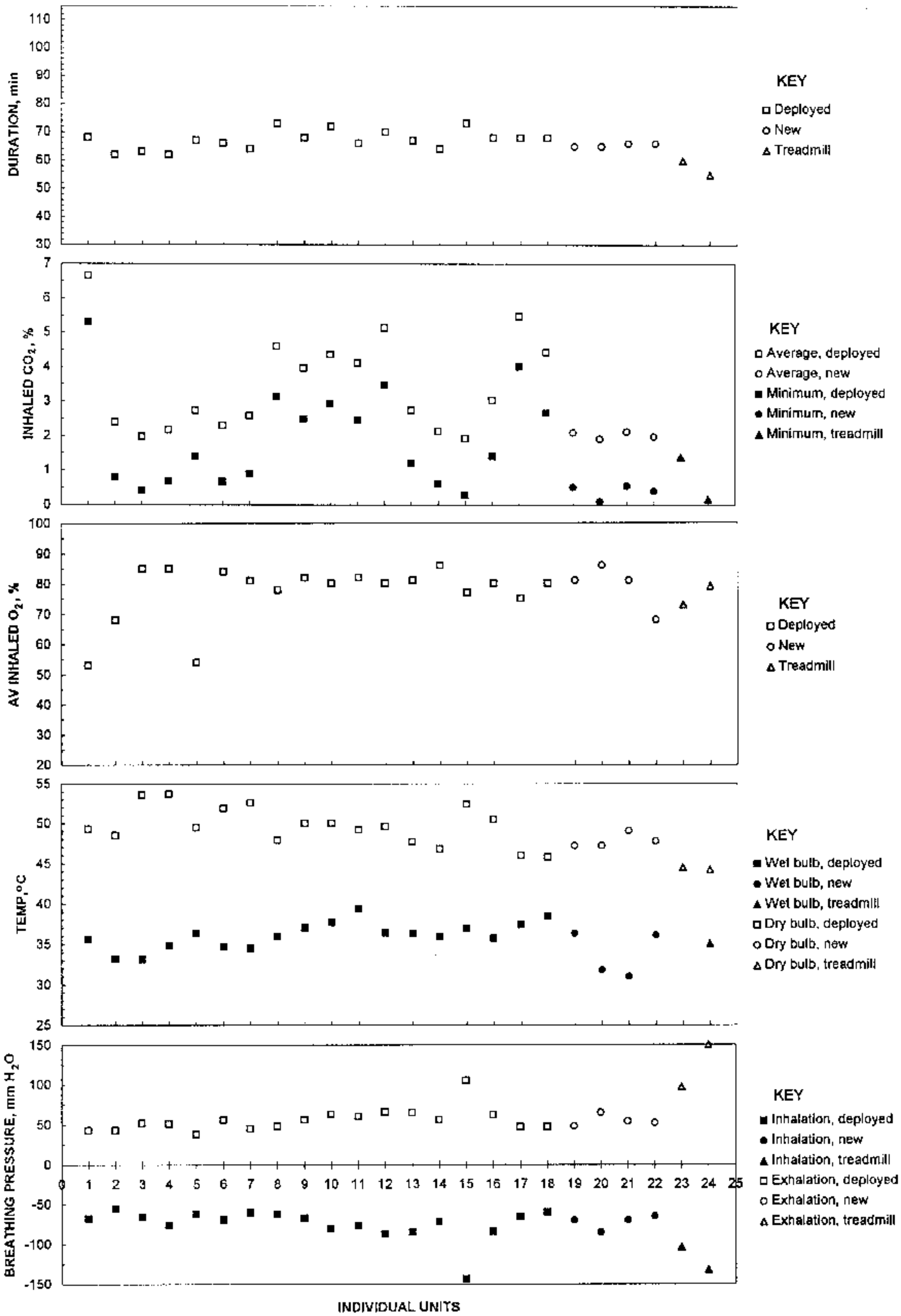

Figure 8.—CSE SR-100 test results.

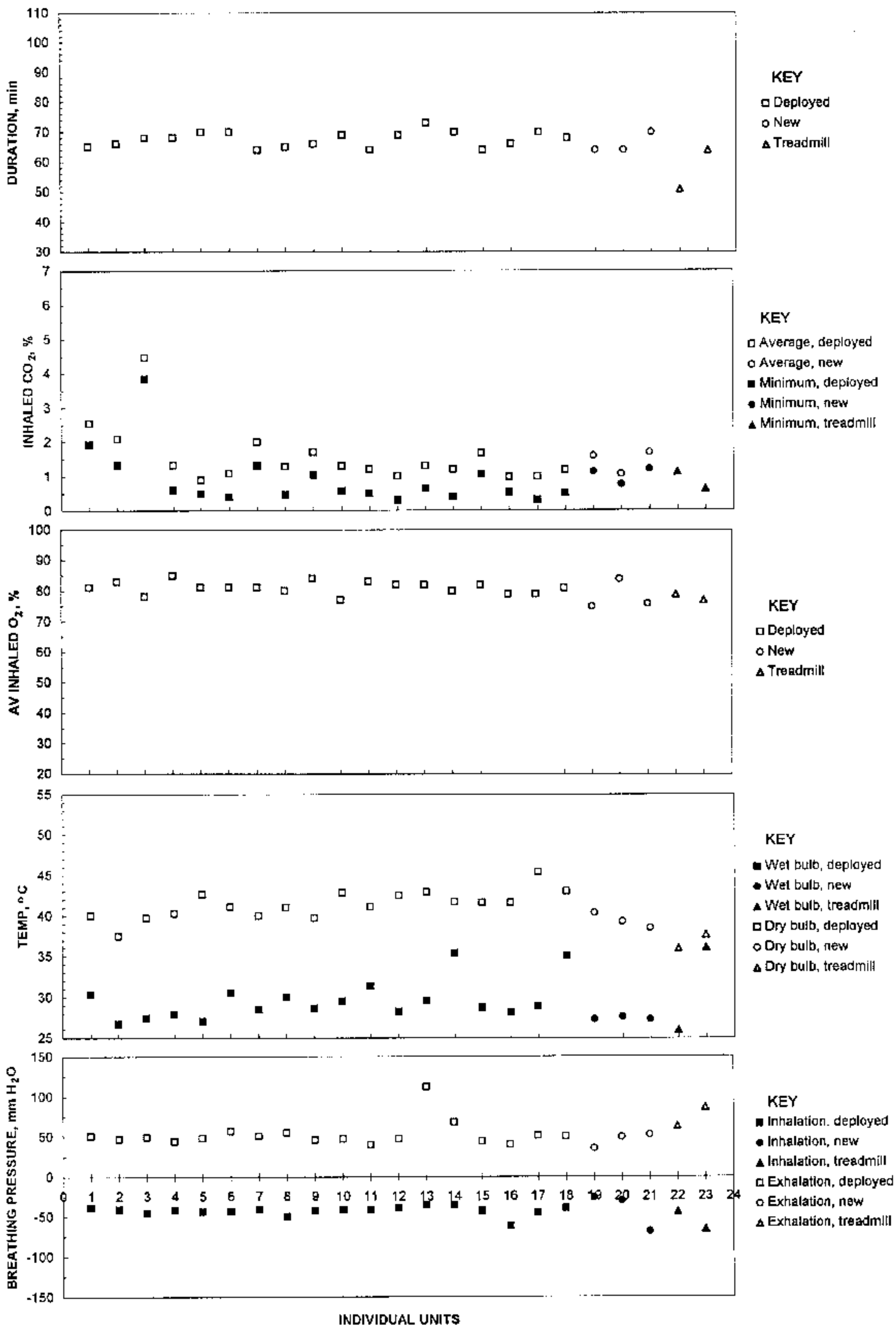

Figure 9.—Draeger OXY-SR 60B test results.

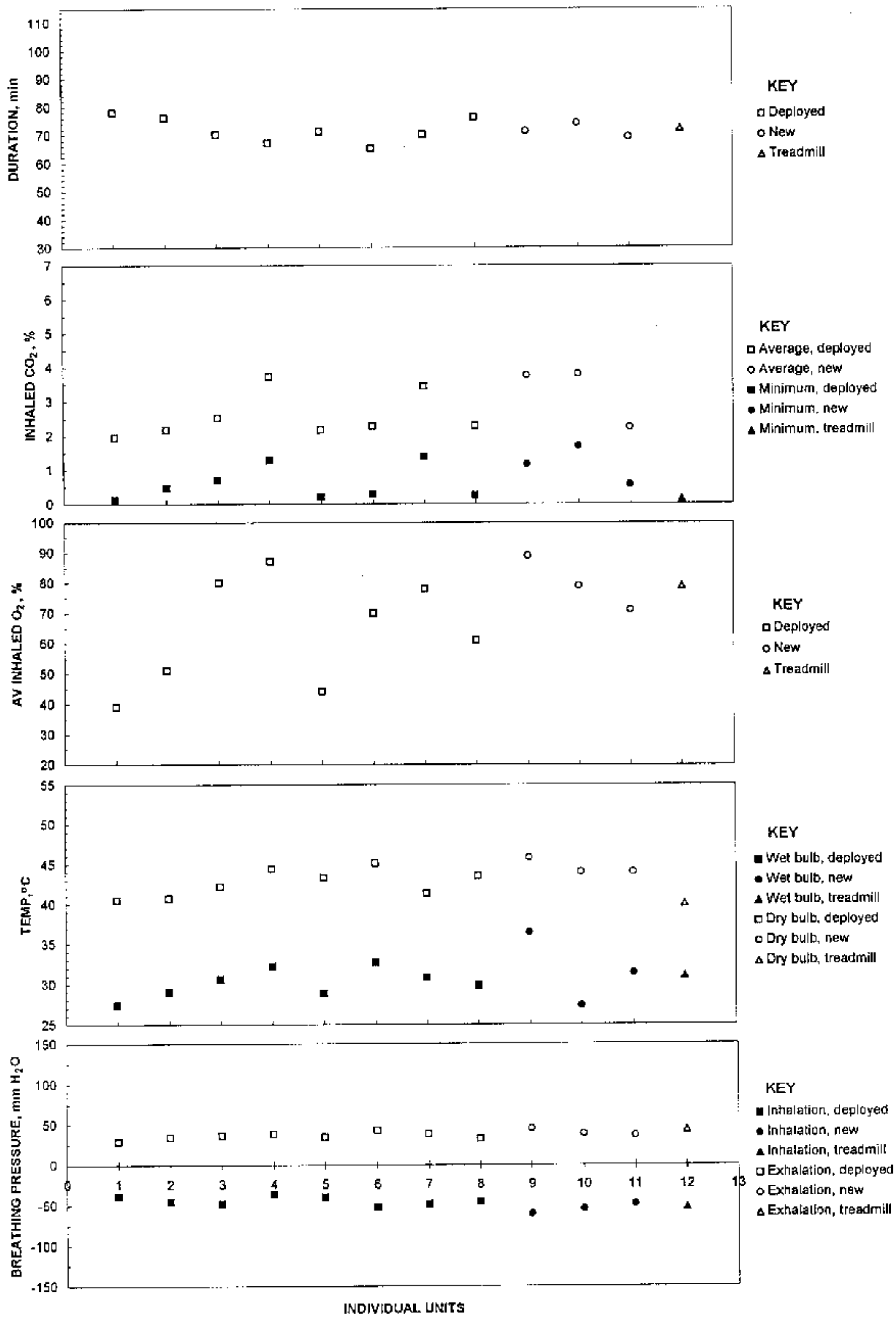

Figure 10.—MSA Portal-Pack test results.

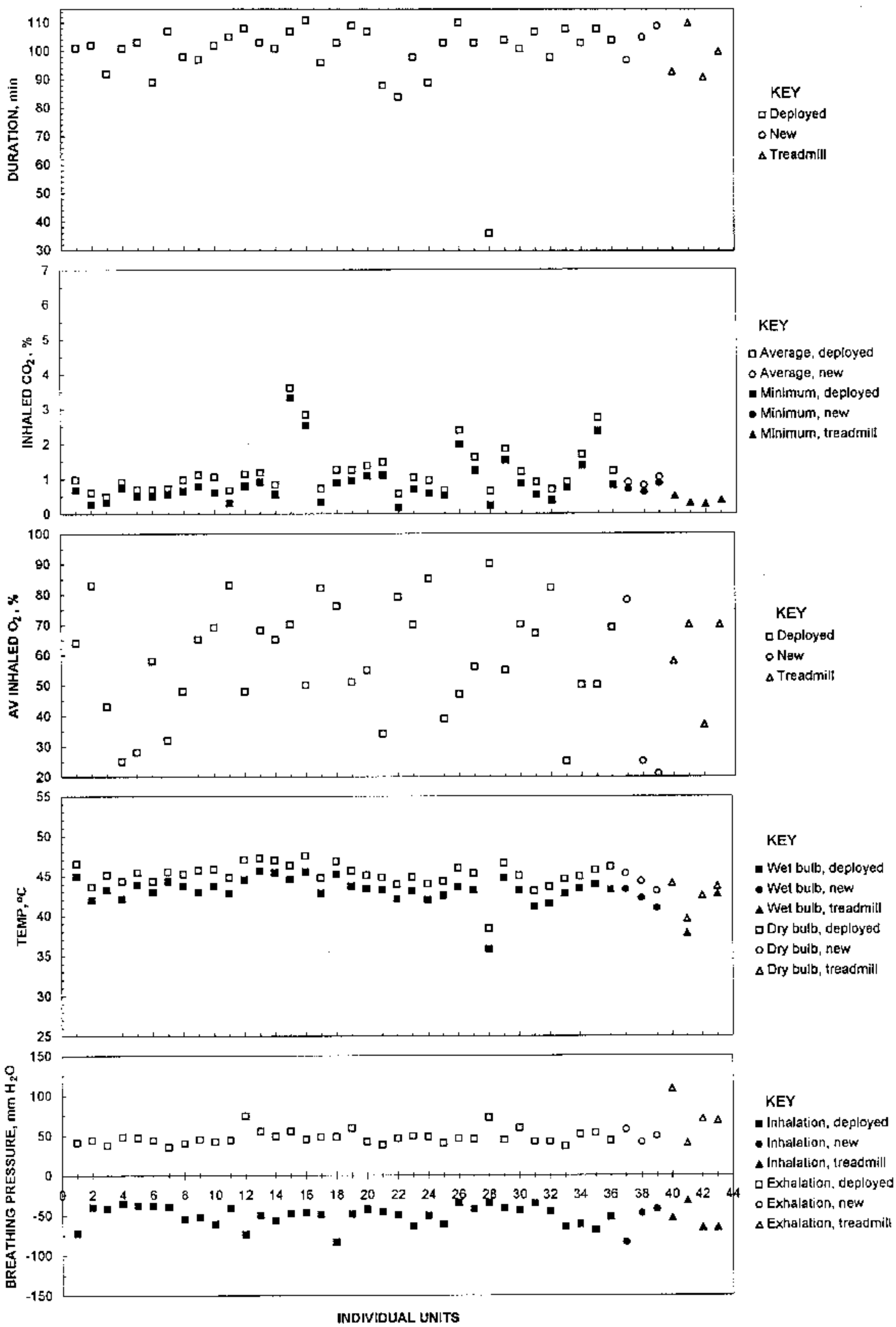

Figure 11.—Ocenco EBA 6.5 test results.

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.

CSE AU-9A1

Three of seven deployed apparatus passed the leak-tightness test, and all three new units passed.

The Wilcoxon rank-sum tests for the inhalation and ex-halation peak pressures showed higher values for new than deployed units (table 4). If this is the result of settling of the chemical absorbent, the inhaled CO_2 values might be expected to be higher due to air channeling, and they are (table 4 and figure 7), but not statistically significantly higher.

All of the apparatus tested on the BMS, new and deployed, reached 4% CO_2 (average inhaled) before the O_2 supply was expended (table 5); one occurred before 60 min. They were permitted to continue until the O_2 supply was expended. The one apparatus tested on a human subject (subject B) reached 4% (minimum inhaled) just as the O_2 supply became expended. This better performance can be explained by the fact that subject B had a VCO_2 of only 1.18 L/min compared with the 1.30 L/min of the BMS. The CO_2-absorbent canister is simply undersized compared with the O_2 supply. The result of high inhaled levels of CO_2 will be increased ventilation rates in most users.

The O_2 gauge of one unit read 500 psi when empty. Such an incident would have no negative consequences unless an escaping user decided to remain in an area with an irrespirable atmosphere longer than necessary for some reason based on the gauge reading.

CSE SR-100

Seventeen of twenty deployed and three of four new apparatus passed the leak-tightness test.

The Wilcoxon rank-sum test for average inhaled CO_2 showed a statistically significant difference between new and deployed units, with deployed units having higher values than new ones (table 4). Table 6 shows that 16 of 20 units ex-perienced CO_2 breakthrough before expenditure of the O_2 supply; 10 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. As mentioned above, the result 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. Breathing pressures in the SR-100 increase rapidly toward end of life, even in new apparatus. Elevated CO_2 levels will ac-celerate this rise. The termination of one treadmill test (human subject C) at 55 min was for high breathing pressures (+250 to −360 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 0.6%.

Figure 8 shows higher breathing pressures in the human subject treadmill tests than in the BMS tests. These could be caused by higher bed resistances or higher peak flow rates in the human test subjects than in the BMS. At the end of the first treadmill test, human subject A was experiencing minimum inhaled CO_2 levels of 3.6%, with unmeasured average inhaled levels even higher. Higher ventilation rates caused by the elevated CO_2 levels is a reasonable explanation for these high breathing pressures. The second treadmill test pressures were even higher, but these occurred with low CO_2 levels. Either the test subject's normal peak flow rates are higher than those of the BMS or the chemical bed had greater-than-average resistance. BMS test 15 also exhibited greater-than-average pressures, which cannot be attributed to higher ventilation rates. The apparatus for BMS test 15 had been carried into the mine and set on a mining machine daily, but six others were as well. This does not mean, however, that all units deployed in a certain way were subjected to equivalent shock and vibration. This particular unit may have suffered greater environmental impact than the others, or it may have been different in manufacture. The inhalation pressure reached our normal negative-pressure termination limit of −200 mm H_2O at 58 min. Termination was called, instead, when the bag was flat.

DRAEGER OXY-SR 60B

Eighteen of nineteen deployed and two of three new units passed the leak-tightness test.

The Wilcoxon rank-sum tests showed that both the wet- and dry-bulb temperatures of new units border on being sig-nificantly lower than deployed units. Two of the tests of deployed apparatus (units 14 and 18) showed wet-bulb temperatures much higher than the others. One treadmill test also showed a wet-bulb temperature as high. These imply increased humidity resulting from the various chemical processes occurring within the bed and its interaction with the user. Regardless of the cause and whether or not it resulted from damage while deployed, the impact on a user would be minimal: the inhaled wet-bulb temperatures never exceeded the human tolerance level in any of the tests.

Five deployed units reached 4% CO_2 before the O_2 supply was expended; all occurred before 60 min. One of these was on a treadmill test; the others, the BMS (table 7). One new unit tested on the BMS also experienced CO_2 breakthrough.

Although the Wilcoxon rank-sum test showed that deployed apparatus, as a group, did not differ with regard to CO_2 levels, the third BMS-tested deployed unit had much higher CO_2 levels than other deployed units, as can be seen in figure 9. Average inhaled CO_2 levels reached 4% at 47 min and 14% at 60 min.

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 AU-9A1	7-23	17	7-23	9	7-23	18	7-23	16	7-23	22	7-23	24	7-23	24
CSE SR-100	23-69	32	23-69	16	23-69	52	23-69	29	23-69	26	23-69	50	23-69	50
Draeger OXY-SR 60B	13-53	24	13-53	35	13-53	22	13-53	13	13-53	14	13-53	24	13-53	30
MSA Portal-Pack	8-28	18	8-28	25	8-28	25	8-28	20	8-28	26	8-28	28	8-28	24
Ocenco EBA 6.5	13-53	38	13-53	26	13-53	22	13-53	18	13-53	20	13-53	38	13-53	23

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

Table 5.—CSE AU-9A1 CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
Deployed: BMS	61	89
	69	96
	66	84
	74	91
	57	68
	60	88
Deployed: Human subject on treadmill	84	84
New: BMS	75	84
	70	93
	75	91

Table 6.—CSE SR-100 CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
Deployed: BMS	23	68
	61	62
	60	67
	65	66
	59	64
	44	73
	47	68
	48	72
	46	66
	31	70
	60	67
	62	64
	70	73
	58	68
	28	68
	35	68
New: BMS	64	65
	63	66

Table 7.—Draeger OXY-SR 60B CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
Deployed: BMS	51	65
	55	66
	47	68
	53	64
Deployed: Human subject on treadmill	51	51
New: BMS	66	70

This unit was carried and stored daily, as were most of the other deployed units.

As with CO_2 levels, the Wilcoxon rank-sum test showed that deployed apparatus, as a group, did not differ from new units with regard to exhalation pressures. However, figure 9 shows units 13 and 14 having higher exhalation pressures than other deployed units. The pressures were normal (around 50 mm H_2O) up to 50 min, then increased sharply. By the end of the test at 70 min, unit 13 reached 170 mm H_2O; unit 14 reached 430 mm H_2O at 73 min. Unit 14 would have challenged a wearer by the end. The second treadmill test had a similar exhaled pressure average. All three of these apparatus were the only ones with serial numbers in the 32,000 range. Whether or not the higher breathing resistances were the result of damage suffered during deployment or of manufacture or both, the user would have been impaired, if at all, only at the end of the apparatus' service life. In the case of the apparatus with the highest pressures, the user would have been inclined
to either modify his/her breathing or slow down to decrease peak flow rates in order to continue use until the complete expenditure of the O_2 supply.

MSA PORTAL-PACK

Six of eight deployed and two of three new apparatus tested for leaks passed.

The Wilcoxon rank-sum tests showed that new units had significantly higher inhalation pressures than deployed units. This would not negatively impact the user.

Six deployed units tested on the BMS reached 4% CO_2 before the O_2 supply was expended; two of these occurred before 60 min (table 8). All three new units tested on the BMS also experienced CO_2 breakthrough; two of these occurred before 60 min.

Table 8.—MSA Portal-Pack CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
Deployed: BMS	69	76
	62	70
	49	67
	63	65
	52	70
	72	76
New: BMS	49	71
	54	74
	64	69

We discovered that the chlorate candles of some units emitted a white smoke when activated. This caused two con-cerns: the reaction of the user to the sight of the smoke and the composition of the smoke. The gas produced from the candles of several units was sampled and analyzed by MSHA's Physical and Toxic Agents Div. These opened and activated units were sealed for later testing with manual starts; other than lower O_2 levels, they functioned satisfactorily as can be seen in figure 10. Both particulate and gaseous components were analyzed. The particulate sample had sodium and potassium salts as the primary contaminants. In addition, a barium salt, with an 8-h threshold limit value of 0.5 mg/m^3, was measured at 1.56 mg/m^3. The gas analysis also detected an unquantified level of benzene. NIOSH was notified of our findings. MSA performed its own gas analysis and detected benzene in one sample, but in a concentration greatly below the short-term exposure limit. We are less concerned about the short-term exposure to these contaminants than user response to visible white smoke. MSA's training videotape mentions the possibility of smoke; the written manual does not. A special notification from the manufacturer will be mailed to all users, or the manual will be updated to include mention of the smoke.

OCENCO EBA 6.5

Four of 39 deployed apparatus tested for breathing circuit tightness passed the leak test, while 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 categories, new units could not be distinguished from deployed units.

The high inhalation pressures exhibited by some of the apparatus on the BMS (figure 11) were caused by activation of the demand valves, some of which are relatively stiff. When the demand valve is not required, the inhalation pressures are low, reflecting low system resistance. The demand valve is called into use when the O_2 supply rate falls below the O_2 consumption rate. Whether and when this happens depends on the O_2 regulator and its factory setting, both of which can vary significantly. The average initial O_2 flow of the apparatus tested was 1.82 L/min ATPD, ranging from 1.53 to 3.66 L/min. The 3.66-L/min flow lowered somewhat after 10 min, such that the final duration for this apparatus was 89 min. Another apparatus (unit 28 in figure 11) had an initial O_2 flow of 2.4 L/min, but this increased after 5 min, as evidenced by relief valve use; this resulted in a duration of 36 min. The short duration and high O_2 flow rate resulted in low inhalation temperatures and high exhalation pressures, as can be seen in figure 11. This incident was reported to NIOSH and MSHA. Ocenco now inspects 100% of the O_2 regulators.

Sixteen deployed units tested on the BMS reached 4% CO_2 before the O_2 supply was expended; none occurred before 60 min (table 9). Several deployed units had much higher CO_2 levels than the rest, as can be seen in figure 11. User response would be as mentioned earlier.

Table 9.—Ocenco EBA 6.5 CO_2 breakthrough times, minutes

Type of unit and test method	CO_2 breakthrough	Final termination
Deployed: BMS	96	101
	105	108
	96	103
	99	101
	77	107
	87	111
	94	103
	104	109
	100	107
	95	98
	87	110
	97	103
	98	104
	96	101
	88	103
	79	108

The O_2 gauges of two units read 500 and 1,000 psi when their cylinders were empty.

When the cylinder valve was opened on one unit to measure its O_2 flow, there was a surge of O_2 such that the friction-fit connecting hose to the flow-measurement instrument was blown off. The O_2 gauge registered a 75-psi drop in cylinder pressure. This phenomenon did not recur when the cylinder valve was reopened for testing.

CONCLUSIONS

The results of this fifth-phase SCSR test study at PRC 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 to allow miners to escape safely during a mine emergency. However, the mining environment appears to have caused some performance degradation in the CSE SR-100: CO_2 levels are higher in deployed units than new ones (table 4 and figure 8). No statistically significant worsening in any performance category was detected in any other apparatus.

Because the Wilcoxon rank-sum test, by its nature, detects small changes in large numbers of units and tends to ignore large changes in small numbers of units, we should also pay attention to performance of individual units. Of concern are apparatus that possibly suffered extreme abuse and exhibited poor performance, yet passed inspection criteria. Examples include a Draeger OXY-SR 60B with high CO_2 levels (figure 9), another OXY-SR 60B with high exhalation pressures (figure 9), and several Ocenco EBA 6.5's with high CO_2 levels (figure 11). Although the Draeger OXY-SR 60B's are no longer in use, the Ocenco EBA 6.5's continue to be used and will be monitored for further signs of deterioration.

The incidents with cylinder gauges on the CSE AU-9A1 and the Ocenco EBA 6.5 indicating 500 psi and higher with empty cylinders suggest that their accuracy should not be relied upon and reaffirms that SCSR's should be used only for emergency escape, not for reentry into irrespirable atmospheres based on perceived remaining duration. Apparatus should be worn until reaching safety, then removed.

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. If not eliminated, this phenomenon must be clearly mentioned during training.

The short-duration Ocenco EBA 6.5 caused by the faulty O_2 regulator shows the importance of 100% inspection of all critical SCSR components.

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