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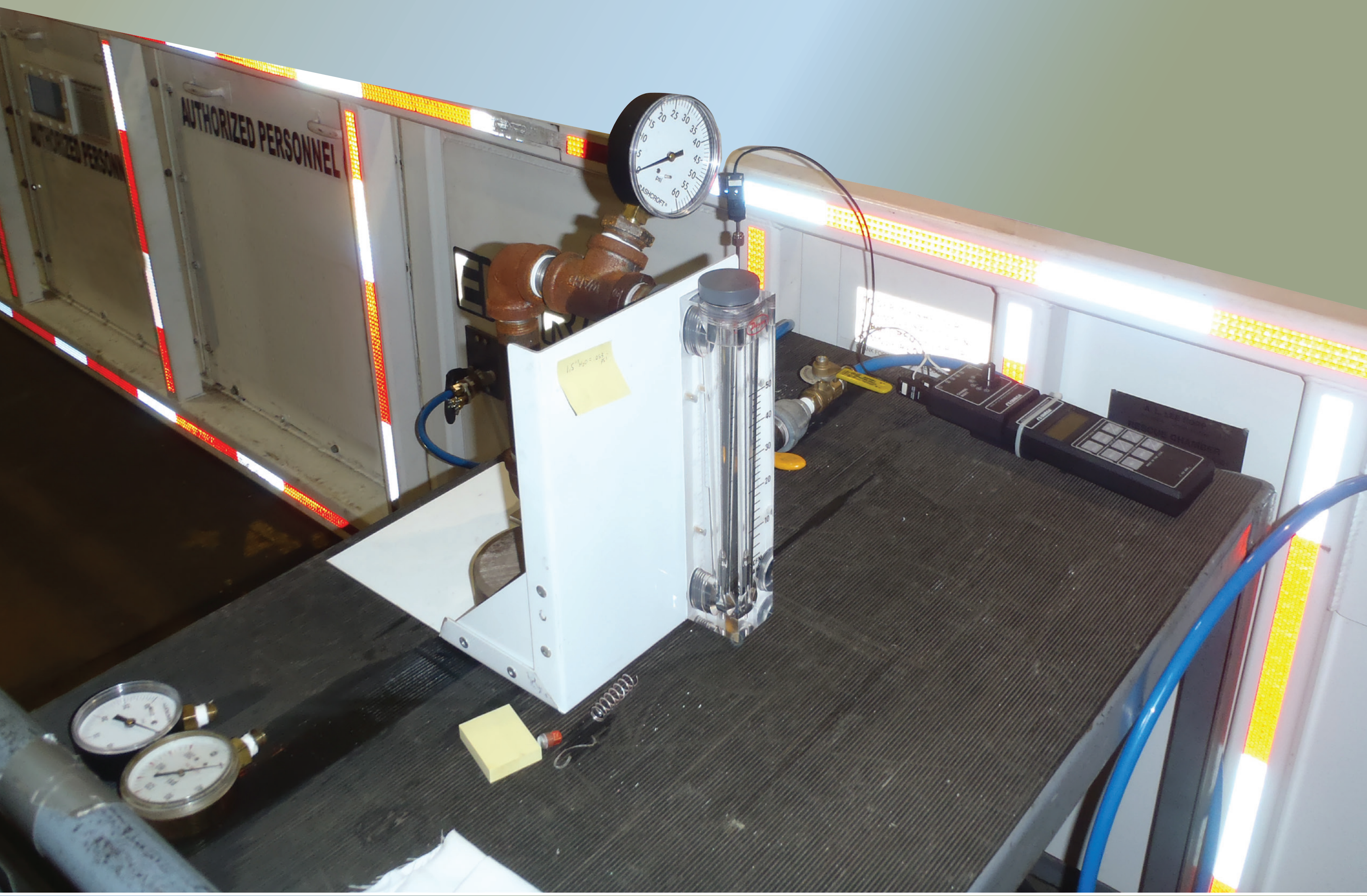
REPORT OF INVESTIGATIONS/2014

Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives



Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Report of Investigations 9694

Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives

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DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Office of Mine Safety and Health Research
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ACRONYMS AND ABBREVIATIONS

ATDSR	Agency for Toxic Substances and Disease Registry
CH_4	methane
CO	carbon monoxide
H_2O	water
I.D.	inside diameter
IDLH	immediately dangerous to life or health
MEO	Mine Emergency Operations
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NMA	National Mining Association
NPT	national pipe thread
OMSHR	Office of Mine Safety and Health Research
OSHA	Occupational Safety and Health Administration
PEL	permissible exposure limit
RA	refuge alternative
REL	recommended exposure limit
SCSR	self-contained self-rescuer
SF_6	sulfur hexafluoride
TWA	time-weighted average
USBM	United States Bureau of Mines

UNIT OF MEASURE ABBREVIATIONS

cu ft	cubic foot
cfm	cubic feet per minute
°C	degrees Celsius
°F	degrees Fahrenheit
°R	degrees Rankine
ft	foot
gm	gram
in	inch
L	liters
ml	milliliter
min	minute
ppb	parts per billion
ppm	parts per million
%	percent
lb	pound
psi	pounds per square inch
psia	pounds per square inch atmosphere
psig	pounds per square inch gage
sec	second
sq ft	square foot
sq in	square inch
SCFH	standard cubic feet per hour
SCFM	standard cubic feet per minute

Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives

Eric R. Bauer, Ph.D., P.E.[1], Timothy J. Matty[2], and Edward D. Thimons[3]

Executive Summary

Background and Methods

The National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) has conducted research to evaluate the effectiveness of purging of mine refuge alternatives (RAs). Two questions were addressed experimentally: (1) Does the current generation of mobile refuge alternatives meet the requirements of 30 CFR[4] § 7.508 (c) (2) which requires RAs to be capable of purging the internal atmosphere from 400 ppm of carbon monoxide (CO) to 25 ppm? (2) What is the relationship between the concentration of noxious gases in the mine atmosphere external to the refuge alternative and the concentration that will be present inside the refuge alternative following entry of miners but prior to purging? The goal of the second question was to evaluate the appropriateness of the 400-ppm criterion, given that ambient post-accident mine concentrations of CO can be in the thousands of ppm.

A tent-type and a rigid steel mobile refuge alternative were used to investigate the first question[5]. Carbon monoxide (CO) and sulfur hexafluoride (SF_6) were used as contaminant gases as part of this study, and the individual experiments were conducted with the purging area of the RA occupied by zero, one, or seven simulated (when CO was used) or live (when SF_6 was used) occupants.

To investigate the second question, the aforementioned RAs were used along with a third airlock constructed for and employed in the experiments. The volume and size of the entry door into the constructed airlock were roughly in the middle of the range of values for the rigid and tent-type RAs. The RAs and constructed airlock were placed in a large sealed reverberation room, and SF_6 gas was released into the reverberation room as a surrogate for CO. Experiments were conducted to determine the gas concentrations inside the airlock after groups of test subjects (representing miners) had entered.

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[4] Code of Federal Regulations. See CFR in references.
[5] There are multiple manufacturers for both tent-type and rigid steel RAs. For the purposes of this study, one of each type was used.

Summary of Findings

The experimental findings indicate that the current generation of mobile refuge alternatives employs techniques that are capable of reducing a CO concentration of 400 ppm within the volume to be purged, as required by the 30 CFR § 7.508 (c) (2) regulation. This answers the first research question in the affirmative.

Test findings indicate that when the airlock entry door is opened, ambient air with a higher CO concentration will begin to move into the airlock. Significantly, as miners move through the airlock they will expedite the turbulent diffusion (sometimes referred to as advective diffusion) of CO into the airlock. The level of CO inside the airlock will continue to increase until the door is closed. The ratio of the CO concentration inside the airlock at that point in time to the ambient concentration of CO outside the RA—i.e. the contamination factor—is shown in Figure 17 for the RAs/airlocks investigated in this study.

Consider the following example to demonstrate the significance of this finding. The contamination factor with five persons entering the airlock is 0.5 in the tent-type RA, as shown in Figure 17. Thus, in order for the internal concentration to be at 400 ppm or less, the ambient CO concentration cannot exceed 800 ppm. For the same five miners in the rigid steel RA, the contamination factor is 0.2, which corresponds to a maximum outside ambient concentration of 2,000 ppm. As a point of comparison, the CO concentration after the explosion at Upper Big Branch Mine in 2010 was approximately 10,000 ppm.

As a consequence of this contamination during entry, the CO concentration inside the airlock could be many times greater than 25 ppm, after four purging cycles have been completed. As the miners move from the airlock into the main body of the RA, some of this contaminated air will be carried into the primary (long-term) refuge space. When the second group of miners enters the airlock, the air will contain a residual amount of CO from the previous group that used the airlock, and therefore after four purging cycles, the level of CO that will be carried into the main chamber could be higher than for the previous group. These findings raise the concern that an unanticipated and potentially toxic level of CO could exist in the airlock after the purging cycles have been completed, and in the main chamber after miners have entered from the airlock.

Summary of Discussion and Recommendations

The findings of this study demonstrate that the starting concentration of CO in the airlock of a mobile RA can be significantly greater than 400 ppm—e.g., in the thousands rather than the hundreds of ppm—and that a portion of the remaining CO will be carried into the main chamber. It should be emphasized that the findings of this study *cannot* be used to quantify the level of contamination that might occur in all commercially available RAs, nor can they be used to establish the level of contamination that could occur in the main chamber of the mobile refuge alternative. The findings *can* be used to conclude that: contamination will occur; that there is an immediate need to assess the hazard that it presents; and that guidance to manufacturers and miners is available by way of this report. Recommendations for conducting a hazard assessment are identified here.

For an effective hazard assessment, a defensible worst-case ambient level of post-accident CO must be established. Given the many variables of an explosion scenario, this will be an inexact endeavor that can be informed by science and the records from past mine disasters, but one that ultimately requires a policy decision. Once this decision is made, it will be possible to assess more completely this hazard, and to provide design requirements to manufacturers as well as training and operating procedures to miners.

The following recommendations are intended as guidance to assess and mitigate hazards presented by airlock contamination[6].

- An ambient CO contamination level must be established for assessment purposes, based on the disaster scenario, and then used to design mobile refuge alternatives and to evaluate them in the approval process.
- The expected contamination factors for a specific RA design should be determined experimentally under a prescribed procedure, which could be the one used in this study, and charts similar to Figure 17 should be developed and applied.
- The expected CO concentration inside the airlock should be calculated, using the information established in the previous two recommendations.
- Ideally, the airlock should be capable of reducing the expected CO concentration to an acceptable level, such as 25 ppm[7]. However, this may be nearly impossible in many cases, given the expected level of contamination, practical limitations on purging air capacity, and time constraints. Given this potential shortcoming, which is unlikely to be overcome simply through a re-engineering of the purging process, additional measures must be taken to protect those who would take refuge.

A redesign of the purging process of mobile refuge alternatives was beyond the scope of this study, and over the longer term, design changes may yield solutions to the airlock contamination problem. However, in the short-term, the following activities are recommended:

- Operational guidance to miners for purging should be based on a prescribed number of air changes, and not based on achieving a target concentration of 25 ppm or less.
- Operational guidance to miners should include continued use of their self-contained self-rescuers (SCSRs) until they are in the main chamber of the mobile refuge alternative and they have determined that the concentration of CO in the main chamber is at an acceptable level.
- A maximum acceptable concentration of CO in the main chamber must be specified. Given the significant difference in volume between the airlock and the main chamber, it is likely that the CO in the heavily contaminated air within the airlock would be diluted to an acceptable level in the main chamber. Notwithstanding, this must be confirmed by engineering analysis of RAs under the specified conditions, including the number of miners, the number of groups that will use the airlock, and the specified contamination level.

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[6] These recommendations apply generally to built-in-place RAs as well as mobile RAs, although this report has focused on the latter.

[7] The beginning and end points, i.e. 400 and 25, define a performance characteristic for the purging system. Given the finding that the starting concentration can exceed 400, it may be appropriate to re-evaluate the end point.

The design of the airlock itself was also not a part of this research study. The two mobile refuge alternatives used in this study are popular commercial models and each has a differently designed airlock (door size and airlock volume). Based on limited observations, the size of the airlock door affects the speed at which miners can enter the airlock, which directly affects the amount of CO that moves into the airlock during entry. Over the longer term, there may be opportunities for manufacturers to incorporate design changes in airlocks to reduce the level of CO contamination.

Introduction

Generally, in-mine refuge alternatives (RAs, also referred to as mobile refuge alternatives and built-in-place shelters) must have the ability to purge or otherwise remove contaminated air from the airlock and/or main chamber caused by personnel entering during emergency conditions, i.e. post-disaster. Effective purging of a refuge alternative airlock is essential if a contaminant-free main chamber is to be realized. In 30 CFR § 7.508, the Mine Safety and Health Administration (MSHA) specifies the following purging criteria: (1) Purging or other effective procedures shall be provided for the airlock to dilute carbon monoxide (CO) to 25 ppm and methane (CH_4) to 1.0% or less as persons enter, within 20 minutes of deploying the refuge alternative; and (2) For testing the component's ability to remove CO, a stable concentration of 400 ppm, ±5%, CO is used as the starting point for purging evaluation 30 CFR § 7.508 (c) (2). Also, 30 CFR § 7.506 states that an automatic means be provided to ensure that the pressure is relieved at 0.18 psi, or as specified by the manufacturer [30 CFR § 7.508 (c) (2)]. This criterion applies to overpressure of the RA and to the pressure relief provided during purging. Other regulations that pertain to purging and removal of harmful gases can be found in 30 CFR § 7 and 75.

The Occupational Safety and Health Administration (OSHA) has set a permissible exposure limit (PEL) for CO at a time-weighted average (TWA) of 50 ppm [NIOSH 2013]. Using a conservative 50% dilution and a starting concentration of 400 ppm, it would require three purges to reduce the concentration to 50 ppm. A fourth purge would be required to reduce the CO concentration from 50 to 25 ppm, which is below the OSHA PEL. A goal of this study was to confirm experimentally whether this level of purging is achievable with the purging mechanism used by RA manufacturers.

The principle that governs the effectiveness of purging is dilution. Dilution is a reduction in the concentration of a chemical (gas, vapor, or solution) resulting from adding uncontaminated gas, vapor, or solution. When this principle is applied to the purging of refuge alternative airlocks, it is assumed that the concentration of a contaminant will be halved as one full airlock volume of uncontaminated air is added. As described in Appendix A, this approach is overly simplistic for RA airlocks, but it is the approach that the mining industry, RA manufacturers, and regulatory agencies are using to design purging systems. This technical oversimplification is based on MSHA 30 CFR § 7 and 75, and offers a significant safety factor. If this dilution holds true, at a starting point of 400 ppm CO, it will take four complete air exchanges to reduce the concentration to 25 ppm, or to $1/16^{th}$ of the original concentration. This would occur as follows: the first volume of air drops the concentration from 400 to 200 ppm; the second from 200 to 100 ppm; the third from 100 to 50 ppm; and the fourth complete air exchange from 50 to 25 ppm. Additional purging and purge air would be required if the CO level in the airlock is greater than 400 ppm and complete contaminant purging is desired.

The purging research performed as part of this study was designed to answer the question: Does the current generation of mobile refuge alternatives employ technology capable of purging the internal atmosphere from 400 ppm of carbon monoxide (CO) to 25 ppm as required by 30 CFR § 7.508? Researchers investigated purging through multiple approaches. First, purging experiments were conducted in a mini purge box to gain a better understanding of the purging phenomena and to familiarize researchers with the instrumentation to be employed in the studies using actual RAs. In these experiments, researchers investigated dilution and the effectiveness of purging by varying the air flow, air quantity, and pressure relief setting. Next, purging experiments in actual RA airlocks using CO and/or SF_6 contaminant gas were conducted.

Background on Carbon Monoxide Toxicity

To understand the effects of carbon monoxide as it applies to post-disaster scenarios in mines, some scientific background is in order. Carbon monoxide is a colorless and odorless gas that is produced by incomplete combustion of carbonaceous material and is the primary toxic contaminant in post-disaster (methane and/or coal dust explosions and fires) mine air. As noted later in this report, CO concentrations of 10,000 ppm and higher are not uncommon in post-disaster ambient mine air. In addition, previous U.S. Bureau of Mines (USBM) explosion and fire research has recorded CO concentrations of 90,000 + ppm [Hofer et al. 1996].

The National Institute for Occupational Safety and Health (NIOSH) and OSHA have established guidelines for CO exposure. The NIOSH recommended exposure limit (REL) is a time-weighted average (TWA) of 35 ppm. For NIOSH RELs, "TWA" indicates a time-weighted average concentration for up to a 10-hour workday during a 40-hour work week. The OSHA permissible exposure limit (PEL) is a TWA of 50 ppm. TWA concentrations for OSHA PELs must not be exceeded during any 8-hour work shift of a 40-hour work week. NIOSH has also established "immediately dangerous to life or health" (IDLHs) concentrations criteria. For CO, the IDLH is 1,200 ppm. Table 1 lists the symptoms of CO exposure.

Table 1. Symptoms of CO exposure

Concentration, ppm	Symptoms
35	Headache and dizziness within six to eight hours of constant exposure.
100	Slight headache in two to three hours.
200	Slight headache within two to three hours; loss of judgment.
400	Frontal headache within one to two hours.
800	Dizziness, nausea, and convulsions within 45 min; insensible within 2 hours.
1,600	Headache, tachycardia, dizziness, and nausea within 20 min; death in less than 2 hours.
3,200	Headache, dizziness, and nausea in five to ten minutes. Death within 30 minutes.
6,400	Headache and dizziness in one to two minutes. Convulsions, respiratory arrest, and death in less than 20 minutes.
12,800	Unconsciousness after 2–3 breaths. Death in less than three minutes.

During a normal post-disaster escape scenario, most miners would have deployed a self-contained self-rescuer (SCSR) at the first sign of disaster or smoke and thus should have isolated their lungs from any contaminants, including CO. Because all current SCSRs isolate the wearer's lungs from the outside environment, the contaminant level is immaterial, unless the wearer removes the mouthpiece for some reason, most likely to communicate with other miners. Therefore, as long as miners keep correctly wearing their SCSRs, allow no leakage of outside air, and do not remove the mouthpiece until the CO level is 50 ppm or less, they will prevent CO poisoning. According to the Agency for Toxic Substances and Disease Registry (ATSDR), acute carbon monoxide poisoning can occur with steady-state exposure (e.g., > 500 minutes) to 300 ppm, or exposure to 1,000 ppm for approximately 80–90 minutes [ATSDR 2012].

Mini Purge Box Experiments

The primary purpose of the purging experiments in the mini purge box was to refine and validate the instrumentation and methodology for the follow-up purging experiments to be conducted in the refuge alternatives. The mini purge box experiments were designed to determine the appropriate process for injecting a 400-ppm concentration of CO into a ventilated enclosure, to understand the purging air flow rates required to obtain the required contaminant reductions, and determine the contaminated air and CO sampling requirements. These experiments helped to refine appropriate data collection procedures and analysis, and contributed to a better understanding of the results of subsequent refuge alternative airlock purging experiments.

Description of Mini Purge Box

A sealed test fixture was constructed from 0.25-in-thick aluminum plate and welded corners, with interior dimensions of 2 ft x 2 ft x 2 ft for a volume of 8 cu ft. An acrylic glass top was fabricated, then sealed and fastened in place to allow for observation of the inside of the box. The enclosure included a purge air inlet, contaminant gas charging inlet, relief exhaust port, and contaminant level sampling ports. The purging inlet used an air flow meter to control the purging rate along with a ball valve to shut off the air flow. The charging port was tied into the purging port with a ball valve to close off the port. The relief exhaust port was located diagonally from the inlet port on the left side of the box in the upper right corner. The relief exhaust was made up of an adjustable low pressure relief valve with a range of 0.13 to 1.3 psig and a pressure gage. Relief pressures less than 0.13 psig can be obtained by removing and replacing the original pressure relief valve with a lower pressure ball valve to regulate and reduce the back pressure. Three contaminant gas concentration sample ports were located diagonally on the front side with the lowest set 6 in x 6 in off the lower right corner, the second in the middle of the front panel, and the third 6 in x 6 in off the upper left corner (Figure 1). The sample ports had extension tubes installed to reach the center of the enclosure parallel to the port.

Figure 1. Mini purge box with pressure relief system and sampling ports.

Test Set-up for Mini Purge Box Experiments

Carbon monoxide (CO) was used as the contaminant gas for the mini purge box tests. The CO was supplied from a pressurized cylinder containing 99.9% CO. The purging air was supplied by an air compressor through an air pressure regulator, dryer, and filter. The pressure regulator was set at 30 psi. The purging air flow rate of 0.833 cfm and relief pressure of 0.53 psig were set and maintained throughout the test.

The experiments were begun by injecting CO into the mini purge box. Once the level of CO exceeded 400 ppm (at most, 550 ppm) the charging port was closed. Then the air and CO inside the mini purge box were allowed to mix for 5 min. Readings of the CO concentration from the three sampling locations after 5 min showed that no layering was observed, showing uniform mixing. The purging port was then opened to its required flow rate for the given test. Contaminated air exited through the relief valve until the concentration of CO decreased to 400 ppm.

At this point, test measurements were begun and the CO concentration was continuously recorded, while purge air volume and elapsed time were recorded manually. Sampling of the contaminant gas level was completed using an Industrial Scientific iTX 4 gas monitor and iSP sample pump. Instrumentation used for the tests included an air flow meter, gas level detector, and stop watch. Table 2 lists the instrumentation specifications.

Table 2. Instrument/apparatus specifications for mini purge box testing

Apparatus	Specifications
Air flow meter	Manufacturer: Dwyer Instruments Model: RMC-102-SSV and RMC-103-SSV Range: 10–100 SCFH and 20–200 SCFH Accuracy: 2% of Full Scale
Gas level detector	Manufacturer: Industrial Scientific Corporation Model: ITX with CO monitoring configuration Range: 0 to 999 ppm Accuracy: 1 ppm, +-5% of reading
Stop watch	Manufacturer: H Heuer Instruments Pty Ltd. Model: Trackstar 7-jewels
Lower pressure relief valve	Manufacturer: Stra-Val Machine Company Model: RVi20-05T Range: 0.13 to 1.3 psig
Lower pressure gage	Manufacturer: NOSHOK, Inc. Model: 25-200-30 Range: 0–30 in H_2O Accuracy: NIST-Certified Calibration

Results of Mini Purge Box Purging Experiments

The initial shake-down tests with the mini purge box showed that to reduce the CO concentration from 400 ppm to 25 ppm, a box volume exchange rate of approximately 3.2 to 1 was needed—that is, 3.2 complete air volumes were required to cause a four-fold reduction in the CO concentration. 30 CFR § 7.508 (a) (1) requires purging to be completed within 20 min of refuge alternative deployment. The 20-min purging requirement is for all occupants to enter, whether they enter all at once or in groups. If the airlock design is such that miners are required to enter as groups, each purge must be an equal percentage of 20 min with the total for all groups being 20 min or less.

Next, experiments were run to determine the air flow rate required to reduce the level of CO in the mini purge box from 400 ppm to 25 ppm in 20, 15, and 10 min. Using the approximate volume exchange rate of 3.2 to 1 as determined previously, an air flow rate was calculated to reach the test criteria of 400 to 25 ppm in 20, 15, and 10 min at a relief setting of 0.53 psig. The tests were repeated with small changes to the air flow rate until the required times (20, 15, and 10 min) were obtained. This adjusted air flow rate was then maintained and the test was repeated three times to verify results (Figure 2). To evaluate the effect of a lower relief setting—i.e. one that is closer to what is suggested in 30 CFR § 7.506—tests at the same air flows were repeated for a relief setting of 0.13 psig (Figure 3). Note: In Figures 2 and 3, several of the graph lines overlap which makes it difficult to see each line separately.