PPE CASE

Personal Protective Equipment Conformity Assessment Studies and Evaluations

Point-of-Use Assessment for Closed-Circuit Escape Respirators Sampled from Mines that use both Subpart O and Subpart H Approved Units: First Phase

Evaluation Period: September 2019 to July 2020

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December 20, 2022

> ***Carriable Subpart H approved CSE SRLD SCSR units that passed the manufacturer's inspection all demonstrated the expected life support capacity over the course of the manufacturer's specified service time. NIOSH identified two Subpart O approved CSE SR2000 SCSR units that did not conform and notified the approval holder who withdrew approval due to changing market conditions while testing continued.***

Long-Term Field Evaluations (LTFEs)[1] provide performance, reliability, and user-maintenance compliance data from the point of use for closed-circuit escape respirators (CCERs). LTFEs for CCERs deployed to underground coal mines are performed jointly by the National Institute for Occupational Safety and Health's (NIOSH) National Personal Protective Technology Laboratory (NPPTL) and the Mine Safety and Health Administration (MSHA). In mining, CCERs are referred to as self-contained self-rescuers (SCSRs).

Previous LTFEs that randomly sampled from mining districts (first phase, second phase, and third phase) focused on respirators approved to Title 42, Code of Federal Regulations, Part 84, Subpart H. In 2019, NIOSH implemented a revised LTFE strategy that includes, for the first time, the collection and evaluation of units approved to the agency's 2012 update to the regulation, Subpart O. This revised strategy targeted units approved to Subpart O that were also exposed to more severe conditions. The strategy further targeted units approved to Subpart H that were within the same mines and exposed to similar conditions as the targeted Subpart O units. All findings obtained from LTFEs using this revised strategy will be documented in PPE (Personal Protective Equipment) CASE (Conformity Assessment Studies and Evaluations) reports by phases—beginning with phase one. **This report represents the first phase of the NIOSH PPE CASE**

[1] A list of acronyms and abbreviations is available in Appendix A.

reporting using the revised LTFE sampling strategy and presents findings for CSE SRLD and CSE SR2000 units that were collected and tested between September 2019 and July 2020. The SR2000 was an approved device for the first two tests. During these two tests, the device was found to be nonconforming. The manufacturer withdrew the approval for the SR2000 on June 19, 2020 before the remaining 38 SR2000 units were tested, citing changing market conditions as the reason for the approval withdrawal. Collection, testing, evaluation, and publication of results for the second and third phase have been delayed by the COVID-19 pandemic.

NIOSH's Revised LTFE Strategy

The revised LTFE strategy was designed to

(1) Verify that devices approved under Subpart O continue to meet approval performance requirements when deployed to the field. No such requirement exists for Subpart H devices; therefore, issues identified by NIOSH during previous LTFEs were not able to be treated as a non-conformance to the approval requirements. For Subpart O devices, failure to meet pre-market Capacity and Performance test requirements during post-market evaluations will be approached directly as approval non-conformance which should lead to quicker corrective action.

(2) Compare the protections provided by Subpart H and O devices at the point of use. At this time, both Subpart H and O devices are permitted by MSHA. This comparison will inform policy discussions between NIOSH and MSHA regarding the use of these devices in underground coal mines.

The revised LTFE strategy evaluates all currently approved Subpart H and O device models as follows:

- Collect, test, and evaluate **Subpart H and O** device types from the same mines and with the same deployment locations, (e.g., worn, mobile cache) and deployment times.
- Compare post-market performance of **Subpart O devices** sampled at the point of use to NIOSH's approval requirements.
- Compare post-market **Subpart H devices** sampled at the point of use to the machine test methods within Subpart O rather than the required human subject tests that had been used for their approval under Subpart H.
- Compare performance characteristics of post-market **Subpart H and O devices** sampled at the point of use for five critical protections (stressor data) — (1) oxygen capacity, (2) inspired CO_2 level, (3) inspired O_2 level, (4) inspired wet-bulb temperature, and (5) breathing resistance—and explore the impact of deployment location and deployment time on these protections. For this evaluation, average stressors for each SCSR test will be compared within SCSR type (i.e., Subpart H devices will be compared to one another, and Subpart O devices will be compared to one another).

NIOSH has taken a different approach from previous LTFEs by seeking smaller sample sizes and targeting specific mines possessing Subpart O and H approved units with the severest of exposures. One of the three mines targeted was closed before units could be collected and the two remaining participating mines provided all the units for this study. Twenty units of each device model were sampled from each collaborating mine site—15 units to be tested at a constant work rate, three units to be tested at a variable work rate, and two units representing an intentional oversampling as an allowance for any visual inspection failures.[2]

Device Types Included in This Report

NIOSH evaluated the CSE Subpart H approved SRLD and CSE Subpart O approved SR2000 in this study. As of April 2, 2019, when the MSHA quarterly inventory report was scanned for this current LTFE test project, there were 38,481 CSE SRLDs and 230 CSE SR2000s in U.S. underground coal mines. The SR2000 was an approved device for the first two tests in April, 2020. However, during these tests, it was found to be nonconforming. The manufacturer subsequently withdrew approval for the SR2000 on June 19, 2020 due to changing market conditions. The remaining 38 SR200 units were tested with the knowledge that the SR2000 was no longer a Subpart O approved device. Both the SRLD and SR2000 **(Figures 1 and 2, respectively)** are chemical-oxygen-generating SCSR units that employ an oxygen gas starter for initial operation while chemical oxygen is subsequently generated through chemical reaction as the sorbent absorbs carbon dioxide from the user's exhaled breath.

Photo by NPPTL

Figure 1. CSE SRLD

Photo by NPPTL

Figure 2. CSE SR2000

[2] NIOSH determined the number and distribution of units based on the minimum regulatory requirements for Subpart O requirements and historical test data of Subpart H devices—data from 868 field-deployed Subpart H units (assessed between 2009 and 2013) were statistically evaluated. Analysis 1: Sample size calculation for comparing two sample populations—this analysis provides insight into the manner in which sample size is expected to affect the minimum mean difference that would be detectable between two sampled populations (e.g., Subpart H vs. Subpart O devices) with a p-value of 0.05 and 80% power. Analysis 2: Sample size calculation for restricting margin of error for population parameters—this analysis provides insight into the manner in which sample size affects the margin of error to expect with 95% confidence when estimating the metric population parameter (i.e., the mean level of duration, percent inspired CO_2, percent inspired O_2, breathing resistance, and inspired wet-bulb temperature).

Subpart H Model

These units were approved by both NIOSH and MSHA under the requirements of Title 42, Code of Federal Regulations (CFR), Part 84, Subpart H as a “1-hour SCSR” as defined in Subpart H and in 30 CFR Part 75.1714-1 – Approved self-rescue devices.

Subpart O Model

These units were approved by both NIOSH and MSHA under the requirements of eCFR :: 42 CFR Part 84 Subpart O -- Closed-Circuit Escape Respirators as a CAP 3 unit, which is required by NIOSH to deliver at least 80L of oxygen when subjected to NIOSH Standard Test Procedures 0602, 0603 and 0604. MSHA considers the CSE SR2000 to be a “1-hour SCSR” as defined in 30 CFR Part 75.1714-1 – Approved self-rescue devices.

Units that NIOSH Sampled

MSHA requires mine operators to file a report of inventory for all SCSRs at a mine. Using this inventory, NIOSH identified three mines as possessing CSE SR2000 units. To determine the deployment location (wearable, mobile cache, or permanent cache), NIOSH contacted all three mines with these device types. **Table 1** below summarizes the deployment strategy for Subpart O devices at each of these three mines. To compare the protections provided by Subpart H and O devices at the point of use, NIOSH also examined the Subpart H devices deployed by the participating mines. Participating mines also deployed CSE SRLD units, which when compared to the Subpart O device of interest (CSE SR2000 units), are manufactured by the same company, use the same underlying technology (i.e., breathing air is generated from a chemical reaction), and are approved as “1-hour SCSRs.” In the text to follow, these Subpart H units (CSE SRLD) will be referred to as the “counterpart” to the Subpart O units (CSE SR2000).

NIOSH collected 20 CSE SR2000 and 20 CSE SRLD units from both mines X and Y in September 2019. Mine Z has been closed making it impossible to collect the desired units.

Table 1. Deployment Strategy for Underground Coal Mines Possessing CSE SR2000 Subpart O Approved Units

Mine Name	Mine Location	CSE SR2000 Count (Subpart O Approved Model)	CSE SRLD Count (Subpart H Approved Model)	CSE SR2000 Deployment Location	CSE SRLD Deployment Location
Mine X	KY	72	1,549	Rail-running and rubber-tire mantrip vehicles in rubber lined boxes	Carried by miners
Mine Y	KY	38	680	Rail-running and rubber-tire mantrip vehicles in rubber lined boxes	Carried by miners
Mine Z	IN	120	905	Stored on mobile mine equipment such as man-trips	Carried by miners

The mine operators were asked to pull units likely to experience the most severe storage conditions just prior to NIOSH's arrival for collection and to note the deployment location of each unit to include type of equipment and job function where appropriate.

In previous LTFEs, NIOSH rejected units targeted for collection that did not pass the manufacturer's visual inspection at the mines. However, the NIOSH revised sampling strategy accepted all units, regardless of visual inspection results, so long as there was remaining service time. This change in strategy allows NIOSH to document the frequency of visual inspection failure and explore these failures in more detail with close examination—surveillance data regarding the condition of deployed respirators in service is valuable in assessing mine operators' training effectiveness and compliance.

Table 2 summarizes the number and manufacturing date ranges of the units collected for this study.

Table 2. Summary of Units Collected

Manufacturer	Model	Number of units collected	Manufacture date range
CSE	SRLD (Subpart H device)	40	01/2018 – 09/2018
CSE	SR2000 (Subpart O device)	40	02/2018 – 11/2018

How NIOSH Tested and Evaluated Sampled Units

NIOSH conducted the following tests and evaluations on both the Subpart O and Subpart H units collected:

(1) visual inspection that miners are required to make before each shift which is applicable to all units and performed by NIOSH at the ABMS (Automated Breathing and Metabolic Simulator) laboratory
(2) laboratory acoustics solids movement detector test which is applicable only to the CSE SRLD units and performed by NIOSH at the ABMS laboratory to measure quantitative sound level
(3) portable acoustics solids movement detector test that must be performed on CSE SRLD units every 90 days by user/mine operator to measure sound level qualitatively (performed by NIOSH upon pick up at mine)
(4) phenolphthalein indicator check
(5) quantitative leak test
(6) ABMS test

Visual Inspection

NIOSH performed the same visual inspections at the ABMS laboratory that a miner is required to conduct prior to using the unit or taking it underground. All units not meeting the manufacturers specifications for the visual inspection must be taken out of service. Manufacturer's recommended visual inspections focus on the integrity of the case, seal, latches, and indicators that are viewable without opening or activating the respirator.

The cases of the CSE SRLD units have moisture and heat indicators to signify water penetration or excessive temperature exposure, respectively (**Figure 3a**). Damage to the case, missing case latches, broken seals, water penetration or excessive heat exposure are reasons for the CSE SRLD unit to fail the visual inspection. The unit is safe for use if all visual inspections pass.

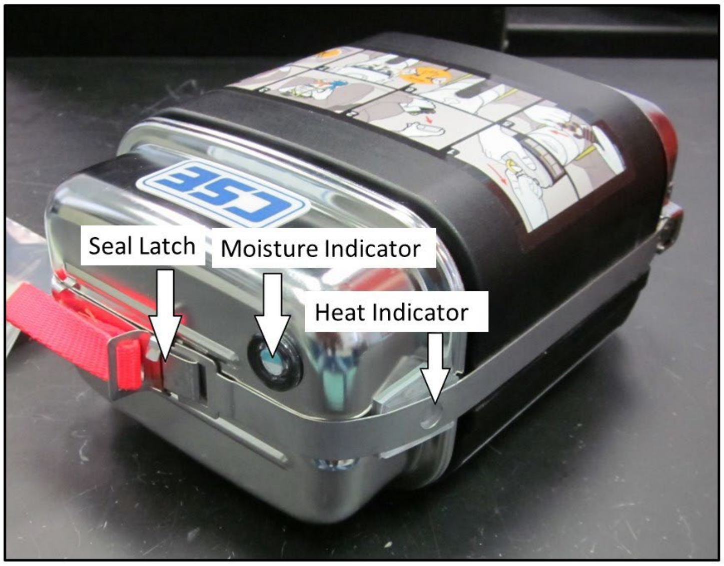


Photo by NPPTL

Figure 3a. Areas of Visual Inspection for CSE SRLD

The cases of the CSE SR2000 units possess an onboard VitalCheck system consisting of a flashing green light in the inspection window that continuously monitors certain conditions in the unit constantly (**Figure 3b**). These include electronic checks to assure that the onboard starter oxygen supply and the chemical bed that remove carbon dioxide and generate oxygen are acceptable, the case has not been opened, and the unit has not outlived its service life. The VitalCheck system reports problems by switching off the green light that flashes in 6-second intervals if all checks are okay. Damage to the case is an additional reason for the CSE SR2000 to fail visual inspection.

Figure 3b. Area of Visual Inspection for CSE SR2000

Phenolphthalein Indicator Check

Upon opening the unit's case and removing the mouthpiece plug, NIOSH wiped each mouthpiece and inner portion of the breathing tube with a swab soaked in phenolphthalein. This action indicated whether the granular sorbent/oxygen generator particles broke down into fine particles and entered the breathing circuit where they could be inhaled by the user. The phenolphthalein-soaked swab changing to pink in color after swabbing indicates the presence of these highly alkaline particles in the breathing zone of the unit.

Quantitative Leak Test

This test assesses breathing circuit integrity but is not required for approval. The leak test employs a vacuum source to induce a vacuum of 300 mm H_2O within the unit's breathing circuit while measuring the inward leakage rate with an in-line mass flow meter. The vacuum source's gas return tubing is connected and sealed on its opposite end to the mouthpiece of the unit being tested. A mass flow meter is installed in the tubing between the vacuum source and the mouthpiece connector to measure the flow rate of gas being evacuated from the unit's breathing circuit when the vacuum source is activated.

As the vacuum is adjusted and stabilized at 300 mm H_2O, the evacuated gas flow rate decreases and stabilizes. The stable evacuated gas flow rate is the unit leak rate. At maximal work rates, inhalation pressure/vacuum should not exceed +200- or -300-mm H_2O [Hodgson 1993] and inward leakage rates should be less than 500 milliliters per minute (mL/min) to reasonably assure user protection for a period equal to or greater than the rated service. The inward leakage threshold of 500 mL/min is a function of the NIOSH 200-ppm, one-hour threshold limit value (TLV) for carbon monoxide (CO). An inward leakage rate of 500 mL/min in a 10% CO atmosphere at a peak inhalation rate of 250 liters per minute over one hour corresponds to a CO volume fraction of 0.0002 or 200 ppm.

Mouthpiece connectors shaped as closely as possible to the internal dimensions of the unit's mouthpiece opening are used to seal the unit to the ABMS trachea. Custom fabrication of these mouthpieces to match the unit's mouthpiece opening is required to optimize the fit and prevent the connection from being a source of inward leakage. Care is taken when inserting the connector into the unit's mouthpiece to be tested and securing it tightly with a wire tie. Putty is used, as necessary, to enhance this seal and stop any residual inward leakage. The mouthpiece connector is tightly sealed to the vacuum source. The vacuum source is provided by a vacuum pump with interconnecting tubing for the QNT. Leakage within the breathing circuit of the unit being tested under vacuum is confirmed by pinching and sealing the breathing hose just below the mouthpiece connector.

Acoustic Solids Movement Detector Test

In addition to the visual checks, the CSE SRLD user instructions states that units are to be tested in the field every 90 days with a portable solids movement sound detector to determine the condition of the chemical bed used to remove carbon dioxide and generate oxygen. The Acoustic Solids Movement Detector (ASMD) is a device used to identify loose particles that lead to channeling of breathing gas flow in the chemical bed of chemical-oxygen-generating CSE SRLD units. CSE SRLD units with such damage promote a decrease in breathing gas residence time in the chemical bed and the hastening of CO_2 breakthrough. The ASMD analyzes the sound induced in a CSE SRLD unit by shaking it in a controlled manner. The sound level produced by the CSE SRLD when shaken is used as an indicator of shock and vibration damage incurred by the chemical bed within the unit. In the field, users make this assessment qualitatively using a handheld CSE Corporation ASMD instrument.

Upon collection at the mine, qualitative sound level assessments were performed on the 40 CSE SRLD units collected using a portable, handheld ASMD provided by CSE. Once at the NIOSH facility, a laboratory version of the handheld ASMD was used. The laboratory version of the handheld ASMD rotates the SRLD at 10 rpm in an anechoic chamber to quantitatively measure sound levels in decibels (dB). A blank calibration unit filled with cement is used to measure a baseline sound level. The results from testing the calibration unit are used to compare with the sound level measured for units under test. Mine deployed CSE SRLD units for which sound levels higher than 60 dB are measured fail the test.

Automated Breathing and Metabolic Simulation Test[3]

The computer controlled ABMS (**Figure 4**) injects carbon dioxide (CO_2) into and removes oxygen (O_2) from its breathing circuit while operating at fixed breathing frequencies and tidal volumes to simulate human metabolic processes [Kamon et al. 1984]. The ABMS machine is an ideal device for evaluating inspired CO_2 and O_2 concentrations in SCSR units due to its high degree of accuracy and repeatability in simulating human CO_2 production and O_2 consumption. By design, an ABMS replicates breathing ventilation (respiratory frequency, tidal volume, flow, temperature, and humidity), O_2 consumption, and CO_2 production.

Photo by NPPTL

Figure 4. Automated Breathing and Metabolic Simulator

A National Instruments' LabVIEW-based software application manages the operation of the ABMS. Test input parameters required to initiate a simulation operation include the metabolic oxygen consumption rate (VO_2), and metabolic carbon dioxide generation rate (VCO_2), respiration rate, and tidal volume set points. LabVIEW software subroutines work to control the piston operation and maintain the VO_2 and VCO_2 set points through the control of the injection rates of CO_2 and N_2 streams into the breathing circuit and the exhaust gas stream

[3] Proper care and maintenance of the ABMS is essential to ensure data quality. Refer to Appendix B for information about NIOSH's recent system upgrades and validation efforts.

flow rate (containing O_2) out of the breathing circuit. Measurements of respiratory gas constituents, O_2 and CO_2, breathing resistances, and wet- and dry-bulb temperatures are recorded at 60 Hz. These measurements are used to provide real-time test data displays and in the final analysis of test performance.

As outlined in the sampling strategy, the majority of collected units were tested and evaluated using the constant[4,5] work rate identified in **Table 3**. For Subpart O approved units, this work rate corresponds to a CAP 3 oxygen delivery volume of $\geq$80 Liters, as outlined in its regulation[6]. For Subpart H approved units where human subjects testing, not ABMS testing, is a requirement, this constant work rate represented the 50th percentile miner—body weight of 87 kg or 192 lbs—performing the one-hour man test 4 as described in 42 CFR, Part 84, Subpart H [Kamon et al. 1975]. The ABMS was programmed to simulate human respiration at a VO_2 of 1.35 (liters/min) L/min, VCO_2 of 1.15 L/min, a ventilation rate of 30 L/min, and respiratory frequency of 18 breaths per minute. During testing, the ABMS monitored metabolic stressors which included inspired levels of CO_2 and O_2, inspired wet- and dry-bulb temperatures, and peak inhalation and exhalation breathing resistances (pressures) continuously until the test was terminated.

Table 3. Constant Average Metabolic Work Rate (CAP 3 Capacity Test)

Metabolic workload	Rate
O_2 Consumption	1.35 L/min
CO_2 Production Rate	1.15 L/min
Ventilation Rate	30 L/min
Tidal Volume	1.68 L/breath
Respiratory Frequency	17.9 breaths/min
Peak Inhalation	83 L/min
Peak Exhalation	67 L/min

The remaining units were tested and evaluated using the variable[7] work rate performance test protocol from Subpart O (**Table 4**). Again, for Subpart O approved units, this varied work rate aligned with the regulation. Although planned, no Subpart H approved units could be tested using the variable work rate Performance test

[4] The constant work rate eliminates nearly all variability in the ABMS.
[5] Approval testing under 42 CFR Part 84, Subpart H using human subjects imposes high and low work rates that are not reproduced by a constant work rate from an ABMS. Human subjects may differ from each other and from ABMS tests in terms of CO_2 production rate, ventilation rate, and respiratory frequency. Thus, although the average work rate (and O_2 consumption) is the same between human subjects and ABMS tests with a constant work rate, ABMS tests shall not be considered equivalent to Subpart H approval testing. However, ABMS tests can be used to provide an indication of unit duration performance (i.e., the length of time that a unit will operate at a constant work rate before the oxygen supply becomes fully expended). Also, stressor levels are continuously monitored during LTFE testing, whereas they are sampled only between work activities in approval testing. In addition, LTFE testing continues until the apparatus breathing gas supply is expended or stressor levels exceed allowable parameters, whereas testing during approval ends at the rated duration, even if the capacity of the apparatus exceeds it.
[6] Refer to NIOSH Standard Test Procedures (STP) 0602, 0603 and 0604.
[7] Since the ABMS must transition between work rates, some variability in the test method is introduced when a variable work rate is used. However, the variable work rate simulates peak, high, and low work rates which could be encountered by an escaping mine worker.

due to the high number of visual inspection failures—the constant work rate tests were prioritized as the constant work rate eliminates nearly all variability that may be introduced by the ABMS itself.

Tests on the ABMS are terminated upon one of three endpoints: exhaustion of the O_2 supply as indicated by peak inhalation pressures reaching -300 mm H_2O, coinciding with an empty breathing bag; average inspired CO_2 levels exceeding 10%; or inspired O_2 levels falling below 15%. When these limits are exceeded, the ABMS gas metabolism is compromised, and further data are not acceptable for analysis. It should be noted that for all testing described in this report, test operations were stopped when the peak inspired breathing resistance exceeded -300 mm H_2O and the breathing bag simultaneously collapsed. Continued operation of the ABMS beyond this point would result in exponentially higher breathing resistances (both peak inspired and peak expired) and damage to the pressure transducer used to measure the breathing circuit pressure, the piston linkage and piston drive motor.

Table 4. Variable Average Metabolic Work Rates (Performance Test)

Metabolic workload	Peak Rate	High Rate	Low Rate
O_2 Consumption	3.00 L/min	2.00 L/min	0.50 L/min
CO_2 Production Rate	3.20 L/min	1.80 L/min	0.40 L/min
Ventilation Rate	65 L/min	44 L/min	20 L/min
Tidal Volume	2.60 L/breath	2.20 L/breath	1.67 L/breath
Respiratory Frequency	25 breaths/min	20 breaths/min	12 breaths/min
Peak Inhalation	176 L/min	122 L/min	52 L/min
Peak Exhalation	152 L/min	102 L/min	52 L/min

Reference Unit Evaluations

Units purchased by NIOSH in April, 2019 were evaluated using the ABMS for performance comparisons with mine deployed units collected in September, 2019. NIOSH tested 11 CSE SRLD and 11 CSE SR2000 reference units after every fourth to fifth mine deployed unit test during this study. The same work rate at which the deployed units were tested was used when testing the reference units. Prior to evaluation, NIOSH performed the manufacturer's recommended visual inspections on the reference units to ensure qualification for ABMS testing. This included the laboratory ASMD testing for the CSE SRLD units.

Stressor Test Data

Stressor data collected in this study were inspired O_2 mole fraction, inspired CO_2 mole fraction, PEPRS MMH2O (peak expired pressure, mm H_2O), PIPRS MMH2O (peak inspired pressure, mm H_2O), and TAVGWB (average inspired wet-bulb temperature). NIOSH averaged the minute-average values of the stressors monitored during ABMS testing of each Subpart H approved unit over its rated service time to standardize the assessment in comparison to previous LTFEs[8]. In contrast to Subpart H unit data analysis, NIOSH averaged the minute-average values of the stressors monitored during ABMS testing of Subpart O approved units over the entire duration of each test, until the breathing gas supply was expended, and the breathing bag collapsed, as per the requirements of 42 CFR Part 84, Subpart O approval testing. This allows NIOSH to compare the results for LTFE

[8] Use of full test duration results for Subpart H approved units introduces stressor data variances that prevent valid comparisons between individual tests and with previous LTFEs.

testing of Subpart O approved units with their approval stressor test data and Subpart O stressor pass/fail criteria.

All average stressor data from the testing of deployed units and reference units were then averaged to obtain a *composite average*, which was used to detect any change in performance of deployed units. NIOSH tabulated this information, along with stressor minimums and maximums for each set of tests, to assess the deployed units' performance.

Results of Visual Inspections, Tests, and Evaluations

Unit Collection

NIOSH planned the collection of 80 units deployed in two U.S. underground coal mines for this study. From this group, 40 units represented CSE SRLD and 40 units represented CSE SR2000. Per the sampling strategy, none of the 80 targeted units were rejected at the mines and all were returned to NIOSH for detailed visual inspection and testing.[9] All CSE SRLD units collected were from miners who had been carrying them and all CSE SR2000 CCER units collected were from mobile mine equipment. **Tables 5** shows the job functions and the number of CSE SRLD units obtained for each job function for this study. Likewise, **Table 6** shows the types of mobile mine equipment and the number of CSE SR2000 units obtained from each mobile mine equipment type for this study.

Table 5. CSE SRLD Miner Job Function Breakdown

Job Functions of Miners Carrying CSE SRLD SCSR Units Collected for This Study	
Job Functions Cited by Mine	**Number of miners carrying SRLD per job function**
Mobile bridge operator	**1**
Bolter operator	**7**
Electrician	**7**
Mine foreman	**3**
Continuous miner operator	**6**
General laborer	**3**
Pre-Shift mine examiner	**2**
Scooptram operator	**8**
Shuttle car operator	**2**
Surveyor helper	**1**

[9] Given the small sample size required to obtain valid test data and the targeting of specific deployment types, previous LTFE study issues associated with the inability to collect targeted units that were missing, removed from service, not feasible to be collected or unreachable due to mine closure/abandonment were eliminated.

Table 6. CSE SR2000 Mobile Cache Location Breakdown

Mobile Mine Equipment Cached Location for CSE SR2000 CCER Units Collected for This Study	
Mobile mine equipment type	**Number of SR2000 CCER Units per location**
EJC Scooptram	**6**
Electric Rail Mantrip	**20**
Diesel Powered Mantrip	**14**

From the 80 collected units, 6 units failed the visual inspection. NIOSH subsequently tested 78 units (two of the units that failed visual inspection were not tested): 38 CSE SRLD units and 40 CSE SR2000 units (**Table 7**).

Table 7. Test Summary for Units Passing Visual Inspection at the Mine and NIOSH Test Laboratory

Model	Targeted	Collected at Mines	Passed Visual Inspection at NIOSH Test Laboratory	Tested	Obtained Valid Test Data
CSE SRLD	40	40	34	34	34
CSE SR2000	40	40	40	40	40
Totals	**80**	**80**	**74**	**74**	**74**

CSE SRLD

Visual Inspection

Six of the 40 CSE SRLD units collected for this study failed the visual inspection and four were tested as per the requirements of the LTFE strategy (the remaining two units that failed visual inspection were not tested because they incurred excessive damage). The failed visual inspections identified when applying the manufacturer's criteria were due to excessive heat exposure (n=3; two scoop operators and one electrician), excessive moisture exposure (n=2; one continuous miner operator and one mine foreman), and a damaged case (n=1; electrician). NIOSH reported information related to these visual inspection failures to MSHA for follow-up with the mines supplying the SRLD units.

Phenolphthalein Indicator Test

None of the CSE SRLD units tested failed the phenolphthalein indicator test.

Quantitative Leak Test

The breathing circuit integrity check of the CSE SRLD using the QNT leak test procedure showed that all units tested had a leak rate less than 500 mL/min (passing limit). The average leak rate for all mine deployed units tested was 27± 30.1 mL/min (average±SD).

Acoustics Solids Movement Detector Test

All units collected at the mine passed the initial qualitative ASMD screening test that used the portable, handheld ASMD provided by CSE. NIOSH tested all 40 CSE SRLD units collected from the mines on the laboratory ASMD to obtain quantitative sound level measurements. During this testing, all sound levels measured less than 60 dB, the pass/fail limit for this test as established by CSE. The average sound level measured for the 40 mine deployed units using the laboratory ASMD was 21±5 dB (A) (mean±SD) with 58% of the units (n=23) having a sound level of 18 dB (A) and 5% of the units (n=2) having the maximum sound level observed of 35 dB (A). An analysis of the 11 reference units showed 10 units as having a sound level of 18 dB (A) and one unit having a sound level of 21 dB (A) (18±1 dB (A)). Comparing the mine deployed units to the reference units, 43% (n=17) of the mine deployed units demonstrated sound levels greater than the average of 18 dB (A) observed for the reference units.

Automated Breathing and Metabolic Simulation Test

The 34 mine deployed CSE SRLD units that passed the previous tests and evaluations were tested on the ABMS using the constant work rate. Too many pre-test inspection failures of the SRLD occurred to run the variable work rate tests and NIOSH decided that it was more important to obtain constant work rate data for the remaining SRLD units that passed the visual inspection testing. This was done to adhere to the minimum number of constant work rate tests required to maintain a statistically valid sample for that portion of the testing. After initiation on the ABMS, all mine deployed and reference CSE SRLD units continued operating until the breathing gas supply was fully expended. All mine deployed and reference units exceeded the NIOSH-approved 60-minute service time and the average duration (when the breathing bag collapsed) for both measured 73 minutes. All CSE SRLD units tested provided acceptable inspired O_2 levels during the entire 60-minute approved service time.

Inspired CO_2 levels measured for one of the 34 mine deployed unit tests exceeded 4% prior to reaching the 60-minute NIOSH-approved service time. Inspired CO_2 levels measured for 23 of the remaining 33 mine deployed unit tests exceeded 4% after the 60-minute service time was reached but prior to the expenditure of breathing gas in the breathing bag. In contrast, none of the 11 CSE SRLD reference units exhibited inspired CO_2 levels exceeding 4% prior to the breathing gas becoming fully expended. Summary statistics for the mine deployed units are provided in **Table 8** and unit-specific data is available in **Appendix C** for review.

Table 8. Summary of CSE SRLD 4% CO_2 Breakthrough Times

	4% Inspired CO_2 Breakthrough Time, minutes	Test Duration, minutes	Inspired CO_2 at 60 minutes, Mole %	Maximum Inspired CO_2, Mole %
Mean	**69**	**75**	**2.79**	**6.44**
SD	**5**	**2**	**0.81**	**1.44**
Min	**49**	**67**	**2.26**	**4.61**
Max	**73**	**77**	**6.42**	**9.91**

NIOSH averaged the minute-average values of the stressors monitored during ABMS testing of both mine deployed and reference CSE SRLD units over the first 60 minutes of the test and the results are presented graphically in **Appendix D** (**Figures 5 through 10**). Sixty-minute data averaging was chosen to be consistent with the approved 60-minute service time for the subpart H approved CSE SRLD SCSR unit.

For the stressor data, the *composite average* (defined earlier) across all mine deployed units that passed visual inspection is shown in **Table 9**. Also shown in **Table 9** is the percent difference between the average stressor data of the mine deployed and reference units (data are shown relative to mine deployed unit values). Mole fraction, as used, is defined as moles of breathing gas constituent, O_2 or CO_2, per 100 moles of breathing gas. A notable difference exists between average inspired CO_2 levels measured for the 34 mine deployed units (1.90 mole %) and the 11 reference units (1.61 mole %) where the mine deployed units were 18.1% higher than the reference units.

Also, inspired CO_2 levels are slightly higher, inspired O_2 levels are slightly lower, and maximum inspired and maximum expired breathing resistances are slightly higher for the mine deployed units. These trends are also noticeable in the least squares fit to the data plots of these stressors shown in **Figures 6, 7, 8, and 9**, respectively, in **Appendix D**. Test duration and wet-bulb temperature are the same or nearly the same for both mine deployed and reference units. It should be acknowledged that the Inspired O_2 levels are just slightly lower for the deployed units and nowhere close to falling below the required pass/fail level.

NIOSH also tested four of six CSE SRLD units that failed the manufacturer's visual inspection. NIOSH did so to determine whether these units were still meeting performance requirements and feels this information is helpful to the approval holder. For example, this information could help manufacturers further assess and consider their unit inspection requirements. Two of these six were not tested, however, because their insulation coverings had loosened which would have exposed the hot metal sorbent container to test operators and the cooler lab atmosphere. The resultant lower sorbent temperature would render invalid test results in comparison to all other tests of units with fully intact insulation coverings. *Composite average* stressor data for the four tests is shown in **Table 10**. As shown, the average inspired O_2 level is lower, and the breathing resistance is higher for the units that were identified as failures in comparison to the mine deployed units that passed visual inspection. It should again be acknowledged that the Inspired O_2 levels for these tests are just slightly lower for the deployed units and nowhere close to falling below the required pass/fail level.

Table 9. CSE SRLD Tested Under a Constant Work Rate, Test Duration and Composite Stressor Data

	DURATION (MIN.)	Ins O2 Mole Frac	Ins CO2 Mole Frac	PEPRS (MMH2O)	PIPRS (MMH2O)	TAVGDB (°C)	TAVGWB (°C)
All SRLD Deployed Unit Data for Perry County Coal Co. Mines E4-1 & E4-2 (34 tests)							
MIN	**64**	**0.6816**	**0.0161**	**51**	**-87**	**38.80**	**32.33**
MAX	**77**	**0.7434**	**0.0328**	**72**	**-62**	**41.12**	**34.09**
AVERAGE	**73**	**0.7269**	**0.0190**	**57**	**-69**	**40.03**	**33.28**
% Difference	**0.44**	**-1.63**	**18.08**	**9.08**	**6.80**	**-2.25**	**-0.16**
SRLD NIOSH Reference Unit Data (11 tests)							
MIN	**70**	**0.7205**	**0.0151**	**47**	**-69**	**39.51**	**32.29**
MAX	**76**	**0.7524**	**0.0173**	**55**	**-58**	**42.18**	**33.91**
AVERAGE	**73**	**0.7390**	**0.0161**	**52**	**-65**	**40.95**	**33.33**

Table 10. CSE SRLD That Failed Visual Inspection Tested Under a Constant Work Rate, Test Duration and Composite Stressor Data

	DURATION (Min.)	Ins O2 Mole Frac	Ins CO2 Mole Frac	PEPRS (MMH2O)	PIPRS (MMH2O)	TAVGDB (°C)	TAVGWB (°C)
SRLD Deployed Unit Failure Data (4 tests)							
MIN	**60**	**0.3886**	**0.0165**	**55**	**-90**	**37.89**	**33.17**
MAX	**77**	**0.7355**	**0.0190**	**74**	**-65**	**41.09**	**34.09**
AVERAGE	**69**	**0.6380**	**0.0174**	**62**	**-76**	**39.90**	**33.65**

CSE SR2000

Visual Inspection

All 40 CSE SR2000 units collected from the mines for this study passed the visual inspection and only minor scrapes and abrasions were observed on their cases. In addition, NIOSH observed all 40 SR2000 units' onboard VitalCheck system's flashing green lights to be blinking 10-11 times per minute, indicating no issues with the starter oxygen supply or the chemical bed were detected by the system.

Phenolphthalein Indicator Test

None of the CSE SR2000 units returned for testing failed the phenolphthalein indicator test.

Quantitative Leak Test

The breathing circuit integrity check of the CSE SR2000 units using the QNT leak test procedure showed that all mine deployed units tested had a leak rate less than 500 mL/min (i.e., passed). The average leak rate was measured at 11±9.3mL/min (average±SD).

Acoustics Solids Movement Detector Test

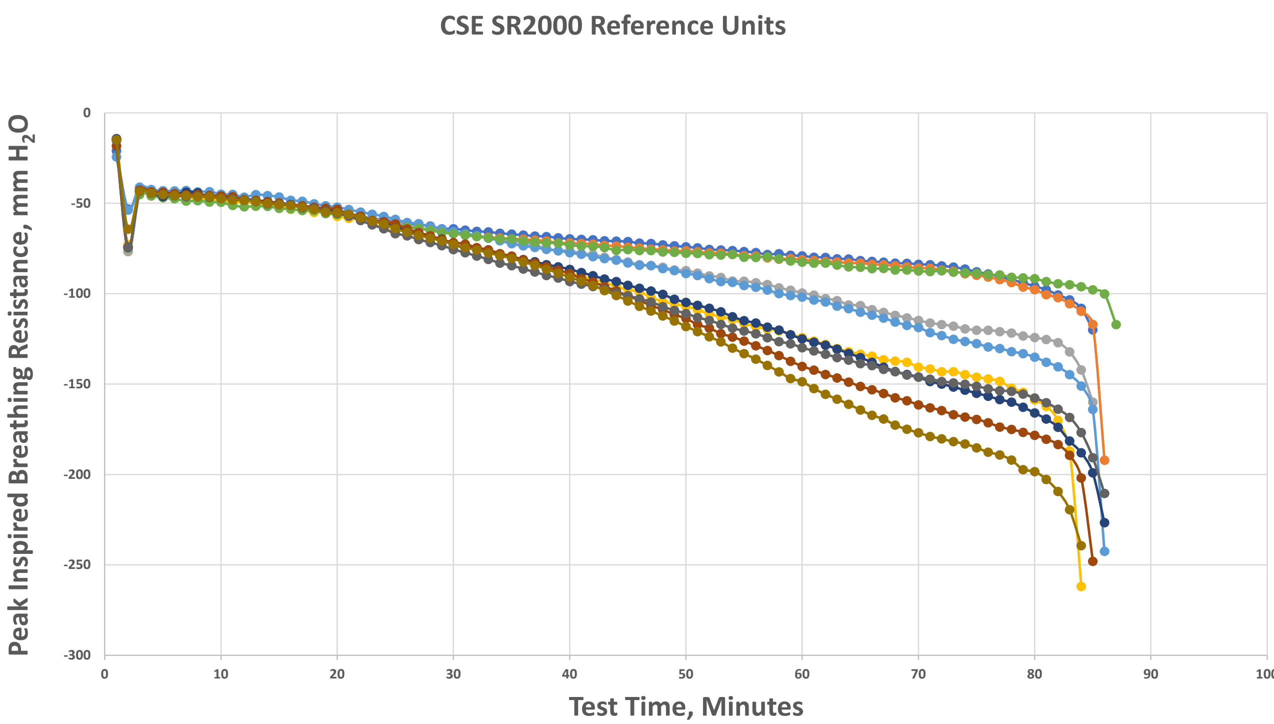
Not applicable to the CSE SR 2000 units per CSE manufacturer instructions.

Automated Breathing and Metabolic Simulation Test

NIOSH initiated tests of mine deployed CSE SR2000 units at a constant (n=35) and variable (n=5) work rate and test failures were immediately observed. Only two SR2000 units operated long enough to deliver the oxygen capacity required by a unit approved to Subpart O as a CAP 3 device ($\geq$80 L). One of the two units that met the Subpart O Capacity test requirement failed due to exceeding the full-test peak breathing resistance delta pressure limit of 200 mm H_2O (221 mm H_2O) The remaining 38 mine deployed units failed due to the peak inspired breathing resistance exceeding the one-minute average excursion limit of -300 mm H_2O. The average duration for 33 units tested at a constant work rate (a Capacity test as outlined in Subpart O) was 47.4 minutes (64 Liters O_2 delivered) while the average duration for five units tested at a variable work rate (a Performance test as outlined in Subpart O) was 30.4 minutes (50 Liters O_2 delivered). Test durations $\geq$ 60 and 42.5 minutes, respectively, are required for a CAP 3 rated unit to provide $\geq$80 L of oxygen and pass the oxygen delivery requirements for Subpart O Capacity and Performance approval tests. The average duration of the two units exceeding the CAP 3 oxygen delivery requirements while undergoing the Capacity test was 68.0 (92 Liters O_2 delivered) minutes.

All but two of the 40 CSE SR2000 unit tests were ended prematurely due to failure characterized by exceeding the -300 mm H_2O inspired breathing resistance stressor limit. This rendered most test data obtained from these tests as not meaningful nor valid. Therefore, NIOSH provided the reporting of stressor data averages only for the two units that exceeded CAP 3 oxygen delivery requirements and not for the entire set of tests. NIOSH tested 12 reference units (11 Capacity tests and one Performance test) interspersed among the 40 CSE SR2000 units evaluated. All but one reference unit passed the required pass/fail criteria. The one reference unit failure was during a Capacity test and was due to the average inspired CO_2 (1.51%) for the full test duration exceeding the 1.50% limit. In keeping with Subpart O test data approval requirements, NIOSH averaged the minute-average values of the stressors monitored during Capacity testing of the 10 reference and two mine deployed units over the entire duration of the test and the results are presented graphically in **Appendix E** (**Figures 11 through 16**).

A comparison of the inspired breathing resistance profiles versus time for reference (**Figure 17A**) and the failed mine deployed (**Figure 17B**, n=33) CSE SR2000 units tested using the CAP 3 work rate provides evidence regarding the reason for failure—excessive inspired breathing resistance (the individual lines on each plot refer to each unit tested). For the reference units, peak inspired breathing resistance increased gradually until at least 80 minutes into the test before falling off rapidly as breathing gas became fully expended and the breathing bags collapsed. As shown, the peak inspired breathing resistance increased rapidly after approximately 37 minutes into each test for the mine deployed units. Total test times ranged from 42 (57 Liters O_2 delivered) to 57 (77 Liters O_2 delivered) minutes for the mine deployed units before the breathing bag collapsed and testing was ended.



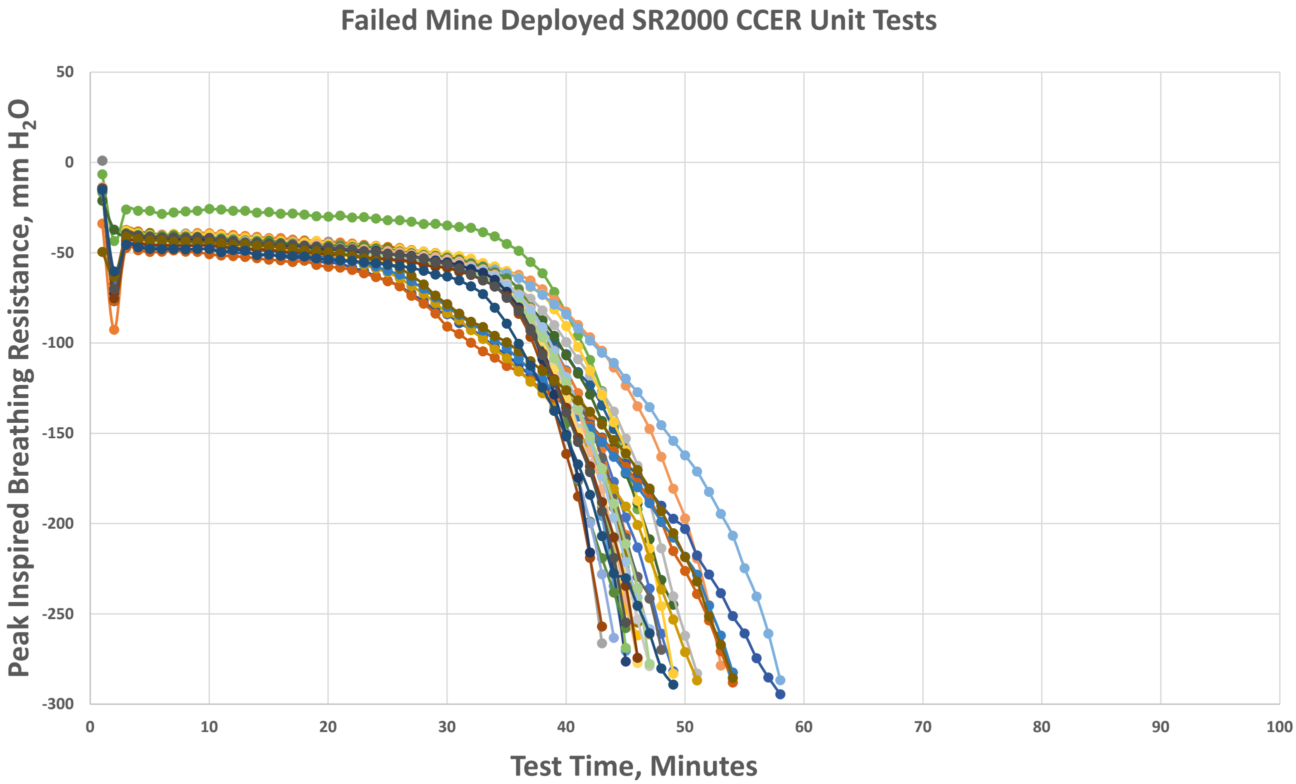


Figure 17A, CSE SR2000 Reference Units (top); Figure 17B, Mine Deployed CSE SR2000 Units (bottom)

Test duration and composite average stressor data are shown for the 11 reference and two mine deployed CSE SRLD units that exceeded the CAP 3 capacity rating in **Table 11**. The percent difference between reference unit mean stressor data versus mine deployed unit stressor data, relative to mine deployed unit mean stressor data, is also shown in **Table 11**.

Table 11. CSE SR2000 Under a Constant Work Rate (Capacity Tests per Subpart O), Test Duration and Composite Stressor Data

	DURATION (MIN.)	FIO2 MOLE FRAC	FICO2 MOLE FRAC	PEPRS (CMH2O)	PIPRS (CMH2O)	TAVGDB (ºC)	TAVGWB (ºC)
CSE SR2000 CCER Mine-Deployed Unit Data (2 tests that exceeded Cap 3 Oxygen delivery)							
MIN	**63**	**0.8175**	**0.0132**	**83**	**-125**	**40.29**	**33.07**
MAX	**73**	**0.8274**	**0.0139**	**96**	**-107**	**42.07**	**33.62**
AVERAGE	**68**	**0.8225**	**0.0135**	**90**	**-116**	**41.18**	**33.35**
% Difference	**-20.0**	**-3.7**	**4.5**	**29.5**	**27.6**	**7.7**	**-1.1**
All CSE SR2000 CCER Reference Unit Data (11 tests)							
MIN	**83**	**0.8188**	**0.0119**	**53**	**-111**	**35.83**	**30.80**
MAX	**86**	**0.8761**	**0.0151**	**85**	**-69**	**42.48**	**34.79**
AVERAGE	**85**	**0.8545**	**0.0129**	**69**	**-91**	**38.24**	**33.72**

CASE Findings

CSE SRLD (Subpart H Approved Device)

This visual inspection failure frequency for CSE SRLD units was 15% indicating a need to further train miners and mine operators who use or own these units to fulfill the requirements of the manufacturer's recommended visual inspections. The six units that failed the visual inspection should have been removed from service and would not have been available to collect if either the proper visual inspections had been adequately performed by their users or the units were removed when the users knew that the inspection criteria were exceeded. Mine operators should engage with miners to ensure that visual inspections are being performed in accordance with the manufacturer's instructions, both in terms of frequency and completeness. These units were collected in September 2019 and were manufactured between January 2018 and September 2018. Thus, the total exposure time to the units' use conditions could not have exceeded one year and nine months. Future collections using NIOSH's revised LTFE sampling strategy will be needed to determine if this failure rate changes as the units are exposed to use conditions for longer periods of time—the NIOSH approval for service life is 5 years when carried and 10 years when cached. It is important to note that service life is defined as the maximum limit after which all units need to be removed even if they continue to pass visual inspection.

While all units tested met the requirements for the qualitative and quantitative sound level testing, it should be noted that, when compared to the reference units, 43% (n=17) of the mine deployed units demonstrated sound levels greater than the average of 18 dB observed for the reference units. This difference in quantitative sound level measurements between mine deployed and reference units indicates that mine exposure caused minor sorbent breakdown to occur. As per the manufacturer, this is expected. In addition to being exposed to the effects of being carried by miners while on foot in the mines, these units were also subject to additional vibration by miners carrying these devices while riding transport vehicles or operating mobile mine equipment. As with the visual inspections, future collections where NIOSH reports its results for the manufacturer's sound level inspection requirements will be needed to determine if this failure rate changes as the units are exposed to use conditions for longer periods of time.

Of importance, this study tested units that were worn by miners whose job types involved riding in mobile equipment: mobile bridge operation (n=1); scoop operator (n=8); and shuttle car operator (n=2). Thus, more than 25% of the units that NIOSH sampled (11/40) were exposed to extremely challenging use conditions that included routine exposure to jolting and jarring. Two of the six visual inspection failures were associated with miners who wore their units while operating mobile mine equipment (scoop operators). Additionally, two other visual inspection failures were associated with electrical personnel. However, it is important to note that units which are carried are subjected to greater abuse, regardless of occupation.

The mine deployed CSE SRLD units (n=34) that passed the manufacturer's inspection criteria all demonstrated the expected life support capacity over the course of the manufacturer's specified service time. Breathing resistances measured for all CSE SRLD units tested were well within limits accepted as tolerable (-300 to +200 mm H_2O) based on research conducted at Penn State University's Noll Laboratory [Hodgson 1993]. The 18% increase in the average inspired CO_2 level and slight increases in breathing resistance, when compared to the reference units, demonstrates that a slight degradation in CSE SRLD unit performance exists because of the units being exposed to use conditions. No trends in stressor data were observed based on individual job descriptions.

Although human-facilitated and machine results are similar, data reported from machine testing is not to be considered a direct equivalent to a Subpart H approval human subject test. Unlike the Subpart H approval testing, which relies solely on human subjects to evaluate the units, NIOSH performs its LTFEs using an ABMS. The ABMS tests are designed to be highly reproducible so comparisons between reference units and mine deployed units are valid. The ABMS tests are also intended to stress the functionality of the units towards the high end of their life support capabilities. While this LTFE uses test conditions that are not directly aligned with the approval requirements for Subpart H approved units[10], it is important to remember that one of the goals of LTFEs is to assure that units passing all required inspection and non-destructive testing requirements, as found in mines, will provide the expected life-support capacity when they are properly used and cared for by users. Unless specifically noted otherwise, the report should be viewed as providing that evidence.

CSE SR2000 (Subpart O Approved Device)

NIOSH recorded all but one mine deployed CSE SR2000 unit tests as failures. NIOSH obtained and evaluated all 40 CSE SR2000 units that passed the manufacturer's visual inspection criteria for this study from two mines where the units were cached on mobile mine equipment. The vibration and shock exposure resulting from this deployment location are suspected to have caused channeling of breathing gas flow in the chemical bed of these chemical-oxygen-generating units.

As is evident when comparing the inspired breathing resistant profiles, the inspired breathing resistance for the mine deployed units is generally flat for the first 30 minutes of the tests. However, the increase in breathing resistance is generally continuous for the reference units not only for the first 30 minutes, but for the entire test. This likely indicates that channeling had occurred in the sorbent bed of the mine deployed units and the breathing gas was taking the path of least resistance through the voids that had been created, resulting initially in an overall lower pressure drop across the sorbent bed for the first 30 minutes followed by a sharp drop off immediately thereafter, ending testing prematurely due to excessive inspired breathing resistance. During this time, the peak inspired breathing resistance for the mine-deployed units was 11.5% lower than the peak inspired breathing resistance for the reference units. A steady increase in inspired breathing resistance for the reference units likely indicates a continuous expenditure of the sorbent as carbon dioxide is scrubbed and oxygen is generated while the breathing gas travels through a homogenous sorbent bed. Inspired CO_2 levels were low to start with for the reference units but were somewhat higher at the start for the mine deployed units, which further bolsters the theory that channeling of breathing gas flow occurred through the sorbent bed for the mine deployed units resulting in inefficient CO_2 scrubbing. Typically, CO_2 levels for the reference unit tests started out at approximately 1.2 to 1.3% before decreasing to approximately 1.1% 10 to 15 minutes thereafter whereas inspired CO_2 levels for the mine-deployed units started off at approximately 1.4 to 1.7% before decreasing to approximately 1.1 to 1.2% 20 to 25 minutes thereafter.

The first two SR2000 units tested were nonconforming and the approval holder was notified. The approval holder submitted a notice to rescind approval to NIOSH before testing of all SR2000 units was completed with changing market conditions being cited as the reason for this decision. As a result, the CSE SR2000 is no longer a

[10] Machine testing with different end points than are required in Subpart H.

NIOSH-approved device and has been removed from all mines that were using them. The performance failure of the CSE SR2000 determined by NIOSH highlights the importance of the LTFE study. Thus, NIOSH's LTFEs demonstrated their importance and value as devices that were unable to meet approval requirements of the Subpart O standard after deployment to the use environment were removed from service and had their NIOSH approval removed. This demonstrates the criticality of pre- and post-market conformity assessment of respirators.

Overall Assessment of the Fourth Phase of NIOSH's LTFEs

NIOSH achieved its goals for the revised LTFE strategy:

(1) Verify that devices approved under Subpart O continue to meet approval requirements when deployed to the field—a Subpart O approved device was removed from the marketplace and from NIOSH's list of approved products based on this study.

(2) Compare the protections provided by Subpart H and O devices at the point of use
   a. Proper execution of visual inspections by miners was better for the Subpart O device—15% of Subpart H units should have been removed from service.
   b. No differences were observed between Subpart H and O devices regarding the phenolphthalein indicator test or the QNT.
   c. Duration for Subpart O reference units was greater than that of Subpart H reference units, 85 (115 Liters O_2 delivered) and 73 (99 Liters O_2 delivered) minutes on average, respectively.
   d. Comparison of duration and stressor data for field deployed units evaluated at a constant work rate (Capacity test) was not possible, because the mine deployed Subpart O units did not meet approval requirements—i.e., no comparison between NIOSH approved products was possible.
   e. Comparison of duration and stressor data for field deployed units evaluated at a variable work rate (Performance test) was not possible due to the (a) insufficient sampling of Subpart H units and (b) because the mine deployed Subpart O units did not meet approval requirements—i.e., no comparison between NIOSH approved products was possible.

A comparison of duration and stressor data for mine deployed Subpart O and H units will be pursued in future LTFEs when other Subpart O devices are sampled. Additionally, NIOSH will increase the amount of its planned oversampling to account for visual inspection failures from two to six units based on this LTFEs findings.

There are numerous challenges associated with collecting a statistically valid sample of Subpart O and Subpart H approved units, testing those units, and reporting on the results in a timely manner. NIOSH has taken a different approach from previous LTFEs by seeking smaller sample sizes and targeting specific mines possessing Subpart O and H approved units with the severest of exposures. Although one of the three mines targeted was abandoned before units could be collected and the two remaining participating mines provided all the units for this study, meaningful information was still obtained and is now being reported. As is evident by the results cited in this report, this new strategy was successful in identifying issues that affect the performance of the Subpart O and H approved device types that NIOSH collected and evaluated. In addition, the smaller sample size and timely testing and data analysis facilitated reporting the results of this study segment to the stakeholders in a much shorter period in comparison to previous LTFEs.

Actions Mine Operators May Take to Protect Miners

NIOSH recommends compliance with manufacturer-specified emergency escape breathing device requirements and instructions. Proper storage and visual inspection practices are crucial to the safe use of these apparatus that are either being carried or stored in a cache. Removal of units failing visual inspection or non-destructive testing is imperative. Any apparatus that fails the visual inspection should be removed from service. Mine operators should review their training and compliance activities related to the respirator inspections for Subpart O and H approved devices, visual and sound level tests (where applicable).

The NIOSH Certified Equipment List (CEL) is the official listing of all NIOSH-approved respirators. Before purchasing respirators for your miners, search the CEL to verify the respirator's approval status as NIOSH may revoke or rescind a respirator's approval—meaning it is no longer a NIOSH-approved product. Sign up for NPPTL's Listserv to receive email notifications relevant to PPE and to stay informed about changes to a respirator's approval status.

Actions Miners May Take to Further Protect Themselves

Miners should familiarize (or re-familiarize) themselves with the manufacturer's visual inspection criteria, donning instructions, and should perform routine inspections of units that are either being carried or stored in a cache, immediately requesting replacements for any units which fail inspection—this is the primary way to ensure that units in service will function as intended. When wearing a NIOSH-approved respirator, follow the manufacturer's user instructions provided with the respirator's packaging, or refer to the manufacturer's website for more information.

Appendix A: Acronyms and Abbreviations

Acronyms and Abbreviations

ABMS	automated breathing and metabolic simulator
CASE	Conformity Assessment Studies and Evaluations
CCER	closed-circuit escape respirator
CFR	code of federal regulations
CO	carbon monoxide
CO_2	carbon dioxide
CPIP	certified product investigation process
dB	decibels
Ins CO_2 Mole Frac	mole fraction inspired carbon dioxide
Ins O_2 Mole Frac	mole fraction inspired oxygen
LTFE	long-term field evaluation
LTR	long-term random field evaluation
MSHA	Mine Safety and Health Administration
N_2	Nitrogen
NIOSH	National Institute for Occupational Safety and Health
NPPTL	National Personal Protective Technology Laboratory
O_2	oxygen
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
QNT	quantitative leak test
PEPRS CMH20	peak expired pressure, centimeters of water column
PIPRS CMH20	peak inspired pressure, centimeters of water column
SCSR	self-contained self-rescuer
TAVGDB	average dry-bulb temperature over inspired breath, ^{o}C
TAVGWB	average wet-bulb temperature over inspired breath, ^{o}C
TLV	threshold limit value
VCO_2	volume of carbon dioxide
VO_2	volume of oxygen

Unit of Measure Abbreviations

breaths/min	breaths per minute
kg	kilogram(s)
L	liter(s)
L/breath	liter(s) per breath
Lb_m	pound mass
L/min	liter(s) per minute
mL/min	milliliter(s) per minute
mm	millimeter(s)
mm H_2O	millimeter(s) of water column
%	percent
Ppm	parts per million
Slpm	Standard liters per minute

Appendix B: ABMS Upgrades to Validate Test Results

NIOSH installed N_2 and CO_2 mass flow controllers on the ABMS to replace needle valves controlled by stepper motors. Included as part of this upgrade was a dual N_2 mass flow controller (MFC) system comprised of a high-flow MFC with a flow range of 0-12 SLpm and a low flow MFC with a flow range of 0-1.7 Slpm operating in parallel. The ABMS software was modified so that the high-flow N_2 MFC closes and the low-flow MFC becomes active at N_2 flow rates less than 1.6 SLpm (the high-flow N_2 mass flow controller is activated when N_2 flow rates again exceed 1.6 L/min). With an ISO 17025 calibration, the flow metering accuracy of the N_2 and CO_2 MFCs is +/- 0.6% of the reading down to 20% of full-scale flow and +/- 0.6% of the reading + 0.12% of the full-scale flow for flow rates less than 20% of full-scale flow. The parallel N_2 MFC system provides a flow rate accuracy of +/- 2.6% at the normal minimum N_2 flow rate of 0.1 SLpm. Similarly, the accuracy of the 0-5 SLpm CO_2 MFC at the normal minimum flow rate of 0.4 SLpm is +/-1.8%. As with N_2 and CO_2 metabolic valves, the modulation of flow by the MFCs in response to set point requirements is paced by software controls to simulate a human's metabolic response.

Low-volume CO_2 and N_2 gas supply cylinders were installed on small weigh scales that are readable to within +/- 0.1 gram. These cylinders replaced large 200-ft^3 gas cylinders used in the past. Flexible tygon tubing conveys the gases to each MFC and isolates the scale to allow free upward deflection of its load cell as the gas cylinders lose weight during test operations. Each scale supporting a gas cylinder is placed on a 3-inch thick granite slab and covered with a Plexiglas enclosure for isolation from vibrations transmitted through the floor and forced/convective air currents, respectively. Accuracy checks of the scales with the flexible gas supply tubing connections to the MFCs in place were performed periodically using known weights to verify weight loss accuracies.

A stand-alone instrument cart containing O_2 and CO_2 analyzers, a gas sample pump/flow control meter, and an electronic moisture remover were installed to sample and analyze the ABMS exhaust gas to determine exhaust gas O_2 and CO_2 levels during testing. Gas sample tubing was connected to the exhaust tube at the discharge of the ABMS exhaust pump and gas sample return tubing was installed directly above the gas sample tubing to return the extracted gas sample. The end of the exhaust pump discharge tubing was connected to a gas spirometer via a three-way valve for periodic collection and measurement of the exhaust gas volumetric flow rate.

Test Results Validation

NIOSH performed validation of test results for all CSE SRLD and SR2000 reference units. VO_2 and VCO_2 were measured three to four times per test over the course of 13- to 21-minute periods, covering nearly the entire test duration. The measurement of these key parameters was accomplished by measuring the exhaust gas volumetric flow rate with a gas spirometer and O_2 and CO_2 exhaust gas concentrations using a separate set of gas analyzers. VO_2 and VCO_2 level set points for all testing were 1.35 SLpm and 1.15 SLpm, respectively. Average VO_2 and VCO_2 levels for all CSE SRLD reference unit tests were 1.362 and 1.157 SLpm, respectively, while average VO_2 and VCO_2 levels for all CSE SR2000 reference unit tests were 1.344 and 1.162 SLpm, respectively (**Tables 12 and 13**). Flow rate accuracies for the injection of CO_2 and N_2 to the ABMS lung and the expulsion of exhaust gas from the ABMS breathing circuit were also validated during this study. This was accomplished for CO_2 and N_2 by comparing recorded CO_2 and N_2 mass flow controller data to total loss-in-weight measurements from CO_2 and N_2 cylinders positioned on high accuracy weigh scales. CO_2 and N_2 consumption deviations between mass flow controller recorded and scale loss-in-weight measurements for all SRLD and SR2000 reference unit tests ranged from 0% to 1.4% (**Tables 12 and 13**). Exhaust gas flow rate accuracy was determined by comparing exhaust gas volumetric flow rate data recorded during the exhaust gas collection period to the volumetric flow rate measured through timed collections of exhaust gas using the gas spirometer. Deviations between the recorded and measured exhaust flow rate ranged from -1.3% to +1.3% for CSE SRLD reference unit testing and -0.4% to 2.8% for CSE SR2000 reference unit testing.

Table 12. CSE SRLD Reference Unit Validation Data

CSE SRLD SCSR Control Unit Testing Validation Data						
Test Number	Test Date	Test VO_2	Test VCO_2	CO_2 Mass Balance % Deviation	N_2 Mass Balance % Deviation	Exhaust Gas % Flow Deviation
1	3/11/2020	1.354	1.154	1.1	1.2	-0.7
6	3/12/2020	1.373	1.154	0.6	0.5	-0.4
11	3/13/2020	1.379	1.153	0.7	0.4	-0.6
16	3/17/2020	1.366	1.153	0.8	0.0	-0.7
21	3/18/2020	1.364	1.148	1.2	1.0	-1.3
26	3/19/2020	1.367	1.153	1.0	0.2	-0.2
31	3/20/2020	1.355	1.166	0.3	0.1	1.3
36	3/24/2020	1.371	1.151	1.2	0.4	-0.8
41	3/26/2020	1.351	1.164	0.3	-0.5	0.3
46	3/30/2020	1.348	1.165	0.2	-0.4	0.8
49	3/31/2020	1.357	1.167	0.1	0.0	0.9

Table 13. CSE SR2000 Reference Unit Validation Data

CSE SR2000 CCER Control Unit Testing Validation Data						
Test Number	Test Date	Test VO_2	Test VCO_2	CO_2 Mass Balance % Deviation	N_2 Mass Balance % Deviation	Exhaust Gas % Flow Deviation
1	4/22/2020	1.359	1.158	0.6	0.3	-0.4
4	4/22/2020	1.355	1.163	0.1	-0.2	1.0
6	6/29/2020	1.349	1.164	-1.3	0.6	1.1
12	6/30/2020	1.345	1.161	-1.0	-0.2	1.9
18	7/1/2020	1.335	1.162	-1.0	-0.2	2.2
26	7/6/2020	1.338	1.158	-0.8	-1.0	1.9
32	7/7/2020	1.362	1.160	-1.3	0.1	1.9
39	7/9/2020	1.354	1.159	-1.4	-0.3	1.9
45	7/10/2020	1.320	1.167	-1.3	-0.2	2.8
50	7/14/2020	1.322	1.163	-0.6	0.6	2.8

Improvements made to the NIOSH ABMS in the use of mass flow controllers to meter and control the injection of CO_2 and N_2 gases to the lung provided a significant reduction in test-to-test data fluctuations. This is evident in the reduced differences between the minimum and maximum stressor values for the CSE SRLD reference units tested during this study segment in comparison to the differences measured when testing reference units during NIOSH's third phase of its LTFEs. Additionally, a new test data validation method was employed for the first time which permitted determination of VO_2 and VCO_2 levels and N_2, CO_2, and exhaust gas mass balance closures immediately upon test conclusion. VO_2 and VCO_2 levels, and N_2, CO_2, and exhaust gas flow rate accuracies for all CSE SRLD and SR2000 reference units tested were well within the +/-5% error band NIOSH deems acceptable for control of these parameters.

Finally, the more frequent use and spacing of reference units amongst mine deployed units provided an improved means to validate mine deployed unit test results in comparison to previous LTFE collection phases. During this study, NIOSH tested a reference unit after every fourth or fifth mine deployed unit test. As shown in Tables 11 and 12, VO_2, VCO_2 and CO_2, N_2, and exhaust gas mass balance closures were determined for all reference unit tests. All reference unit validation data checks were subsequently determined to be well within the +/-5% error band established by NIOSH for ABMS testing. This bracketing of mine deployed unit tests with reference unit tests in which these advanced ABMS operating parameters were determined to be within required tolerances provided for a much smaller window of uncertainty, if any were to exist, for the mine deployed unit tests performed between reference unit tests. As test results for each reference unit throughout this study were determined to be valid immediately after the test ended, NIOSH established assurances that test results for the mine deployed unit tests performed up to that point were also valid.

Appendix C: Unit-Specific Inspired CO_2 Data

Table 14. Unit-Specific Data for CSE SRLD 4% CO_2 Breakthrough Times

4% Inspired CO_2 Breakthrough Time, minutes	Test Duration, minutes	Inspired CO_2 at 60 minutes	Maximum Inspired CO_2, Volume %
49	67	6.42	9.91
65	76	3.30	8.96
67	76	3.05	8.24
68	75	2.87	6.75
68	76	2,87	6.92
68	72	2.65	5.43
68	75	2.63	6.08
68	74	2.38	7.01
69	76	2.71	6.73
69	72	2.61	5.17
69	77	2.84	8.44
70	76	2.64	6.56
70	72	2.65	4.61
70	76	2.67	6.43
71	75	2.52	5.83
71	75	2.54	5.75
71	77	2.37	8.27
71	77	2.53	6.46
72	73	2.34	4.62
72	74	2.45	4.86
72	76	2.58	5.72
72	75	2.26	5.64
73	76	2.58	5.09
73	75	2.45	5.04

Appendix D: ABMS Testing of the CSE SRLD Stressor Data

Tote containers were purchased for storing SCSR units upon retrieval at the mine and back at NPPTL until testing was performed. During CSE SRLD testing, the units to be tested were selected randomly from 7 storage containers. As one storage container was emptied, units were randomly drawn from the next storage container and this process continued until all storage containers were emptied. Each test was given a number in the sequence in which it was tested starting with 1 for the first test, which was a reference unit, and ending at 49 (also a reference unit) when all units had been tested. Therefore, the assigned unit number was used to identify the order of testing. Reference units were tested every fifth test as shown in the plots below by the **red square**. Trendlines for both the mine deployed and reference units are also shown to further enable comparison between the two types of units. Those units that failed visual inspection were tested at the end of CSE SRLD SCSR testing, and the test data is not included in the plots below. These visual inspection failure tests account for those portions of the plot where there are less than four CSE SRLD units between reference units. It should be noted that since all units were tested in random order, any slope of the trendlines other than zero should assumed to be zero. The purpose of the trendlines is to compare the magnitude of the mine deployed unit duration and stressors in comparison to the reference units.

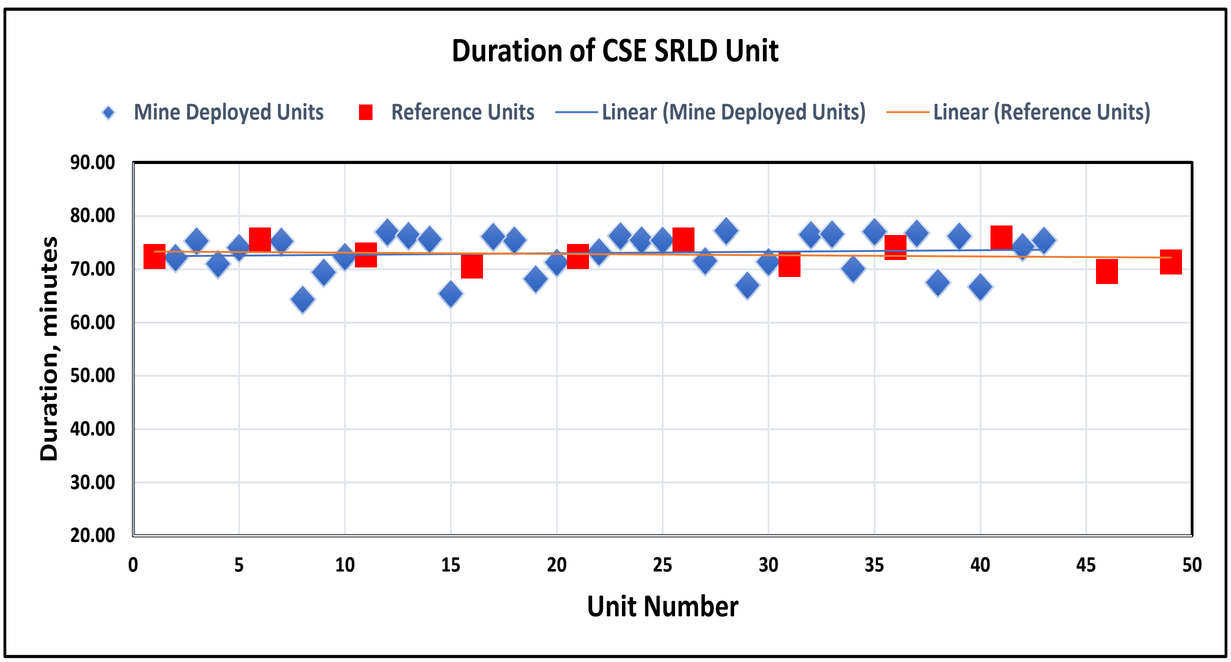


Figure 5

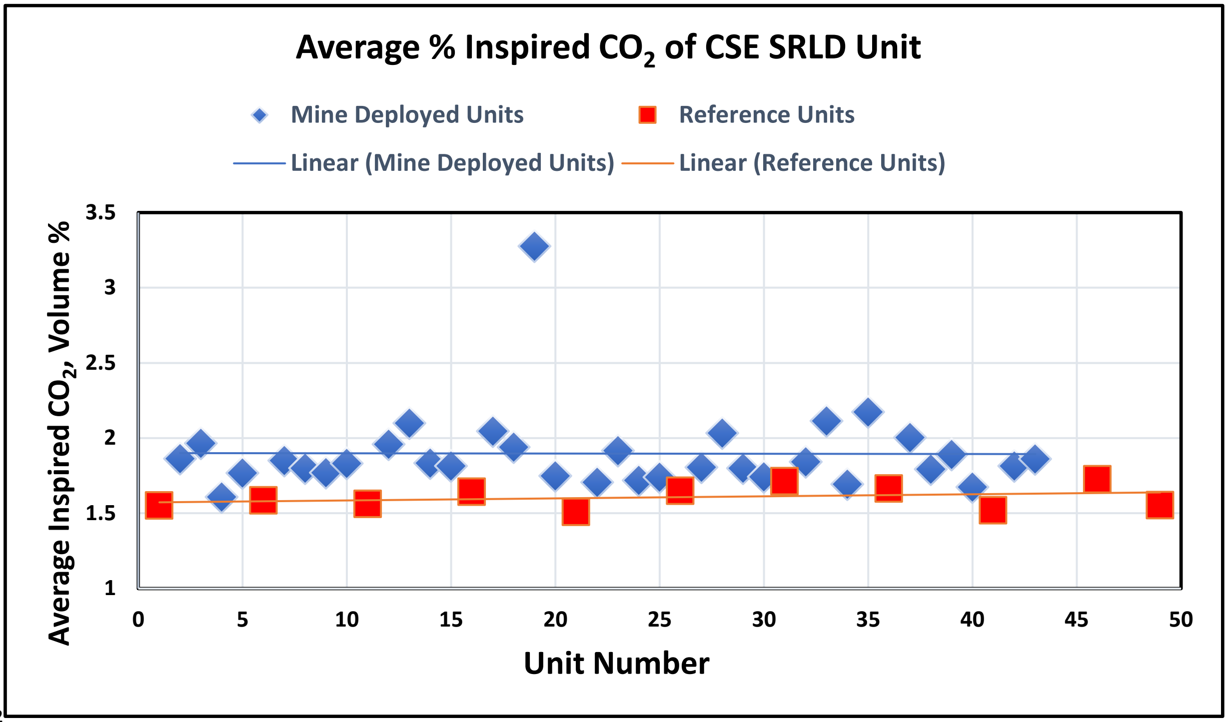


Figure 6

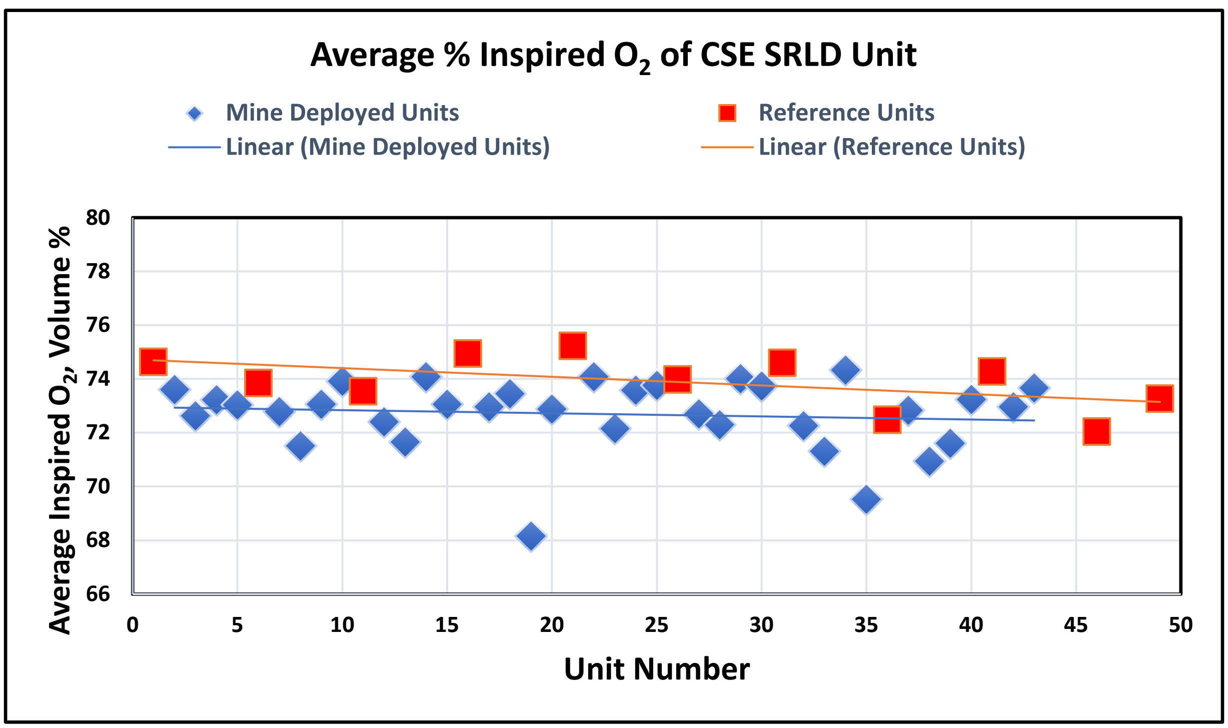


Figure 7

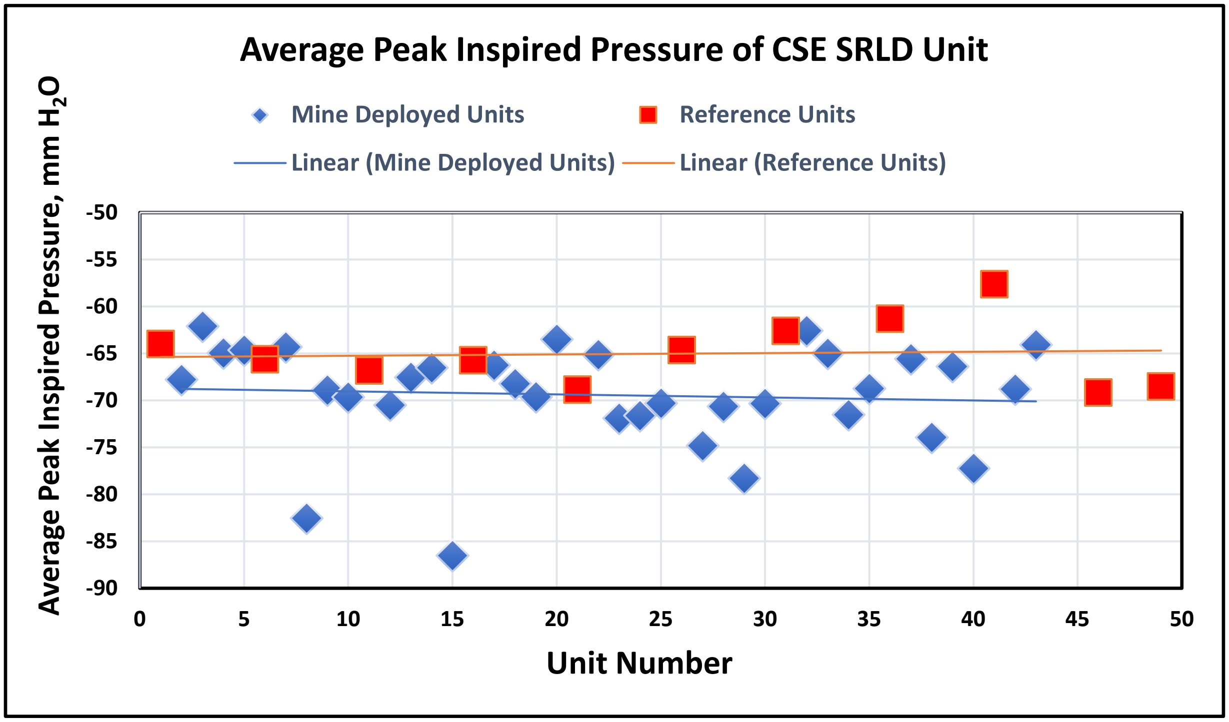


Figure 8

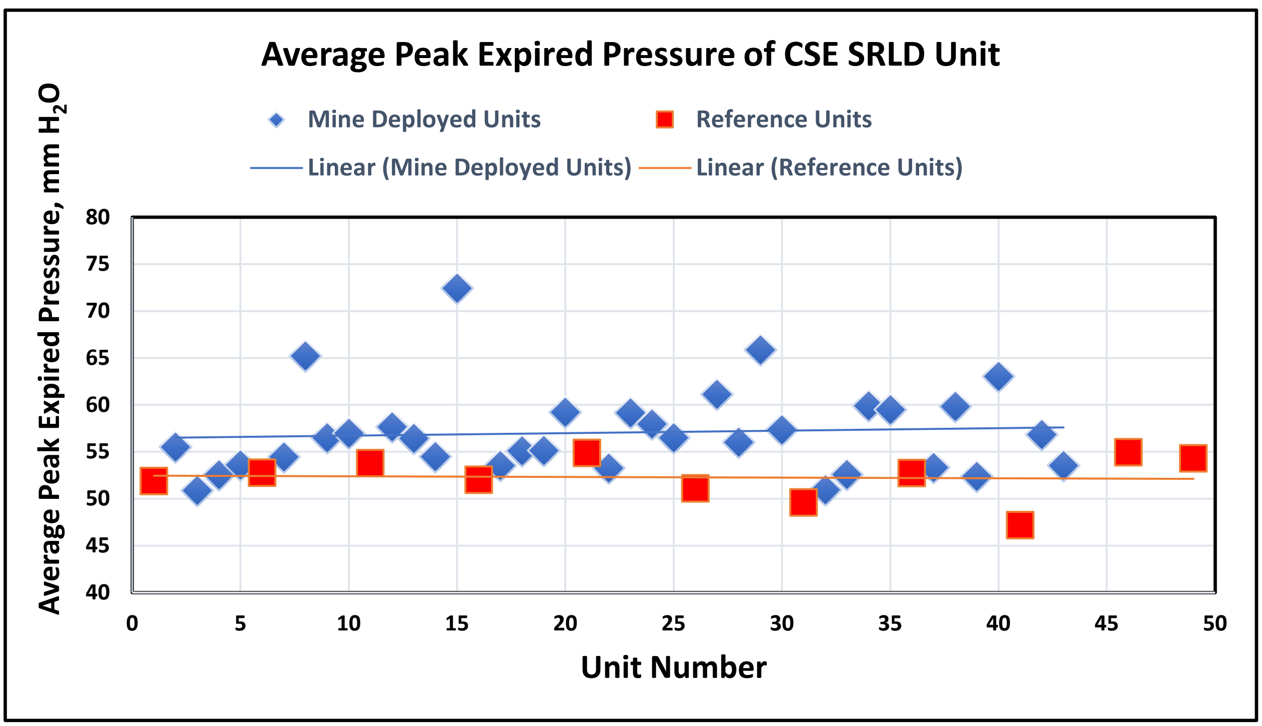


Figure 9

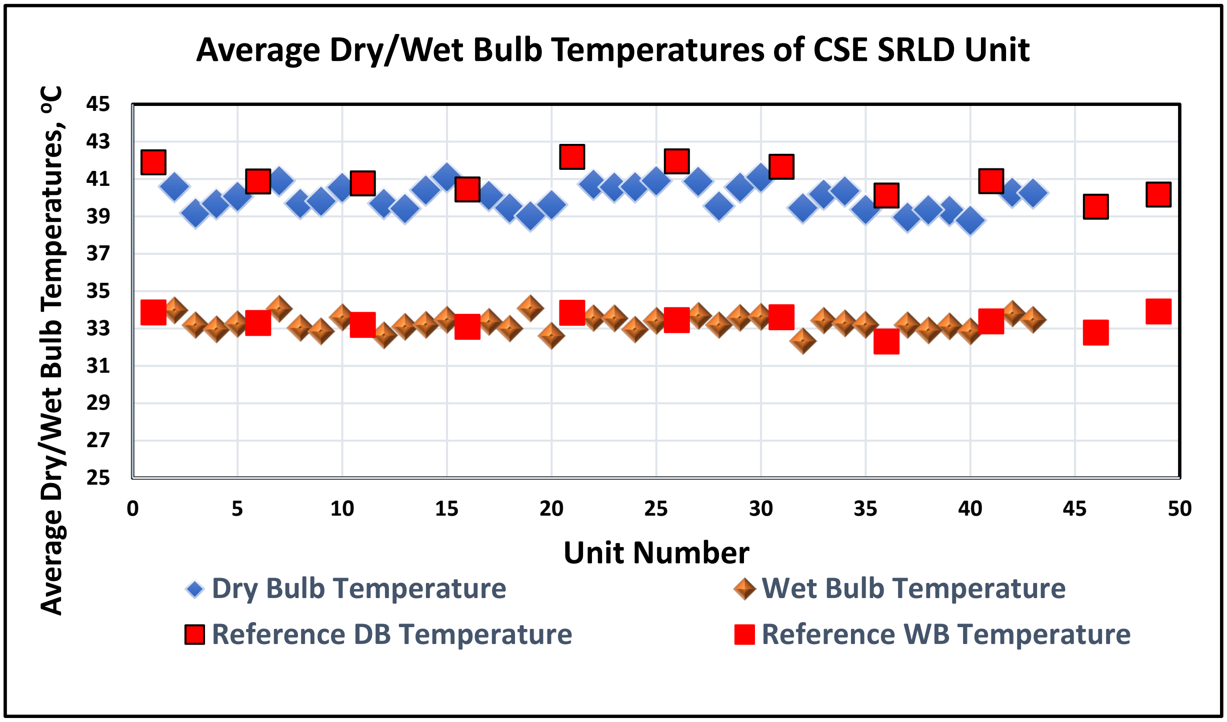

Average Dry/Wet Bulb Temperatures of CSE SRLD Unit
Average Dry/Wet Bulb Temperatures, °C
45
43
41
39
37
35
33
31
29
27
25
0
5
10
15
20
25
30
35
40
45
50
Unit Number
Dry Bulb Temperature
Wet Bulb Temperature
Reference DB Temperature
Reference WB Temperature

Figure 10

Appendix E: ABMS Testing of the CSE SR2000 Stressor Data

Tote containers were purchased for storing SCSR units upon retrieval at the mine and back at NPPTL until testing was performed. During CSE SR2000 testing, the units to be tested were selected randomly from 8 storage containers. As one storage container was emptied, units were randomly drawn from the next storage container and this process continued until all storage containers were emptied. Each test was given a number in the sequence in which it was tested starting with 1 for the first test, which was a reference unit, and ending at 50 (also a reference unit) when all units had been tested. Therefore, the assigned unit number was used to identify the order of testing. Reference units were tested approximately every fifth test as shown in the plots below by the **red square**.

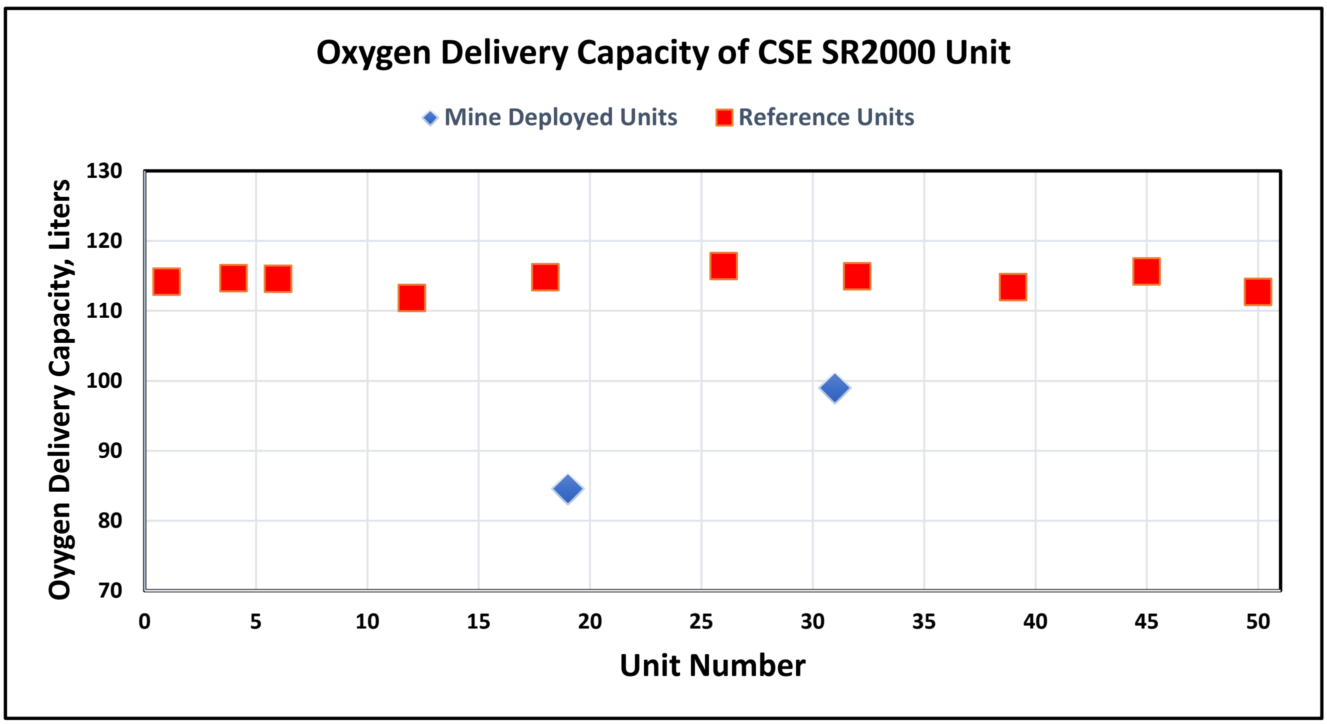


Figure 11

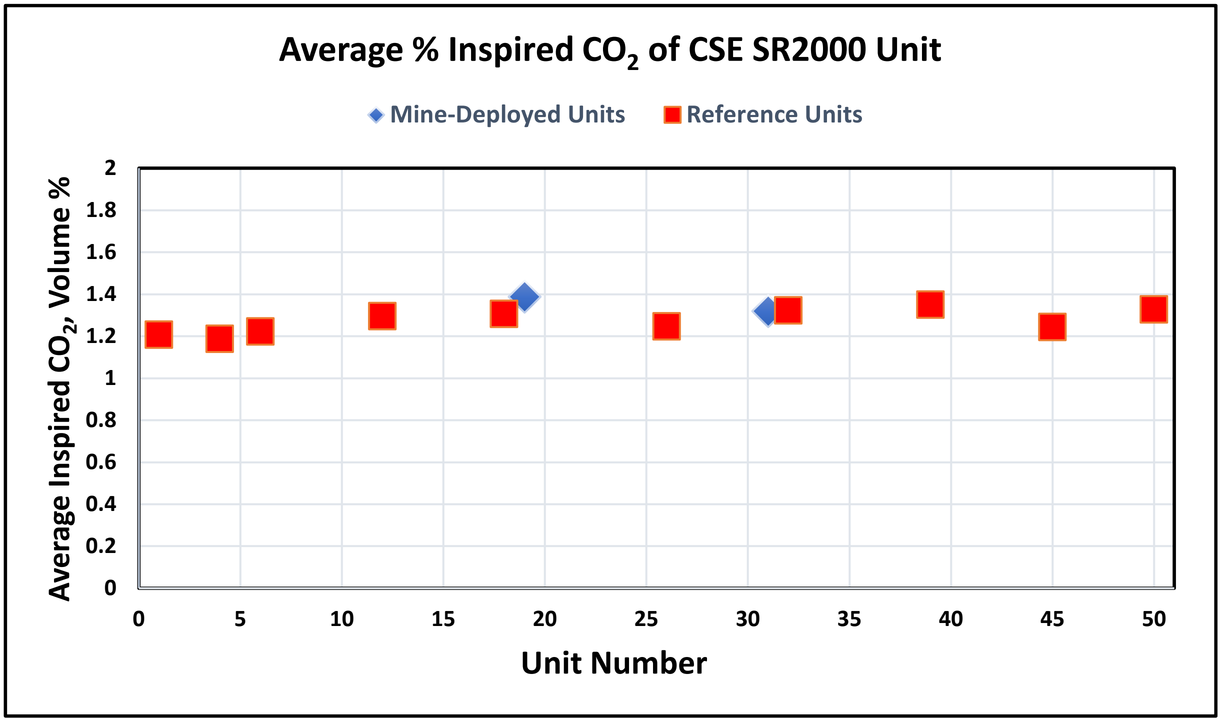


Figure 12

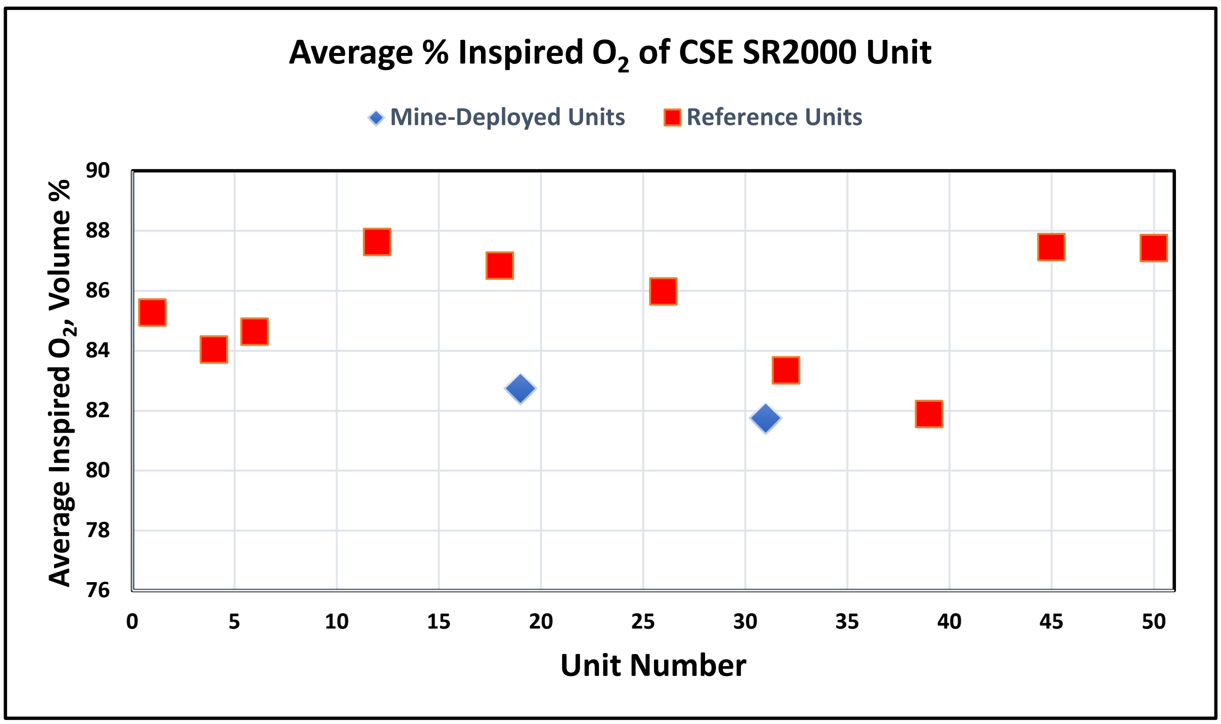


Figure 13

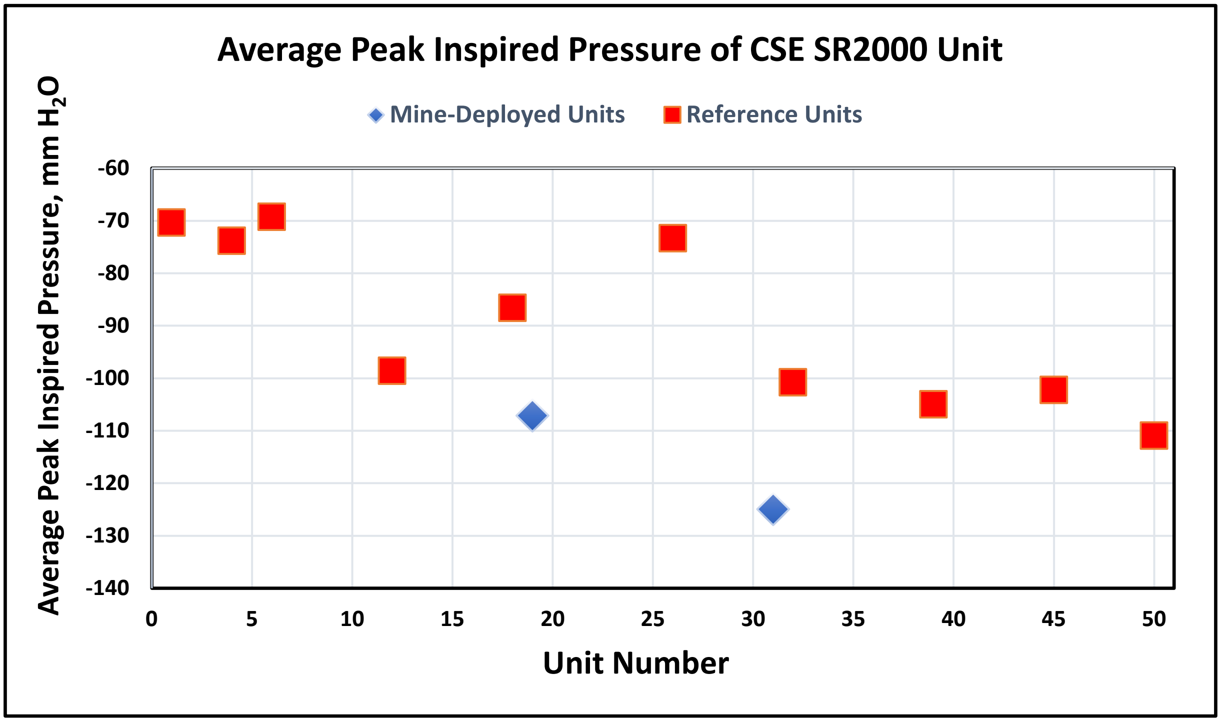


Figure 14

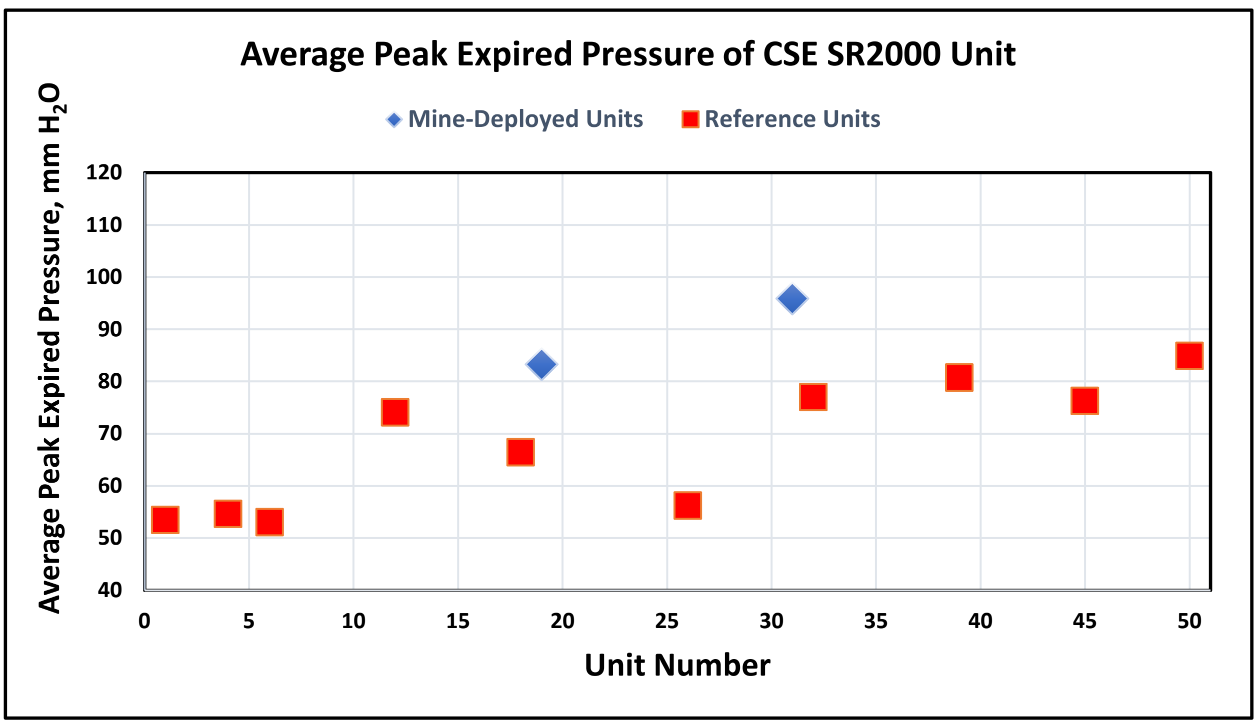


Figure 15

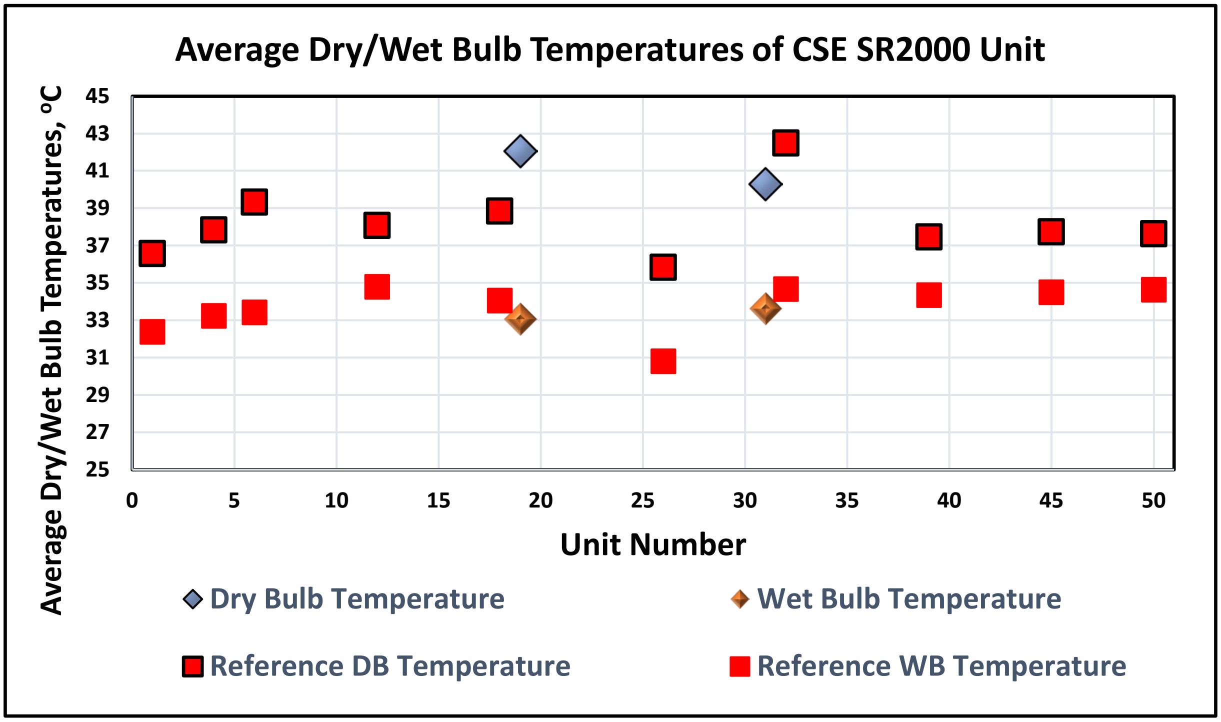

Average Dry/Wet Bulb Temperatures of CSE SR2000 Unit
Average Dry/Wet Bulb Temperatures, °C
45
43
41
39
37
35
33
31
29
27
25
0
5
10
15
20
25
30
35
40
45
50
Unit Number
Dry Bulb Temperature
Wet Bulb Temperature
Reference DB Temperature
Reference WB Temperature

Figure 16

Acknowledgements

Thanks are extended to the Mine Safety and Health Administration, The United Mine Workers of America, Mine Operators, Manufacturers, Mine Workers, and NIOSH NPPTL personnel that supported and continue to support the long-term field evaluation of respirators in U.S. underground coal mines.

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Kamon E, Bernard T, Stein R [1975] Steady state respiratory responses to tasks used in federal testing of self-contained breathing apparatus. Am. Ind. Hyg. *36*(12): 886-896, https://doi.org/10.1080/0002889758507361.

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Suggested Citation

NIOSH [2022] PPE CASE: Point-of-Use Assessment for Closed-Circuit Escape Respirators Sampled from Mines that use both Subpart O and Subpart H Approved Units: First Phase. By Walbert G, Moore S, Monaghan W, and Simons J. Pittsburgh, PA U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, NPPTL Report Number P2022-0102.

Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health