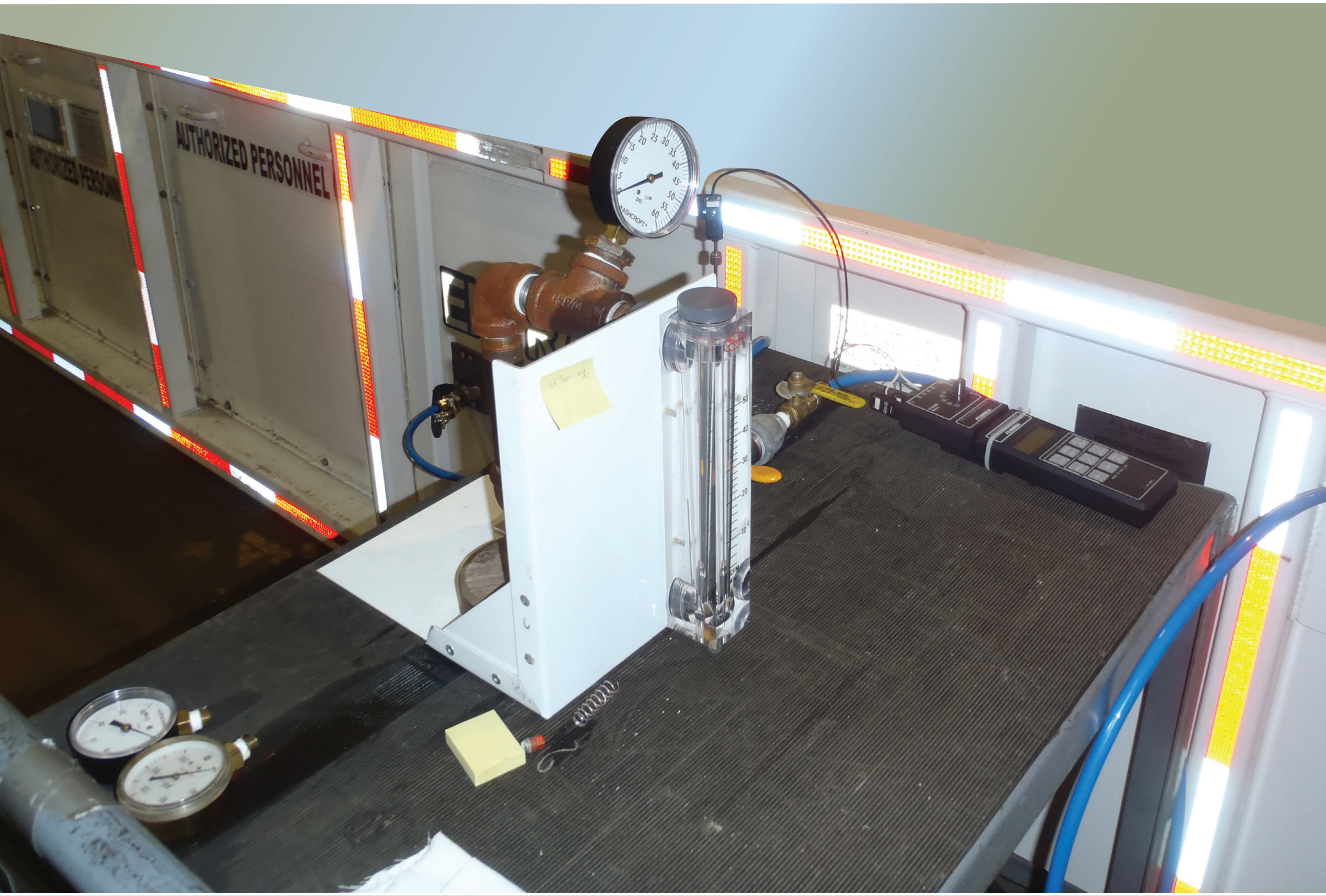
RI 9694

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

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Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives

Eric R. Bauer, Timothy J. Matty, and Edward D. Thimons

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
Pittsburgh, PA • Spokane, WA

March 2014

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NIOSH [2014]. Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives. By Bauer ER, Matty TJ, Thimons ED. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2014–116, RI 9694.

DHHS (NIOSH) Publication No. 2014–116

March 2014

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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.

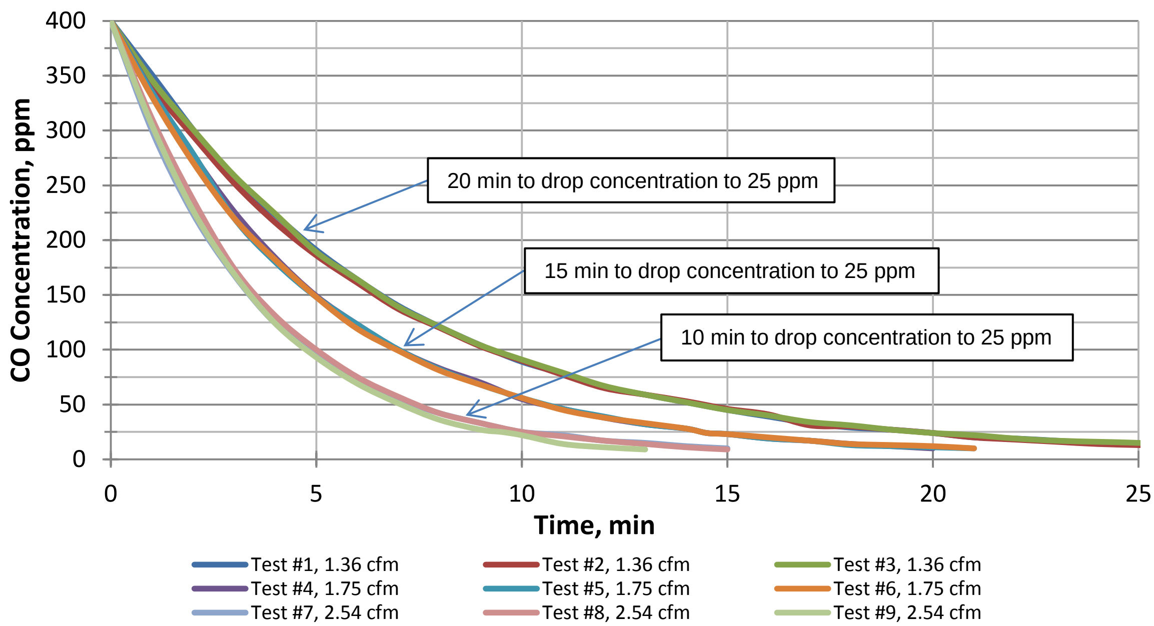

Figure 2. Mini purge box test results at 0.53 psig relief pressure and three different purge air flow rates.

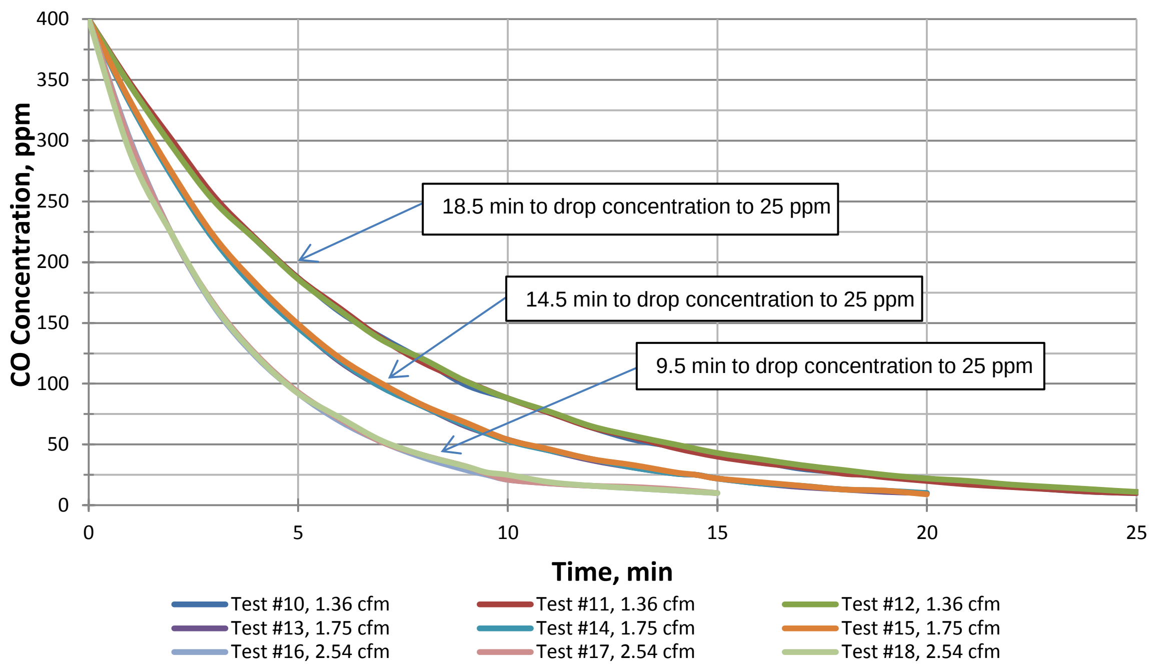

Figure 3. Mini purge box test results at 0.13 psig relief pressure and three different purge air flow rates.

Table 3 presents the results of these tests and shows that by increasing the air flow rate, the time to purge from 400 to 25 ppm was reduced, while at the same time the exchange rate, or volume of air required to purge, was relatively unchanged. Reducing the relief setting from 0.53 psig to 0.13 psig resulted in only a minor reduction of the time to purge and exchange rate. These purging experiments were conducted to gain a better understanding of the purging phenomena and to familiarize researchers with the instrumentation to be employed in the later studies using actual RAs. Therefore, purge times shorter than 10 minutes were not conducted.

Table 3. Test results for purging at 0.53 and 0.13 psig relief pressures

Purge Air Flow, cfm	Time to Purge from 400 to 25 ppm CO, min	Exchange Rate[1]	Relief Setting, psig
1.36	20	3.4	0.53
1.75	15	3.3	0.53
2.54	10	3.2	0.53
1.36	18.5	3.1	0.13
1.75	14.5	3.2	0.13
2.54	9.5	3.0	0.13

[1] Exchange Rate = (Time to reach 25 ppm (min) x Air Flow Rate (cfm)) / Enclosure Volume (cu ft)

Because followup RA purging tests in actual RAs would be done using sulfur hexafluoride (SF_6) tracer gas and this testing would require that the purge air be shut off for 20 sec after each complete volume of purge air was added, mini purge box experiments were run at a flow of 1.71 cfm with the purge air being shut off after each full air exchange and with a continuous flow. These tests were performed at a pressure relief valve setting of 0.0 psig. Table 4 shows the test results and indicates that there was not a measureable difference in the purging results whether the flow was continuous or intermittent.

Table 4. Comparison of average CO concentration reduction for continuous purging air flow versus on/off purging air flow

a. Purge air steady (0.0 psig relief setting). Purge air flow was 1.71 cfm, and the time for one complete airlock air volume was 4.7 min.

Purge Number[1]	Average Reduction in CO Concentration for Each Airlock Air Volume, %
1	57
2	59
3	55
4	25

[1] Purge air flow time for purge number 4 was significantly less than the time for the previous purges because a concentration of 25 ppm was reached prior to the fourth complete air volume exchange.

b. Purge air on/off (20 sec, 0.0 psig relief setting). Purge air flow was 1.71 cfm, and the time for one complete airlock air volume was 4.7 min.

Purge Number[1]	Average Reduction in CO Concentration for Each Airlock Air Volume, %
1	56
2	56
3	54
4	36

[1] Purge air flow time for purge number 4 was significantly less than the time for the previous purges because a concentration of 25 ppm was reached prior to the fourth complete air volume exchange.

Summary: Mini Purge Box Experiments

The mini purge box experiments were successful in that they accomplished their intended goal of allowing NIOSH researchers to gain a better understanding of the purging phenomena and to familiarize them with the instrumentation to be employed in the studies using actual RAs. The experiments revealed that a CO concentration of 400 ppm could be diluted to 25 ppm in less than four air exchanges. In addition, it was shown that by increasing the purge air flow rate, the time to purge from 400 to 25 ppm could be reduced while maintaining a similar exchange rate. It was also found that reducing the relief setting from 0.53 psig to 0.13 psig resulted in only a minor reduction of the time to purge and exchange rate. Finally, the results show that there is not a measureable difference in the purging results whether the purge air flow was continuous or intermittent.

Refuge Alternative Airlock Purging with Carbon Monoxide

CO purging tests were performed on two RA airlocks in accordance with MSHA standards for testing of RA airlocks. According to 30 CFR §7.508, the airlock purge system must be capable of reducing the concentration of CO from 400 to 25 ppm within 20 min of the RA being deployed. Within this 20-min time period, the designed maximum number of occupants for the RA must be able to enter the airlock, purge, and enter the main portion of the chamber. This could require multiple purges if the airlock is not designed to allow all occupants to enter at one time. If the purging process is designed appropriately, the exchange ratio volume should not be greater than 4 to reduce the CO concentration from 400 to 25 ppm.

Tests were performed to determine if it was possible to purge the airlocks in 20 min or less. Two different refuge alternative airlocks were used in the testing: an inflatable tent-type RA airlock and a rigid steel RA airlock. The tests consisted of purging the airlocks at various air flow rates to determine the exchange ratio and time to reach a CO concentration of 25 ppm. Three different variations of the tests were performed on one airlock and two on the other.

The tent-type RA airlock was evaluated with the airlock empty of any occupants, then with one simulated occupant, and finally with seven simulated occupants. The rigid steel RA airlock was evaluated with no occupants and one simulated occupant. The evaluation employing only one simulated occupant might be considered the worst-case scenario because the airlock volume is reduced by the least amount.

The airlock was loaded with a concentration of up to 425 ppm and allowed to stabilize for five minutes. Then a set purging air flow was allowed to enter the airlock. Three CO recorders were used to monitor the CO concentration in the airlock. The sampling points were located at various heights within the airlock to ascertain if uniform mixing of the contaminant occurred. When the CO concentration was reduced to 400 ppm the test was initiated and data recording begun. Once the CO level dropped below 25 ppm on all the CO recorders, the test was stopped. The test was then repeated at different purging air flow rates.

Description of Mobile Refuge Alternative Airlocks

Two actual mobile RA airlocks were used for these purging tests. One was a 7-man capacity airlock that was part of a 35-man inflatable tent-type RA (Figure 4). The manufacturer specified the airlock volume as 57 cu ft. The RA was designated a training model in that the tent was inflated using a blower system rather than by compressed air bottles. The second airlock was an 8-man capacity airlock and was part of a rigid steel RA (Figure 5). This RA was also designated as a training model, and had a total capacity of 8 occupants. It was never intended to have an airlock that was purged. The manufacturer designed the RA to purge the airlock and main chamber simultaneously rather than just the airlock. The airlock was measured to have a free volume of 153.5 cu ft. Both airlocks came supplied with a purging relief system, but neither were supplied with purge air supply inlet ports.

Figure 4. Airlock in a tent-type mobile refuge alternative.

Photo by NIOSH

Figure 5. Airlock in a rigid steel mobile refuge alternative.

The tent-type RA airlock had two relief ports that were gravity style with an exhaust area of 6.8 sq in each and a relief pressure of approximately 0.18 psig. One relief port exhausted air from the airlock to the outside while the second was installed to purge from the airlock back into the chamber.[8]

The rigid steel RA was supplied with two, spring-operated relief ports with an exhaust area of 8.29 sq in each and relief pressures of approximately 0.5 psig. In the airlock, one relief port permitted air to flow from the main chamber into the airlock while the other purged from the airlock to the outside environment. NIOSH modified the pressure relief port that vented from the airlock to the outside by changing the springs to allow for a lower relief pressure. These ports were installed in this manner because the RA manufacturer intended that all eight occupants would enter the airlock and proceed directly into the chamber without stopping. After both of the airlock doors were closed, the entire chamber would be purged through the airlock to the outside.

Tests were performed at given air flow rates in both purging rooms to determine the time required to reduce the CO concentration in the airlock from 400 to 25 ppm. In addition, the airlock volume exchange ratio at the given air flow rates was determined. Both airlocks were tested at six different air flow rates with no occupants and then the tests were repeated with one simulated occupant. The tent-type refuge alternative airlock was also tested with seven simulated occupants. Because test results showed that purging from 400 to 25 ppm in four or fewer air exchanges was easy to accomplish, there was no attempt at testing various designs of purging port configurations, vent size, or locations.

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[8] The RA manufacturer confirmed that this second port was installed backwards. Its intended purpose was to allow the exhaust of air from the main chamber into the airlock in the event of overpressure in the main chamber. This relief port would be closed during purging and, as such, would have no impact on the purging tests. Therefore, it was taped shut.

Simulation of Occupants for Testing Procedures

Occupants were simulated by fabricating containers (boxes) from wood and sealed with plastic and tape. Each box was identical and had a volume of 2.83 cu ft. This volume was derived from a study conducted by Ward on the body volume of adult men [Ward 1967], and from surveys conducted by McWilliams et al. [NIOSH 2012] and by the National Mining Association [NMA 2011] on the average age of coal miners. Boxes of the appropriate volume were used to simulate actual human beings.

Test Procedure for CO Purging of Refuge Alternative Airlocks

Because the tent-type mobile RA airlock was not supplied with a purge air inlet, the entrance handle was removed and a supply port, three CO sampling ports, and a door latch were fabricated to fit the existing entrance handle opening. The rigid steel RA airlock was modified also, allowing for the installation of the purge air inlet port and three CO sampling ports. The purge air inlet port was plumbed to discharge just above floor level of the rigid steel RA airlock, whereas the purge air inlet port discharged through the door at mid-height in the tent-type RA airlock. Because the purge configuration for all RAs varies, no attempt was made to match the purge inlet configurations for these two airlocks. However, an attempt was made to keep the inlet and outlet as far apart as possible, given the modification limitations provided by the two RA manufacturers. The purge air inlet port for the tent-type RA airlock was ½-in NPT pipe with a flat deflector plate on the discharge side. The purge air inlet port for the rigid steel RA airlock consisted of a ½-in NPT pipe inlet into the chamber and ½-in I.D. tubing inside the airlock, discharging horizontally 1 in off the floor parallel to the main chamber entrance door. Simplified purge air flow schematics for the two RA airlocks are illustrated in Figures 6 and 7.

The purge air for the tent-type RA airlock was supplied from a high-pressure cylinder bank of 12 pressurized air cylinders connected to a common manifold and pressure regulator. The plumbing from the supply air to the airlock purging ports consisted of an air pressure regulator, air flow shutoff valve, flow control valve, air flow meter, pressure gage, temperature probe, and CO charging port with valve. Because of the large volume of air required to perform the tests on the rigid steel RA airlock, a portable air compressor was used with a maximum air flow capacity of 125 SCFM at 125 psi. This required a moisture/oil separator between the air pressure regulator and the shutoff valve.

Figure 8 illustrates the plumbing diagrams for the tests. All purge plumbing for the tent-type and rigid steel RA airlocks utilized the same plumbing from the flow control valve to the purging port inlets. The only difference was from the shutoff valve to the air supply because of the different purging air supplies. For all tests, CO was used as the charging (contaminant) gas and was released from a pressurized cylinder containing 99.9% CO.

The gas sample ports had extension tubes installed to reach the center of the airlocks, with all tubes of equal length to keep the sample time constant and equal. The two sample ports for the tent-type RA airlock were located 4 inches off the floor and ceiling with a third located in the middle. The rigid steel RA airlock had the sample tubes located 6 in off the floor and ceiling with the third in the middle. Each sample port was connected to an Industrial Scientific iSP motorized sample pump that used an Industrial Scientific iTX multi-gas monitor/recorder. The airlocks had a low-pressure gage installed to record the internal pressure of the airlock during purging. Table 5 lists the instruments and specifications for this testing.

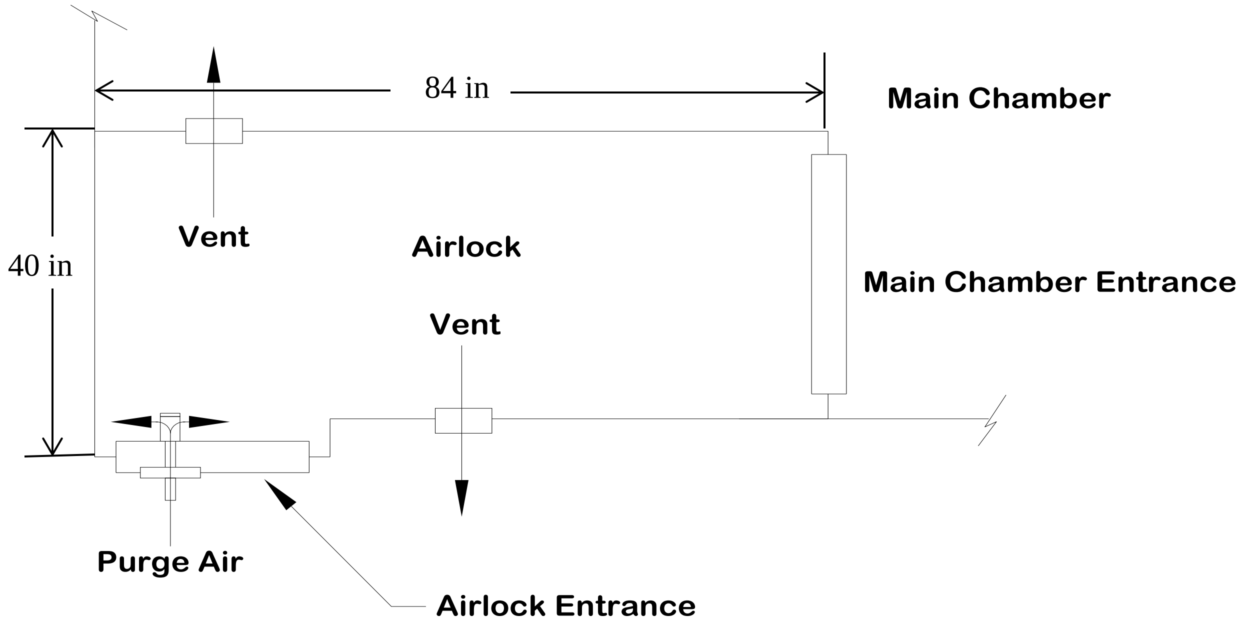


Figure 6. Plan view of air flow schematic for the tent-type refuge alternative airlock during purging.

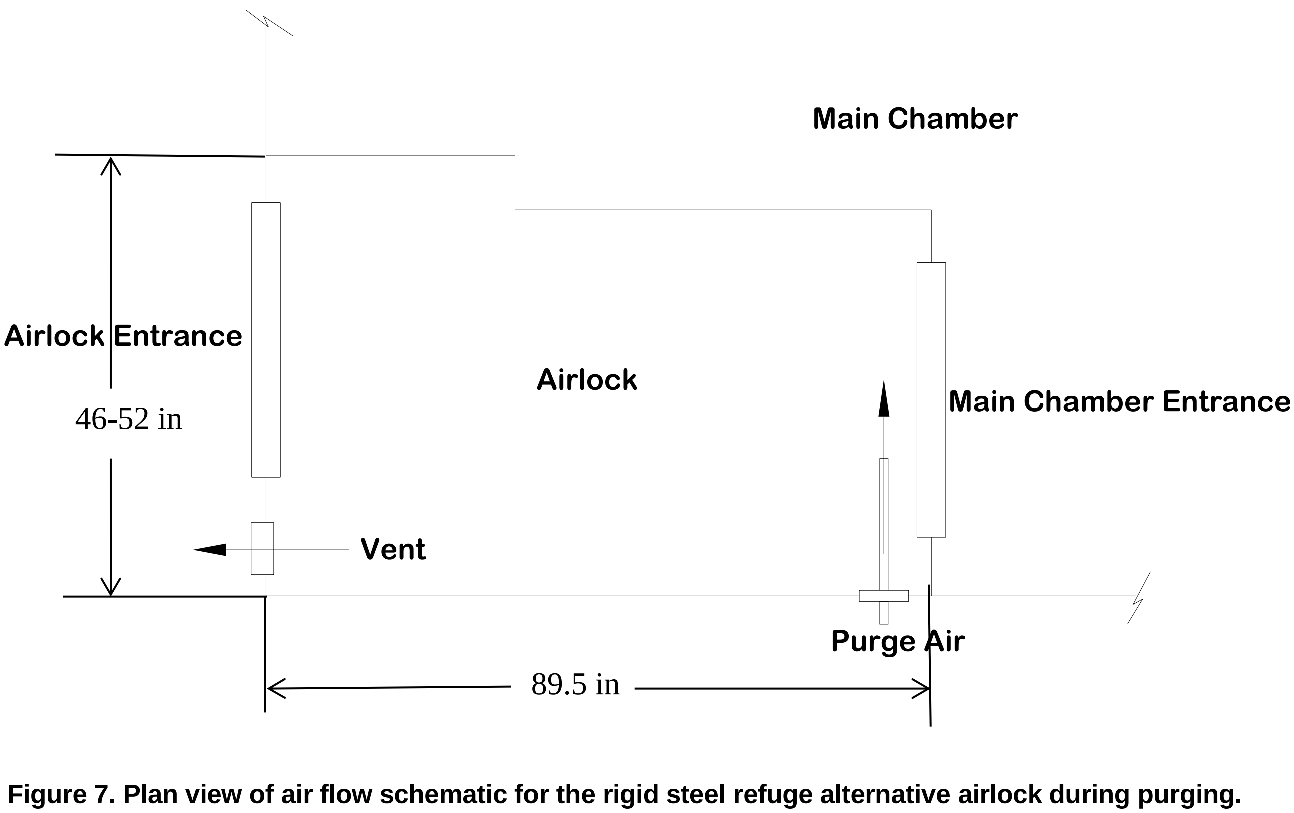
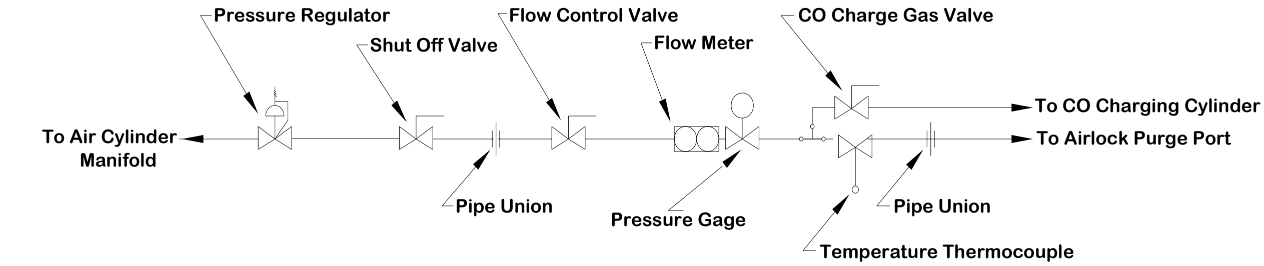


Figure 7. Plan view of air flow schematic for the rigid steel refuge alternative airlock during purging.

Tent-Type Refuge Alternative Airlock Purge Plumbing Diagram



Rigid Steel Refuge Alternative Airlock Purge Plumbing Diagram

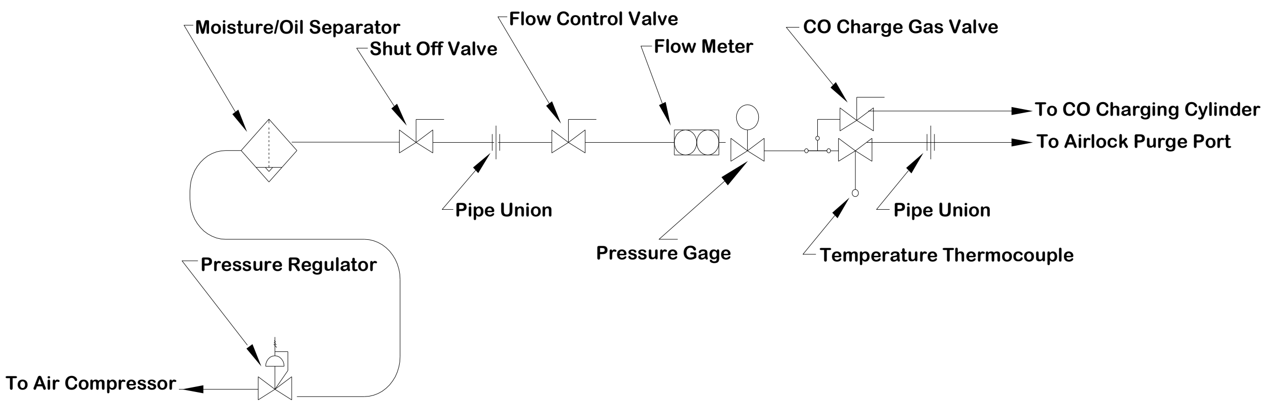


Figure 8. Purge plumbing diagrams. Top diagram is for the tent-type refuge alternative airlock. Bottom diagram is for the rigid steel refuge alternative airlock.

Table 5. Instrumentation and apparatus used during purging of CO from mobile refuge alternative airlocks

Apparatus	Test Parameter Measured	Specification
Air flow meter	Purge air flow rate	Manufacturer: Dwyer Instruments, Inc. Model: VFC-122 Range: 0–50 SCFM Accuracy: 2% of Full Scale
Gas level detector	CO contaminant concentration and total time of test	Manufacturer: Industrial Scientific Corporation Model: ITX with CO monitoring configuration Range: 0 to 999 ppm Accuracy: 1 ppm, ±5% of reading Recording: Set at 1 sample every 2 sec Included air temperature monitoring
Gas sampling pump	CO contaminant concentration	Manufacturer: Industrial Scientific Corporation Model: iSP Sample Distance: up to 100 ft
Stop watch	CO stabilization time	Manufacturer: H Heuer Instruments Pty Ltd. Model: Trackstar 7-jewels
Air pressure gage	Purge air pressure on airlock side of flow meter to correct air flow	Manufacturer: Ashcroft, Inc. Model: 35W1005PH 02L 60# Range: 0–60 psi Accuracy: 1%, NIST-Certified Calibration
Lower pressure gage	Airlock internal pressure	Manufacturer: NOSHOK, Inc. Model: 25-200-30-H_2O Range: 0–30 in. H_2O Accuracy: NIST-Certified Calibration
Air temperature thermocouple	Purge air temperature on airlock side of flow meter to correct air flow	Manufacturer: OMEGA Engineering, Inc. Model: JMQSS-125G-6 Type: J
Thermocouple meter	Purge air temperature on airlock side of flow meter to correct air flow	Manufacturer: OMEGA Engineering, Inc. Model: HH23A Accuracy: NIST-Certified, 0.1% accuracy, .1 degree resolution in degree F & C

Tests were completed with no occupants, one simulated occupant, and seven simulated occupants for the tent-type RA airlock, and no occupants and one simulated occupant for the rigid steel RA airlock.[9]

Each test was designated with an identification label for documentation. All tests performed on the tent-type refuge alternative airlock began with "TT," while the tests in the rigid steel RA airlock began with the letters "RS." This RA designation was followed by the uncorrected air flow setting, and finally an indication of whether the air lock was occupied or unoccupied and the number of occupants. For example, TT-20-0 refers to a test in the tent-type RA airlock, 20 cfm uncorrected air flow, and unoccupied, while RS-30-1 refers to a test in the rigid steel RA airlock, 30 cfm uncorrected air flow, and one simulated occupant. For each test, the air flow rate, pressure, temperature, and airlock internal pressure were documented. The serial numbers of the iTX multi-gas monitors were recorded along with their sample locations, recording start time, and the purging start time. Any other occurrences that were observed during the tests were also noted on a data sheet. Prior to each test, the three iTX multi-gas monitors were set to record at a sample rate of one sample every 2 sec. The time clocks for the three monitors were synchronized as well. Then each of the iTXs were zeroed and checked against a calibration gas of 100 ppm CO to verify accuracy. If any inaccuracy was found the units were recalibrated.

Initially, the air flow shutoff valve was opened all the way and the air flow rate for the given test was set using the flow control valve. Once set, the flow control valve was not adjusted during the tests. The air flow for starting and stopping the purging was controlled by the shutoff valve. For charging the airlock with CO, approximately 10 cfm of air was allowed to enter the chamber while the CO was added to the air. Once the CO concentration inside the airlock reached approximately 450 ppm, the CO was shut off and the air flow continued until the multi-gas monitors indicated a CO concentration of between 400 and 420 ppm. The multi-gas monitors were then set to begin recording the CO concentration.

The CO concentration was allowed to stabilize in the air lock for 5 min before purging was initiated. After the 5-min stabilization period the air flow shutoff valve was opened, allowing the purging air to enter the airlock at the previously set flow rate. Once the purging began, the air flow, outlet pressure, air flow temperature, and airlock internal low pressure were recorded. The iTX multi-gas monitor's recording was stopped once all the monitors were reading below 25 ppm of CO. At the completion of each test, the air flow control valve was reset to the next desired air flow rate and the procedure repeated until all six tests for the given condition were completed. The data were then downloaded from the iTX multi-gas monitors and placed into a spreadsheet for analysis. The air flow meter was corrected at this time to SCFM which was used during the data analysis.

[9] Although it would have been logical to conduct tests with seven and eight simulated persons in the rigid steel RA as well, compressor malfunctions, including excessive amounts of oil in the air, prevented the two additional tests from being completed. The excessive oil might have damaged the CO monitoring equipment and necessitated frequent cleaning of the flow control and monitoring equipment.

Data Analysis and Test Results for CO Purging Experiments

Using the recorded data from the air flow meter, flow meter outlet pressure gage, and air flow temperature, the air flow meter readings were corrected back to standard units (SCFM). The equation to correct for nonstandard operating conditions is:

$$\boldsymbol{Q_2 = Q_1\ x\ \sqrt{(P_1\ x\ T_2)/(P_2\ x\ T_1)}} \tag{1}$$

where: Q_2 = Standard flow corrected for pressure and temperature, SCFM;

Q_1 = Actual or observed flow meter reading, cfm;

P_1 = Actual pressure (14.7 psia + gage pressure), psig;

P_2 = Standard pressure (14.7 psia, which is 0 psig), psig;

T_1 = Actual temperature (460°R + temp °F), °F; and

T_2 = Standard temperature (530°R, which is 70°F), °F.

The data were downloaded from the iTX multi-gas monitors and placed into an analysis spreadsheet with their designated sample locations (high, middle, low). The recorded data was analyzed and the longest time required to purge from 400 to 25 ppm level of CO was recorded.

The airlock volume used during the analysis was the actual empty volume minus any simulated occupants. From the corrected air flow rate, volume of the airlock, and time to reach the 25 ppm CO level, the exchange ratio was determined. Volumes used during the exchange ratio calculations are shown in Table 6. The exchange ratio calculation follows:

$$\boldsymbol{Exchange\ Ratio = \frac{\left(\frac{t_1}{60}\right)x\ f_1}{v_1}} \tag{2}$$

where: t_1 = Time to reach 25 ppm CO, min;

f_1 = Corrected air flow rate, SCFM; and

v_1 = Volume of airlock with no occupants, one occupant, or seven occupants, cu ft.

Table 6. Airlock volumes used during exchange ratio calculations

Chamber Type	Number of Occupants	Airlock Volume, cu ft
Tent-type	0	57.0
Tent-type	1	54.2
Tent-type	7	37.2
Rigid steel	0	153.5
Rigid steel	1	150.7

Once all the individual series of tests with the same conditions and various air flow rates were completed, the resultant data was combined and tabulated as shown in Tables 7 and 8. This data was used to plot all three iTX multi-gas monitor readings of the CO concentration and the time required to reach a CO concentration of 25 ppm. A representative example of the data is plotted in Figures 9 and 10 for the tent-type and rigid steel RA airlocks, respectively. Figures 9 and 10 illustrate that the three gas sample locations gave nearly identical readings (making it difficult to see the readings for "Low" on the line graphs in these figures), which indicated that complete mixing was occurring within the airlocks for the case of no occupants and one occupant. The tests of the 7 simulated occupants in the tent-type RA airlock display an initial variance between the three iTX multi-gas monitors, signifying that some layering was taking place during the initial stages of purging, but eventually the readings converged, indicating that complete mixing did occur as the purging progressed.

Table 7. Tabulated data for tent-type RA airlock purging of CO with various number of occupants, purge air flow rates, and relief pressure of 0.18 psig

Test[1]	Air Flow Setting Uncorrected, cfm[2]	Air Flow Corrected, SCFM[3,4]	Number of Simulated Occupants	Exchange Ratio Corrected for Occupants[5]	Time to Purge, sec	Volume of Air Used to Purge, cu ft
TT-20-0	20	24.67	0	2.63	365	150.1
TT-25-0	25	34.04	0	2.98	300	170.2
TT-30-0	30	47.93	0	3.36	240	191.7
TT-35-0	35	63.08	0	3.41	185	194.5
TT-40-0	40	84.52	0	3.80	154	216.9
TT-45-0	45	105.15	0	4.24	138	241.8
TT-20-1	20	24.85	1	2.74	358	148.3
TT-25-1	25	34.70	1	3.02	282	163.1
TT-30-1	30	48.95	1	3.29	218	177.9
TT-35-1	35	67.27	1	3.65	176	197.3
TT-40-1	40	85.93	1	3.76	142	203.4
TT-45-1	45	105.66	1	4.30	132	232.5
TT-20-7	20	26.14	7	2.83	242	105.4
TT-25-7	25	37.55	7	3.43	204	127.7
TT-30-7	30	53.61	7	4.27	178	159.0
TT-35-7	35	70.95	7	5.91	180	212.9
TT-40-7	40	99.15	7	8.26	186	307.4
TT-45-7	44	114.10	7	10.32	202	384.1

[1]Files ending in 0 are no occupants, 1 is one simulated occupant, and 7 is seven simulated occupants.
[2]Air flow setting on flow control valve.
[3]Corrected using Equation (1).
[4]Actual pressure ranged from 6 psi for the 20 cfm air flow to 73 psi for the 44 cfm air flow test. In addition, temperatures ranged from 10°F to 50.5°F because the purge air was supplied from compressed air bottles.
[5]All exchange ratios were corrected for volume (number of occupants) using Equation (2).

Table 8. Tabulated data for rigid steel RA airlock purging of CO with various numbers of occupants, purge air flow rates, and relief pressures

Test[1]	Air Flow Setting Uncorrected, cfm[2]	Air Flow Corrected, SCFM[3,4]	Number of Simulated Occupants	Exchange Ratio Corrected for Occupants[5]	Time to Purge, sec	Relief Pressure, in H_2O[6]	Volume of Air Used to Purge, cu ft
RS-24-0	22	27.69	0	2.83	942	2.0	434.7
RS-30-0	26	35.79	0	3.03	780	2.5	465.3
RS-34-0	30	47.08	0	3.09	606	3.0	475.5
RS-36-0	34	60.56	0	3.28	500	3.5	504.7
RS-40-0	38	76.69	0	3.30	396	3.5	506.2
RS-44-0	42	95.42	0	3.56	344	4.0	547.1
RS-22-1	22	28.08	1	2.84	916	1.5	428.7
RS-26-1	26	36.45	1	3.04	756	2.0	459.3
RS-30-1	30	47.44	1	3.06	584	2.5	461.7
RS-34-1	34	60.38	1	3.44	516	3.0	519.3
RS-38-1	38	76.31	1	3.36	398	3.5	506.2
RS-42-1	42	96.43	1	3.60	338	3.5	543.2

[1]Files ending in 0 are no occupants, and 1 is one simulated occupant.
[2]Air flow setting on flow control valve.
[3]Corrected using Equation (1).
[4]Actual pressure ranged from 8.5 psi for the 22 cfm air flow to 62.5 psi for the 42 cfm air flow test. In addition, temperatures ranged from 62°F to 71°F because purge air was supplied from a diesel-powered compressor located outside the building.
[5]All exchange ratios were corrected for volume (number of occupants) using Equation (2).
[6]Indicated on the low pressure gage that measured the airlock internal pressure. Internal pressure increased as the flow rate increased because the relief valve was spring operated. Increased pressure is required to compress the spring, resulting in a larger relief outlet opening that allows more purge air to flow out of the airlock.

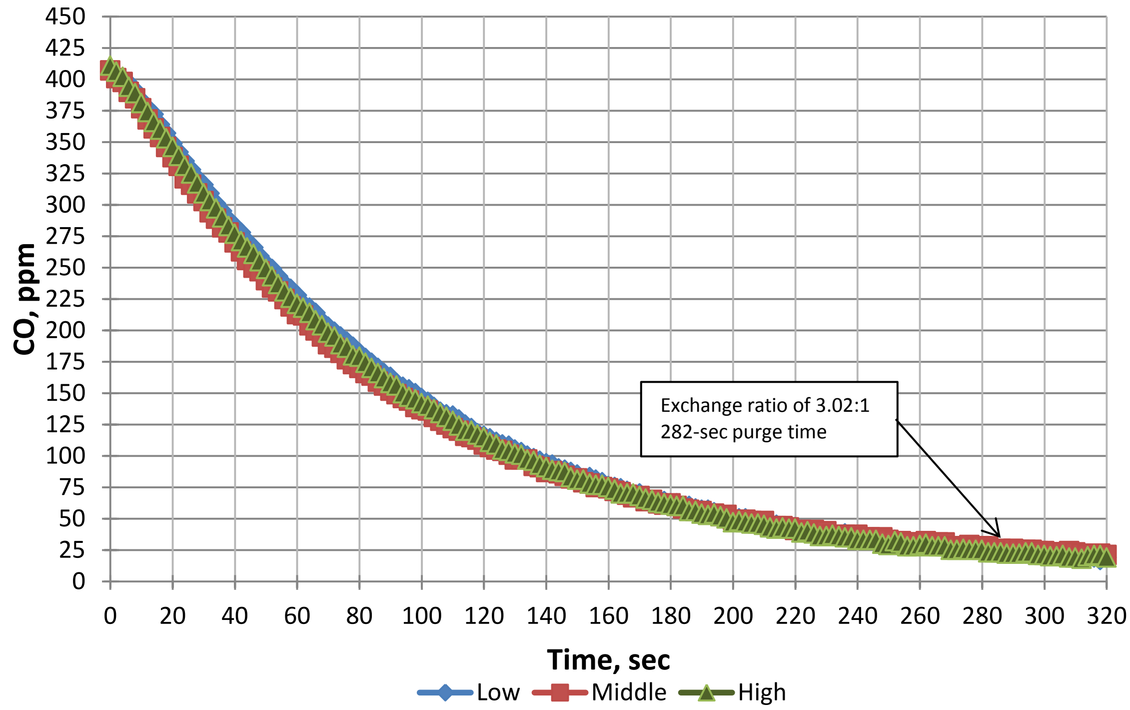


Figure 9. Representative example of data for carbon monoxide (CO) purging of airlock for a tent-type refuge alternative, test TT-25-1.

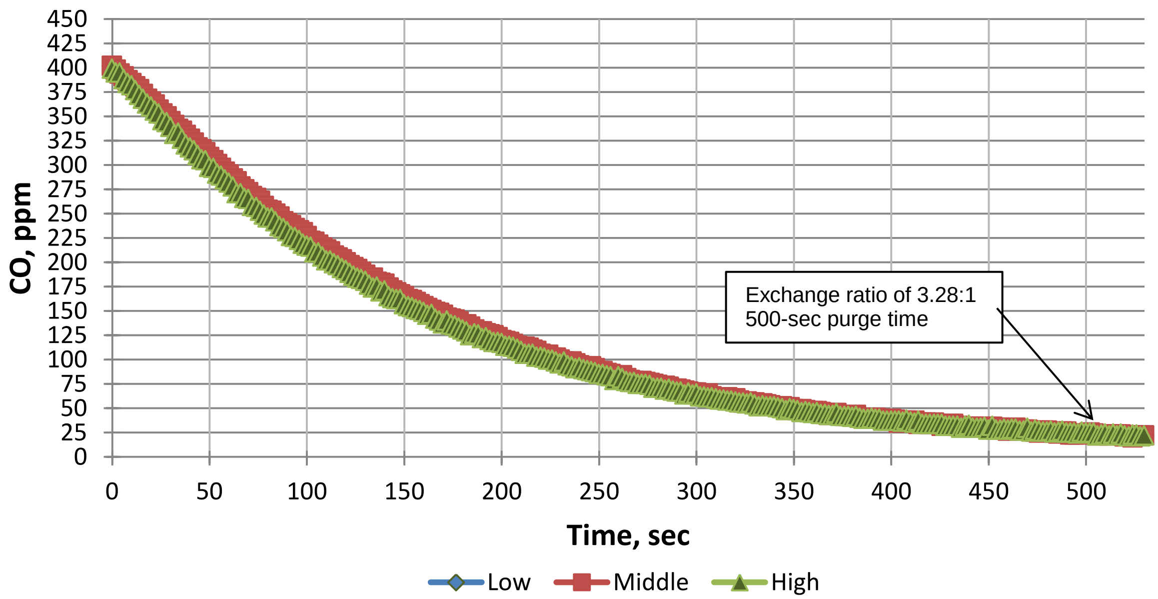


Figure 10. Representative example of data for carbon monoxide (CO) purging of airlock for a rigid steel refuge alternative, test RS-36-0.

The data were analyzed to compare exchange ratios, air flow rates, time to purge to 25 ppm, and total volume of air required to purge. A regression analysis was performed and included for each condition plotted.

The graphs of purge time (400 to 25 ppm CO) versus air flow rate (Figure 11), the total volume of air required to purge (400 to 25 ppm CO) versus air flow rate (Figure 12), and the exchange ratio (volume of air required to purge from 400 to 25 ppm CO/purge room volume) versus air flow rate (Figure 13) show several interesting findings:

- Figure 11 indicates that at an airflow rate of about 70 SCFM, purging efficiency decreases with seven occupants in the tent-type RA. No such effect was noticed for any of the other airlock/occupant combinations.
- Figure 11 also illustrates that purge time from 400 ppm to 25 ppm CO is reduced as the air flow is increased, except for the seven-occupant tent-type RA airlock above 70 SCFM.
- Figure 12 depicts the relationship between purge air flow and total air volume required to purge the airlocks. It reveals that as the air flow increases the total volume of air to reduce CO from 400 to 25 ppm increases.

A final characteristic of purging and an important part of these tests is the exchange ratio as determined by the ratio of the volume of purge air to the airlock volume. "Effective" airlock purging occurs when the exchange ratio is 4 or less. Airlock purging is designed to reduce the contaminant to 1/16th (400 to 25 ppm CO) of its original concentration in four or fewer air exchanges. Figure 13 illustrates that for the tent-type airlock and rigid steel airlock with zero or one occupant, the exchange ratio was less than 4 for nearly all air flow rates. It was above 4 for the tent-type airlock (regardless of the number of occupants) when the air flow exceeded about 90 SCFM and, with seven simulated occupants, the exchange ratio was greater than 4 once the air flow exceeded approximately 50 SCFM. Even though the time to purge remained nearly constant at air flows above 50 SCFM as illustrated on Figure 13, a significantly larger volume of air is needed to purge the CO from 400 to 25 ppm.

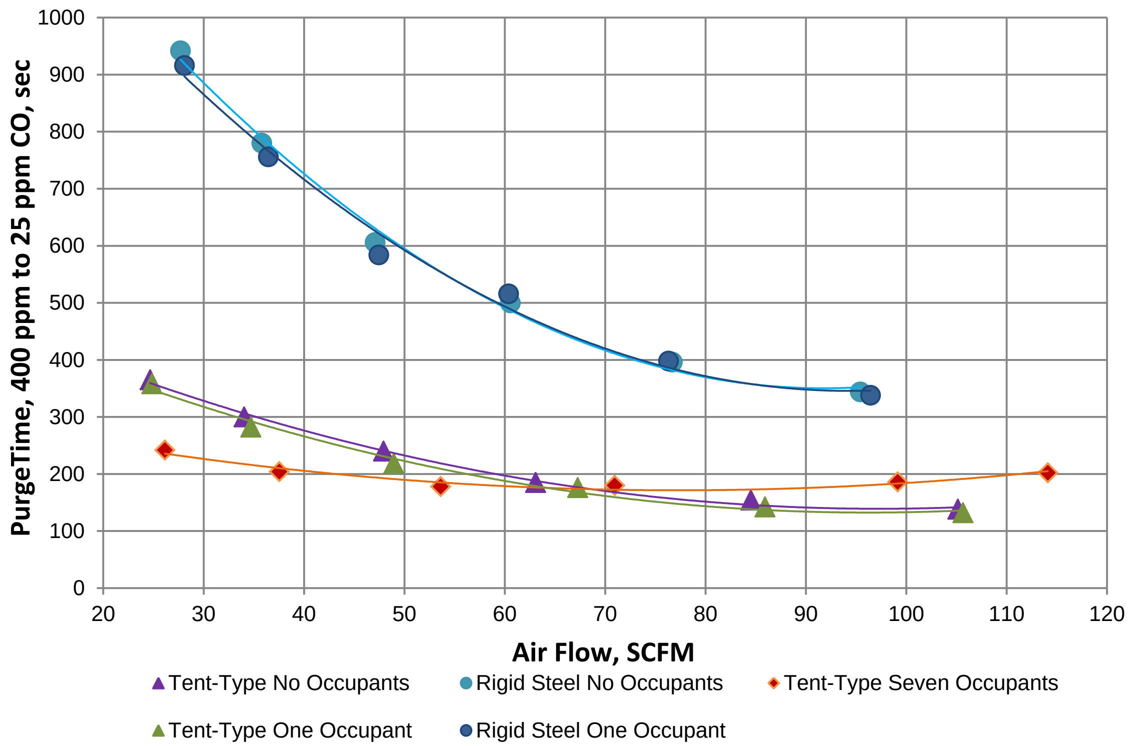


Figure 11. Graph of time required to purge versus air flow rate.

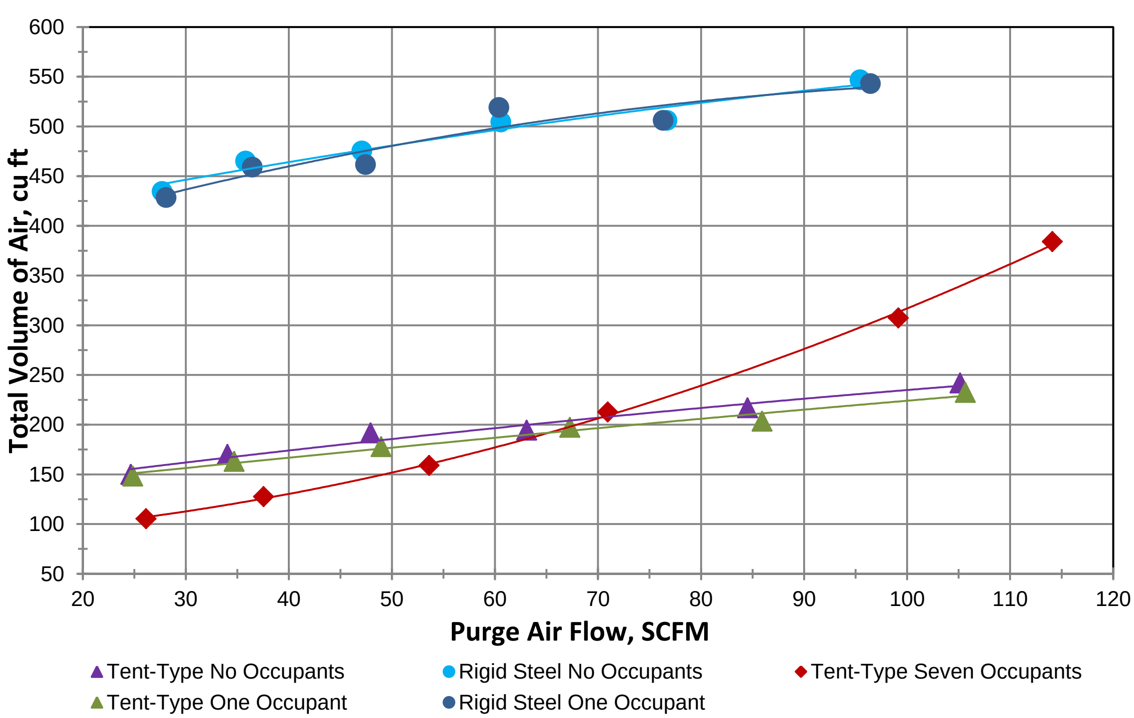


Figure 12. Graph of total volume of air required to purge versus air flow rate.

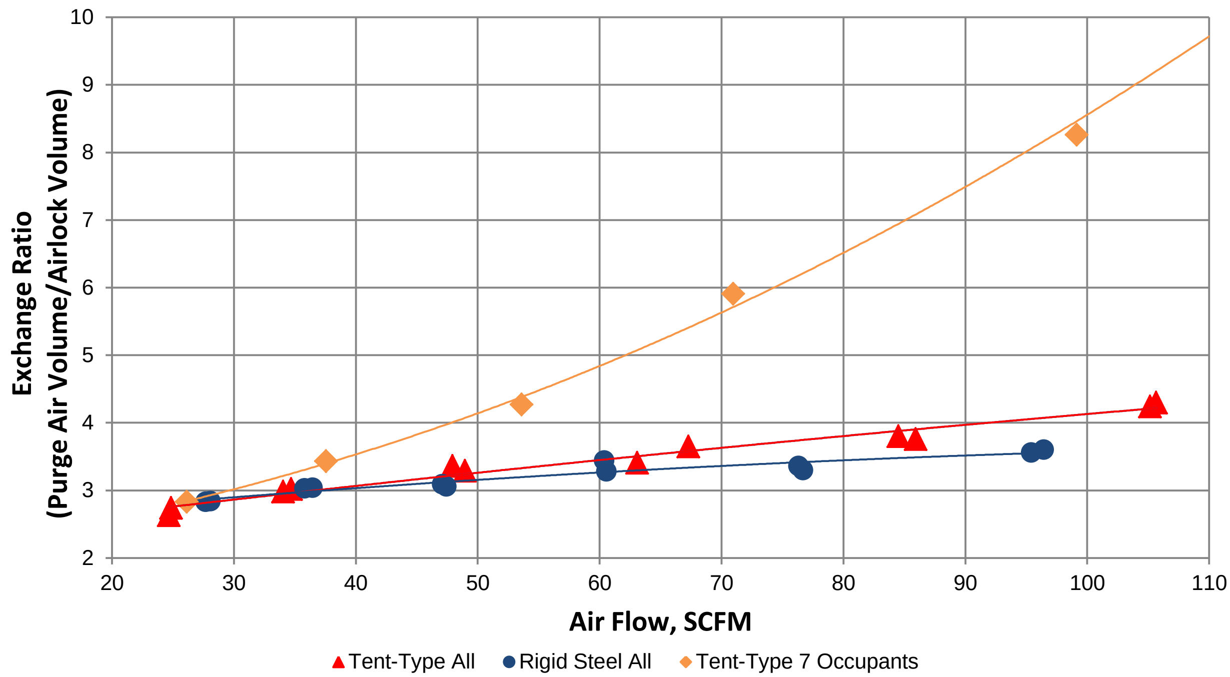


Figure 13. Graph of exchange ratio versus air flow for the tent-type and rigid steel mobile refuge alternative airlocks.

Summary: Refuge Alternative Airlock Purging with Carbon Monoxide

The airlock purging with carbon monoxide research was completed in two different RA airlocks with zero, one, or seven simulated occupants. In general, purging was shown to be effective and occurred in fewer than four air exchanges. The exception was when seven simulated occupants were placed in the tent-type RA airlock with an empty volume of 57 cu ft. In this case, the exchange ratio was greater than 4 when air flows above approximately 50 SCFM were used for purging.

It was also determined that the time to purge from 400 to 25 ppm decreased as the air flow increased, but at the expense of requiring greater quantities of purge air and higher exchange rates. Finally, regression analyses of the data indicated that the tests were very repeatable and thus might be used for estimating purge times, purge air volumes, and exchange ratios for other RA airlocks with different volumes and numbers of occupants

Airlock Purging with Sulfur Hexafluoride

The final series of tests to determine if the current generation of mobile RAs employ technology capable of purging the internal atmosphere from 400 to 25 ppm CO as required by 30 CFR § 7.508 were completed using sulfur hexafluoride (SF_6) as the contaminant gas and purging with live occupants inside the tent-type mobile RA airlock.

A large room containing the RA was filled with a uniform low concentration of SF_6 and the SF_6 entered the airlock when the airlock door was opened and researchers, representing miners, entered the airlock. After 5 min to allow for complete contaminant gas mixing in the airlock, the airlock was purged at the air flow rates used in the CO purging experiments. The only difference was that after each complete airlock air volume of purge air was injected into the airlock, the purge air was shut off for approximately 10 to 15 sec so that SF_6 concentration samples could be collected by the occupants in the airlock. During the original CO purging experiments, the purge air was continuously injected. This on/off procedure was continued for six complete airlock air volume exchanges.

Results of Airlock Purging with Sulfur Hexafluoride

Table 9 includes the results of the SF_6 purging of the tent-type RA airlock with one or five live occupants inside. While not identical for both cases, Table 9 shows that the first four purges were more efficient than what occurred during the CO purging experiments. The reduction, or dilution, was above 50%, ranging from 52% to 73%. The purging of SF_6 with live occupants in the airlock was more efficient but more variable than when the tests were conducted with simulated occupants and CO as the contaminant gas.

Table 10 presents a comparison of purging efficiency with one simulated or live occupant, purge air flow of approximately 86 SCFM, and CO or SF_6 contaminant gas. Table 10 illustrates that the CO purging was very consistent at reducing the contaminant concentration (46%–52%) for each complete air volume exchange, while during the SF_6 purging the efficiency was greater in most instances but more variable as well.

Some of the test variables that could explain the differences observed between the CO purging and SF_6 purging are included in Table 11. Both test approaches show that purging can be effectively achieved, reducing CO purging room concentrations from 400 to 25 ppm in four or fewer complete air exchanges.

Table 9. Results from SF_6 purging of tent-type RA airlock

a. One person entering (Test 1)

Purge[1]	Average SF_6 Concentration, ppb	Reduction of SF_6 Concentration, %	Cumulative SF_6 Reduction, %	Four Volume Exchange Goal, ppb
Start	107.11	0	0	6.69
1	40.70	62	62	6.69
2	10.91	73	90	6.69
3	5.05	54	95	6.69
4	2.88	43	97	6.69
5	2.28	21	98	6.69
6	2.03	11	98	6.69

[1]Purges 1 through 6 denote one complete airlock volume of purge air.

b. One person entering (Test 2)

Purge[1]	Average SF_6 Concentration, ppb	Reduction of SF_6 Concentration, %	Cumulative SF_6 Reduction, %	Four Volume Exchange Goal, ppb
Start	137.37	0	0	8.59
1	56.79	59	59	8.59
2	16.19	72	88	8.59
3	5.32	67	96	8.59
4	2.42	55	98	8.59
5	1.81	25	99	8.59
6	1.61	11	99	8.59

[1]Purges 1 through 6 denote one complete airlock volume of purge air.

c. Five persons entering

Purge[1]	Average SF_6 Concentration, ppb	Reduction of SF_6 Concentration, %	Cumulative SF_6 Reduction, %	Four Volume Exchange Goal, ppb
Start	149.25	0	0	9.33
1	57.98	61	61	9.33
2	18.92	67	87	9.33
3	6.33	67	96	9.33
4	3.03	52	98	9.33
5	2.27	25	98	9.33
6	2.01	11	99	9.33

[1] Purges 1 through 6 denote one complete airlock volume of purge air.

Table 10. Comparison of purging efficiency for the CO and SF_6 purging, one occupant, 86 SCFM

Contaminant Gas	Purge[1]	Initial Concentration (C_i)	Contaminant Concentration after each Purge (C_p)	Contaminant Concentration Reduction, %[2]
Carbon monoxide	1	405 ppm	189 ppm	53
Carbon monoxide	2	405 ppm	87 ppm	54
Carbon monoxide	3	405 ppm	42 ppm	52
Carbon monoxide	4	405 ppm	22 ppm	48
Sulfur hexafluoride	1	107 ppb	41 ppb	62
Sulfur hexafluoride	2	107 ppb	11 ppb	73
Sulfur hexafluoride	3	107 ppb	5 ppb	55
Sulfur hexafluoride	4	107 ppb	3 ppb	40

[1] Purges 1 through 4 denote one complete airlock volume of purge air.
[2] Percentage of Reduction = $(1 – C_p/C_i) \times 100$, where C_i is initial concentration and C_p is the subsequent purge concentration. C_i and C_p change for each subsequent percentage of reduction calculation.

Table 11. Test differences or variables that may be responsible for differences in purging efficiency

Test (Contaminant Gas)	Test Observations	Test Differences/Variables
Carbon monoxide purging	Consistent contaminant reduction Consistently efficient purging	Simulated occupant(s) No extraneous air movement Continuous purge air flow Instantaneous data recording Reliable and accurate gas sampling Controlled testing Constant purge relief pressure
Sulfur hexafluoride purging	Variable contaminant reduction Improved purging efficiency	One or five human occupant(s) Possible occupant-generated air movement On/Off purge air flow Sample collection lag Vacutainer sampling slightly less accurate Semi-controlled testing (human subject involved) Variable purge relief pressure

Summary: Refuge Alternative Airlock Purging with Sulfur Hexafluoride

The airlock purging with sulfur hexafluoride research revealed that the purging of the tent-type RA airlock with live occupants and SF_6 as the contaminant gas was more efficient, but also more variable, than the purging of CO with simulated occupants. The percentage of contaminant reduction for the first three purges with live occupants in the airlock ranged from 52% to 73% as compared to 52% to 54% when the simulated occupants were in the airlock. Some reasons have been proposed but not verified as to why the purging with SF_6 as the contaminant gas and live occupants was more efficient but also more variable. However, the key finding is that the SF_6 testing, as with the CO testing in both the mini purge box and the actual RAs, showed that purging can be effectively achieved, which reduces CO concentrations in a purging room from 400 to 25 ppm in four or fewer complete air exchanges.

Airlock Contamination Research

Miners enter most mobile refuge alternatives (RAs) through an airlock room. If carbon monoxide (CO) or other harmful gases from the ambient post-disaster mine air enter the airlock as the miners enter, purging must be conducted to reduce the contaminant to an acceptable level. In the case of CO, it must be purged to a concentration of 25 ppm or less before the miners enter the main chamber of the RA. For RA approval, 30 CFR § 7.508 (c) (2) states that “For testing the component’s ability to remove carbon monoxide, the structure shall be filled with a test gas of either purified synthetic air or purified nitrogen that contains 400 ppm carbon monoxide, ± 5 percent.” This has been interpreted to mean that the highest concentration of CO that will need to be purged from a RA airlock after miners have entered is 400 ppm, but the ± 5 percent criteria indicates that the actual maximum concentration is 420 ppm.

Historical Data on Measured Post-Disaster CO Concentrations

A review of historical data related to ambient CO concentrations in underground coal mines following mine disasters shows a wide range of measured CO concentrations. The resulting CO concentrations depend upon the type of disaster (mine fire, CH_4 explosion, or coal dust explosion), the extent of the fire or explosion, and whether or not the ventilation system is disrupted or destroyed by the event. RAs need to be designed to function and handle the expected range of CO concentrations—thus the higher CO concentrations that could be present following a disaster must be considered when evaluating the use of mobile RAs.

Some examples of high CO concentrations can be found in the measurements recorded during some of the major coal mine disasters. Gas measurements taken by the Mine Safety and Health Administration (MSHA) in the first borehole at the Upper Big Branch Mine following the 2010 explosion showed CO concentrations at the borehole, which was not far from a portable RA, as high as 14,250 ppm CO (1.4% CO) [Wharry 2013]. Table 12 presents some of the CO concentrations measured in the Upper Big Branch Mine in the hours and days after the disaster occurred. It reveals that CO concentrations can vary widely throughout the mine and can be above 400 ppm even four days post-disaster.

Table 12. Example of CO concentrations measured post-disaster at the Upper Big Branch Mine

Mine Location	Day/Time[1]	CO, ppm	Reference
Bandy Bleeder Fan	First Night/9:42 pm	4,350	Command Center Log, D-0042A, p. 13 [MSHA 2010a]
HG22 Mouth	First Night/10:07 pm	122	Command Center Log, D-0105, p. 7 [MSHA 2010b]
Glory Hole Heading	First Night/10:22 pm	774	Command Center Log, D-0042A, p. 16 [MSHA 2010a]
HG22 Switch	First Night/11:00 pm	40–80	Interview Transcript, I-0024a, p. 21 [MHS&T 2010b]
HG 22, 3 Breaks inby Miner Panel	First Night/11:30 pm	8,676	Command Center Log, D-0042A, p. 19 [MSHA 2010a]
HG22, Xcut 22, at Section Mantrip	First Night/12:15 am	9,999	Command Center Log, D-0042A, p. 21 [MSHA 2010a]
Crossover Belt	First Night/NTR[2]	280	Interview Transcript, I-0259, pp. 28–29 [MHS&T 2012]
LW Tail	First Night/NTR	9,999 (Solarises pegged)	Interview Transcript, I-0259, p. 50 [MHS&T 2012]
LW Headgate	Second Day/NTR	5–6	Interview Transcript, I-0045, p. 38 [MHS&T 2010a]
Areas “A”, “B”, “D”	Fourth Day/7–8:00 pm	382–1,169	Command Center Log, D-0105, pp. 26-28 [MSHA 2010b]
FAB 135, Behind Temp Seal No. 3	Seventh Day/3:00 pm	1,592	MEO Log Book, D-0032A, p. 60 [MSHA 2010c]

[1] Date/Time is relative to the time of the explosion which occurred at 3:02 pm.

[2] NTR = No time reported

In another example, in the Willow Creek Mine fire in 1998, the concentration of CO reached approximately 38,000 ppm. These concentrations were higher than normally found in most mine disasters in the U.S. due to the presence of liquid hydrocarbons. During the fire recovery at Willow Creek while under apparatus, the ambient air contained less than 2% O_2, 60 to 65% CH_4, and approximately 2,500 to 3,000 ppm CO [Trackemas 2013]. Mine rescue teams taking gas measurements during rescue and recovery after the Willow Creek Mine disaster in 2000 reported CO concentrations up to 4.9% (almost 50,000 ppm) [MSHA 2001].

After the Sago Mine disaster, CO concentrations were measured at the drift mouth and through Borehole No. 1 which was drilled into the section where the miners were barricaded [MSHA 2007]. At the drift, the highest concentration recorded was 2,600 ppm approximately 8 hrs after the initial explosion. At Borehole No. 1, the highest concentration was 1,052 ppm, which was measured shortly after the borehole was completed approximately 23 hrs after the event.

The above concentrations are in line with CO data obtained from coal mine dust explosion tests conducted in the Bruceton Experimental Mine of the USBM. MSHA publication IR 1231 cites 63 gas samples collected from 37 full-scale coal mine dust explosions in the Bruceton Experimental Mine [Hofer et al. 1996]. Of the 63 gas samples collected, only 11 showed CO mine ambient concentrations less than 1% (10,000 ppm), while the remaining samples showed CO concentrations ranging from 1% to 9.7% (10,000 to 97,000 ppm). These are representative of the CO concentrations that could occur in a mine following a coal dust explosion if the mine ventilation system was not providing replacement air to the affected area of the mine.

The above examples demonstrate that it is safe to assume that ambient CO concentrations in coal mines following a mine disaster could easily exceed 1%, or 10,000 ppm.

Test Procedure for Airlock Contamination Research

In order to determine the potential resulting CO concentration inside an RA airlock, the ratio of inside to outside contaminant concentration must be estimated. The NIOSH Office of Mine Safety and Health Research (OMSHR) conducted sulfur hexafluoride (SF_6) tracer gas experiments to estimate this ratio under a variety of conditions, including different numbers of miners entering the airlock, different door open times, and different size airlocks and airlock doors. Under these variety of conditions, an estimate of the ratio of the resulting airlock CO concentration to the CO concentration in the ambient mine atmosphere outside of the airlock was made.

The primary objective of this research was to estimate the possible concentration of contaminated gas that could be found in a mobile refuge alternative airlock after occupants enter and prior to purging of the airlock relative to the concentration in the external ambient mine environment. This is important to know because it dictates the quantity of purge air and time needed to reduce the contaminant (presumably CO) level to 25 ppm prior to occupants entering the main chamber of the RA. To estimate the concentration of contaminated air that could enter an RA airlock as miners enter, a series of experiments were conducted using sulfur hexafluoride (SF_6) tracer gas and live occupants entering an airlock. A protocol, "CO Entering Purging Room with Miners Entry (Test Plan 1)," was developed and externally reviewed (Appendix B). SF_6 was used as the post-disaster mine air contaminant instead of CO for obvious safety reasons, and because the two gases behave similarly at the concentrations used during the testing. As noted by Dr. Peter Lagus [Lagus 2013], an expert in tracer gas use and detection:

> . . . any gas at less than 1% concentration in air acts just as the air acts. . . . My thirty some years of experience in using various tracer gases, especially SF_6, has continually proven this to be true. We have seen it repeatedly in our studies of air movement in nuclear power plants when we study the impact of opening doors in clean rooms. When a volume of air moves, a small concentration of heavier molecules does not move differently.

As further evidence of the similar behavior of CO and SF_6 in air, Wallace and Hobbs [1977] state:

> In contrast to molecular diffusion, the mixing due to the motions of macroscale air parcels does not discriminate on the basis of molecular weight. Within the range of levels where this process predominates, atmospheric composition tends to be independent of height.

All the tests involved in this research followed the same basic procedure and were conducted in the reverberation room in Building 154 at the NIOSH OMSHR facility in Bruceton, PA (Figure 14). Initially, the reverberation room and RA airlocks were ventilated to eliminate all traces of contaminant. Air samples were collected using vacutainer sample bottles and sample collection needles (Figure 15) in the reverberation room at a height of approximately 4 ft and in the RA airlock to verify that no contaminant concentration was present.


Photo by NIOSH

Figure 14. Refuge alternatives in OMSHR's reverberation room in building 154 at the OMSHR Pittsburgh site, Bruceton, PA.

Figure 15. Vacutainer sample tube and needle assembly used to collect SF_6air samples.

After the airlock door was closed, a quantity of SF_6 designed to obtain a concentration of approximately 150 ppb SF_6 in the reverberation room was released into the air stream of one of the fans. The concentration of SF_6 was kept below 200 ppb because this was the upper range of the chromatograph being used. Higher levels would have required dilution with pure air prior to analyzing each sample. Also, the NIOSH recommended exposure limit (REL) for SF_6 is a time-weighted average (TWA) of 1,000 ppb; thus the tests concentrations were kept well below that level.

The air in the reverberation room was mixed using a number of fans for 30 minutes to ensure that a uniform distribution was obtained (Figure 16). Air samples were collected at designated locations at intervals of 10, 20, and 30 min after SF_6 release to verify that a uniform SF_6 concentration was obtained. Prior to subjects entering the airlock, all fans were turned off. Next, the airlock door was opened and a number of subjects (1, 3, 5, 7, or 8) entered the airlock then shut the airlock door. The total time the airlock door was open was noted. After 5 minutes, samples of the air inside and outside the airlock were collected. The subjects were then allowed to exit the airlock at which time ventilation of the airlock and reverberation room was initiated. When the test was complete the sample vacutainer tubes were taken to be analyzed by OMSHR technicans using a calibrated chromatograph.

It should be noted that the entering of live occupants into the airlocks during this testing was not conducted to exactly replicate how miners would enter post-disaster. NIOSH personnel who served as live occupants for this testing wore street clothes only; they were not wearing mining boots, coveralls, coats, hard hats, belts and cap lamps, nor carrying other work-related items. In addition, NIOSH personnel were not wearing SCSRs as would likely be the case for miners entering a refuge alternative post-disaster. NIOSH personnel did not “drill” or practice beforehand to expedite their entering, but did discuss positioning, especially when seven or eight persons were entering to try to mininmize the congestion and time. Finally, because the same personnel were used in many of the tests, subjects likely became more efficient and took less time as the testing progressed.

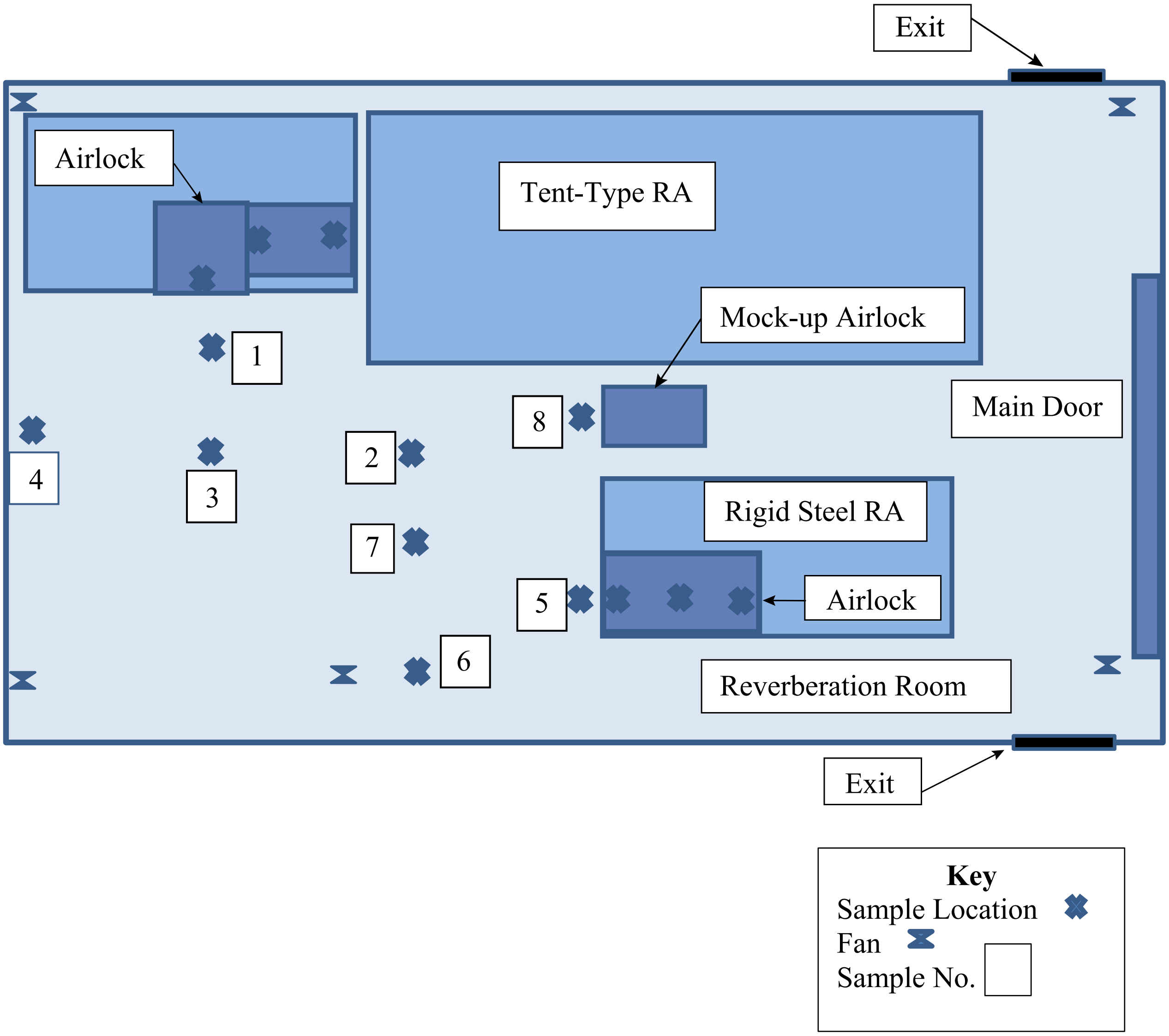


Figure 16. Reverberation room showing mobile refuge alternative locations, fan locations, and sample recording locations. Sample locations 1, 2, 3, and 4 are for tent-type refuge alternative airlock test, locations 5, 6, and 7 are for the rigid steel refuge alternative airlock test, and location 8 for the mock-up airlock tests. Note: Drawing is not to scale.

Adjustment for SF_6 in the Breath of Airlock Occupants

During an actual post-disaster entrance into an airlock by miners, they would likely be wearing SCSRs to isolate their lungs from the contaminated ambient mine air. Also, after entering the airlock, they would not contribute to the contaminant level in the airlock. In contrast, during the contaminated air inflow testing in this study, the lungs of the subjects entering the airlock were not isolated from the ambient atmosphere contaminated by SF_6. In this case, there would be a contribution to the airlock contamination level from the occupants breathing due to the SF_6 in their lungs.

The SF_6 that can be introduced into the airlock from an individual's lungs must be accounted for in the analysis. To account for this, some general information as to an average individual's lung capacity and body volume are needed. In general, an average person's lung capacity is about 6 L (0.212 cu ft) of air. Assuming that the average person entering the airlock weighs 180 lb, their body volume is about 2.8 cu ft. Therefore, the solid volume of the individual is their total volume minus their open lung space volume, or 2.588 cu ft (2.8 cu ft – 0.212 cu ft).

If the volume of an empty airlock is *V* cu ft, then 0.212 cu ft/(*V* – 2.588 cu ft) is the ratio between an individual's lung volume and the resulting volume of the airlock after the individual enters the airlock. If *Y* is the concentration of SF_6 in the ambient air (reverberation room), then the amount of SF_6 that results in the airlock from the breath of one individual that enters can be calculated as:

$$I = (Y \; x \; 0.212)/(V - 2.588) \qquad (3)$$

where: *I* = Amount of SF_6 that results in the airlock from the breath of one individual, ppb;

Y = Concentration of SF_6 in the ambient air, ppb; and

V = Volume of empty airlock, cu ft

As an example, if the ambient SF_6 concentration in the reverberation room outside the airlock is 150 ppb (*Y*), and the empty volume of an airlock is 57 cu ft (*V*), then the contribution to the airlock SF_6 concentration from one person entering the airlock with SF_6 in their lungs is 0.58 ppb (150 x 0.212)/(57 – 2.588).

If the number of individuals entering the airlock is *N*, then the equation to be used to calculate their contribution is:

$$TI = ((Y \; x \; 0.2120) \; x \; N)/(57 - (N \; x \; 2.588)) \qquad (4)$$

where: *TI* = Total SF_6 contribution from all individuals, ppb;

I = Amount of SF_6 in the airlock from the breath of one individual, ppb; and

N = Number of individuals entering the airlock.

Based on this equation, if seven individuals enter the 57 cu ft volume airlock and the SF_6 concentration in the reverberation room is 150 ppb, then their contribution to the SF_6 concentration in the airlock is 5.72 ppb ((150 x 0.212) x 7)/(57 -(7 x 2.588 cu ft)).

The calculation completed above is the worst-case scenario given that it involves the lowest volume airlock (57 cu ft) and the maximum occupancy (7 persons) that NIOSH tested. Larger airlocks and/or fewer occupants will reduce this impact. For example, seven persons entering the rigid steel airlock (155 cu ft) would introduce an increase of only 1.63 ppb into the airlock.

These contributions from occupants' lungs to the SF_6 concentrations in the airlocks have been subtracted from the resulting concentrations. If miners were to remove their SCSRs before entering the airlock, then they might also bring ambient CO into the airlock in their lungs. The above analysis could be used to evaluate miners' CO contribution post-disaster if their lungs were not isolated by wearing an SCSR.

Airlock Contamination Research Results

The airlock contamination testing was completed in three different size airlocks. The first was the airlock in a tent-type mobile refuge alternative. The RA and airlock occupancies were 35 and 7 persons, respectively. The airlock volume at full chamber deployment was 57 cu ft. In addition, the airlock door opening was 25.5-in high x 24-in wide, or 4.25 sq ft. The second airlock was part of a rigid steel RA. Both the RA and airlock had a design capacity of 8 persons. In this case the airlock volume was approximately 153.5 cu ft. For this airlock the door opening was 46.25-in high x 29.5-in wide, or 9.5 sq ft. Finally, a mock-up airlock was constructed from wood with a volume of 102 cu ft and door opening of 36-in high x 26.75-in wide, or 6.7 sq ft. The mock-up airlock volume and door size were designed to fall halfway between the other two RA airlocks and doors. The reason for this was to have an airlock and door sized such that it would be easier for the occupants to enter than the smaller airlock but slightly more difficult to enter than the larger airlock. The size of the door opening and the time for occupants to enter are believed to be important factors in how much contaminated air enters the airlock.

Air samples were collected at three specific times: prior to releasing SF_6 to ascertain the pre-release contaminant levels in the airlock and reverberation room, if any; after SF_6 release to ascertain the quantity and distribution of the tracer gas in the reverberation room; and after subjects entered the airlock to determine the airlock and outside contaminant concentrations. The samples were then sent for chromatograph analysis of SF_6 concentration. After the samples were analyzed for SF_6 concentration, they were recorded in an Excel file from which the analysis was completed.

Airlock Contaminant Concentration versus Outside Contaminant Concentration

Experiments were conducted for 1, 3, 5, 7, and 8 subjects entering the airlocks, depending on the design capacity. Since the outcome desired was to estimate the potential airlock contamination as subjects entered, the ratio of contaminant concentration inside the airlock to the concentration outside the airlock was calculated, then this ratio versus the number of subjects entering the airlock was plotted (Figure 17). Table 13 summarizes the data used to generate the plot shown in Figure 17. The results indicate that for the smallest airlock that was part of the tent-type RA, from 20% to 58% of the outside contaminant concentration entered the airlock, depending on the number of subjects entering the airlock. For the largest airlock (the steel RA airlock), from 5% to 32% of the outside contaminant concentration entered. For the mock-up airlock, 7% to 19% of the outside contaminant concentration entered.

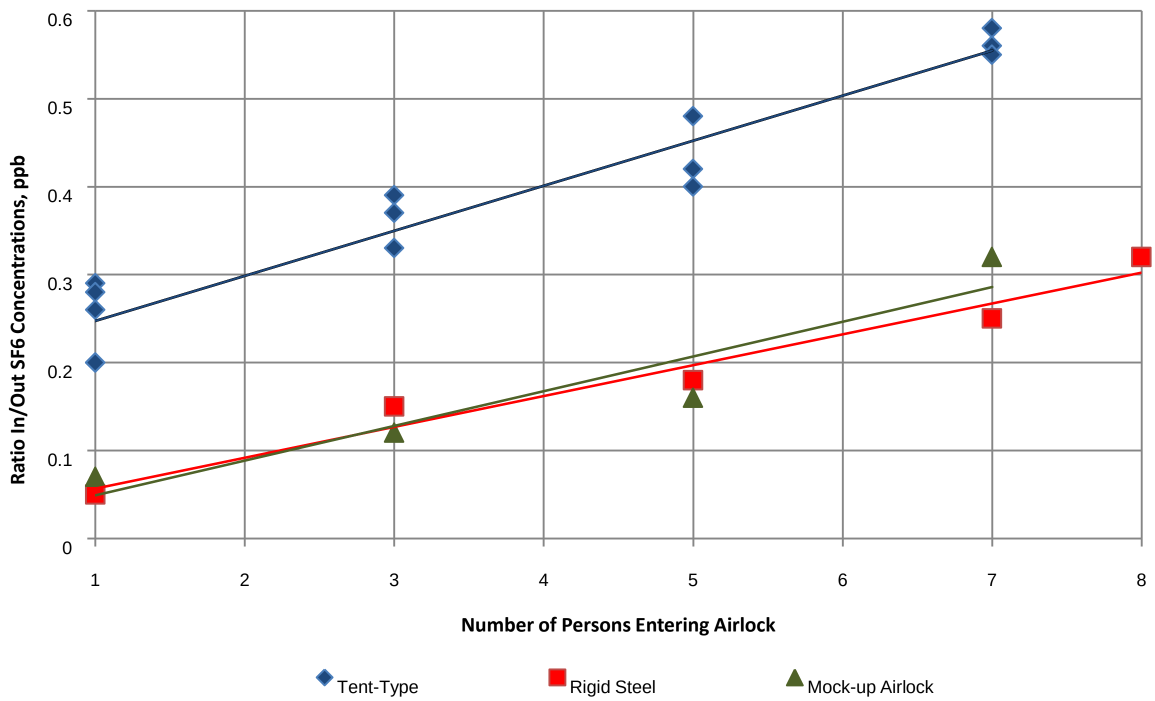


Figure 17. Graph of the ratio of SF_6 concentration (surrogate for carbon monoxide) in the airlock and outside the airlock versus the number of subjects entering the airlock (from data in Table 13).

Table 13. Data for comparing contaminant ratio and number of subjects entering the airlock

Chamber	Number of Subjects Entering Airlock	Time to Enter, sec	Door Size, sq ft	Airlock Volume (Empty), cu ft	Airlock Volume (Occupied), cu ft	SF_6 Contaminant Ratio (Inside Airlock vs. Outside)[1,2]
Tent-type	1	20	4.25	57	54.2	0.20
Tent-type	1	20	4.25	57	54.2	0.20
Tent-type	1	20	4.25	57	54.2	0.26
Tent-type	1	20	4.25	57	54.2	0.28
Tent-type	1	20	4.25	57	54.2	0.29
Tent-type	3	36	4.25	57	48.5	0.39
Tent-type	5	38	4.25	57	42.9	0.48
Tent-type	7	70	4.25	57	37.2	0.58
Rigid steel	1	15	9.50	153.5	150.7	0.05
Rigid steel	3	28	9.50	153.5	145.0	0.15
Rigid steel	5	15	9.50	153.5	139.4	0.18
Rigid steel	7	31	9.50	153.5	133.7	0.25
Rigid steel	8	42	9.50	153.5	130.9	0.32
Mock-up airlock	1	12	6.70	102	99.2	0.07
Mock-up airlock	3	17	6.70	102	93.5	0.12
Mock-up airlock	5	21	6.70	102	87.9	0.16
Mock-up airlock	7	25	6.70	102	82.2	0.19

[1] Inside airlock and outside SF_6 concentrations calculated from several samples taken inside or outside the airlock.
[2] Includes consideration for contaminant in occupant's breath.

Next, additional tests were completed that allowed the subjects to enter the tent-type airlock as quickly as possible. The data collected and used for generating the plot (Figure 18) are included in Table 14. Table 14 indicates that, in general, as the time to enter decreases the contaminant ratio decreases, while Figure 18 illustrates that the contaminant ratio can vary by as much as 18%.

Table 14. Data from tent-type airlock entrance where time varies

No. of Subjects Entering	Time to Enter, sec	SF_6 Contaminant Ratio (Inside Airlock vs. Outside)
1	20	0.20
1	20	0.20
1	20	0.26
1	20	0.28
1	20	0.29
1	40	0.36
1	60	0.38
1	80	0.43
3	36	0.36
3	36	0.37
3	36	0.39
3	14	0.39
3	16	0.25
5	38	0.40
5	38	0.42
5	38	0.48
5	25	0.39
5	28	0.32
7	70	0.55
7	70	0.56
7	70	0.58
7	29	0.44
7	55	0.43

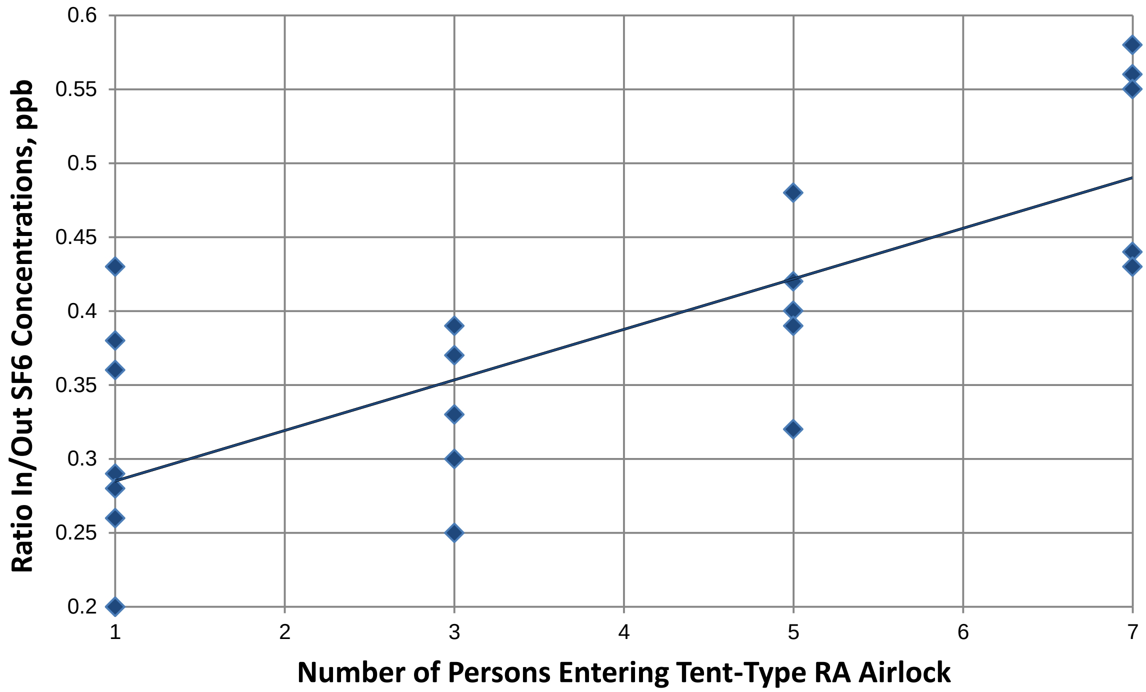


Figure 18. SF_6 contamination ratio versus number of persons entering tent-type refuge alternative airlock at varying entry times.

Summary: Airlock Contamination Research

The airlock contamination research revealed that the contaminated air concentration inside an RA airlock after refuging miners enter could be as high as 58% of the exterior concentration, especially when the airlock volume and door size are small and restrict or slow the miners' entry. The percentage of outside contaminant entering a small airlock that was part of a tent-type mobile refuge alternative ranged from 20% to 58%, while for a larger airlock in a rigid steel RA it ranged from 5% to 32%. Analyses suggest that the number of miners entering the airlock and the time the airlock door is open are the most important factors with respect to the contaminant concentration, although airlock volume, door size, and physical configuration are likely factors as well. Factors that should be considered when designing RA airlocks and doors include step-over height and width, airlock height and length, door width and height, and door closing mechanisms. Airlocks and doors should be designed to maximize miners' abilities to enter the airlock and close the outside door as quickly as possible.

Discussion and Recommendations

The purging research, which included CO testing in the mini purge box and the actual tent-type and rigid steel RA along with the SF_6 testing in the tent-type RA, indicates a number of important findings:

- The current generation of mobile RAs does employ techniques that are capable of reducing a CO concentration of 400 ppm to 25 ppm in a purging room as is required by the 30 CFR § 7.508 regulation.
- Purge time from 400 ppm to 25 ppm CO is reduced as the air flow is increased, except in the case of a seven-occupant tent-type RA airlock at flows above 70 SCFM.
- As the purge air flow increases, the total volume of air to reduce CO from 400 to 25 ppm increases.
- "Effective" airlock purging occurs when the exchange ratio is 4 or less. Airlock purging is designed to reduce the contaminant to $1/16^{th}$ (400 to 25 ppm CO) of its original concentration in four or fewer air exchanges. This research showed that for the tent-type airlock and rigid steel airlock with zero or one occupant, the exchange ratio was less than 4 for nearly all air flow rates. It was above 4 for the tent-type airlock (regardless of the number of occupants) when the air flow exceeded about 90 SCFM; with seven simulated occupants, the exchange ratio was greater than 4 once the air flow exceeded approximately 50 SCFM.
- Testing shows that up to 60% of the outside contaminant concentration could enter the airlock as the miners enter. Depending on the size of the airlock, size of the airlock door, number of miners entering the airlock, and total time the airlock door is open, the percentage of outside contaminant found in the airlock after miners entered ranged from a low of 5% for one person entering a large, rigid steel RA airlock to 60% for seven persons entering a small, tent-type RA airlock. This implies that depending on the post-disaster CO concentration found outside of a mobile refuge alternative, the concentration inside the airlock after miners enter could be significantly more than the 400 ppm level that all mobile refuge alternatives are designed to dilute to 25 ppm.

Establishing the parameters of an explosion scenario, including the post-explosion environment, is an inexact endeavor because the circumstances of both vary widely from event to event. If a set of worst-case parameters is selected from historical disasters, then it quickly becomes a nearly impossible problem to design, build, and deploy a mobile refuge alternative with the requisite characteristics. It is noteworthy that prior to the deployment of RAs in 2007, all coal miners relied on the practice of barricading, which offered virtually no protection from contaminated air. Nonetheless, the findings of this research and new information on likely contaminant concentrations within the airlock indicate a need to define the disaster conditions under which refuge alternatives are expected to provide safe refuge, and then to re-examine the design parameters for mobile refuge alternatives.

Sound scientific research can inform decisions to require certain specifications and operational characteristics of mobile refuge alternatives, but given the difficulty of defining a "disaster scenario," these decisions are ultimately policy in nature. Accordingly, the following recommendations are intended as guidance to determine appropriate purging requirements for refuge alternatives.

- An ambient CO contamination level should be established, based on the disaster scenario, and 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, or alternatively a chart similar to Figure 17 could be applied.
- To compute the expected CO concentration inside the airlock, the information resulting from the first two recommendations should be used in conjunction with the expected number of miners per group entering the airlock.
- Ideally, the airlock should be capable of reducing the expected CO concentration to an acceptable level, such as 25 ppm[10]. 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 mobile refuge alternatives, or the operational procedures for deploying and using them, was beyond the scope of this study. As a starting point to addressing this shortcoming, 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. This must be confirmed by engineering analysis of RAs and under the specified conditions, including the number of miners, the number of groups that will use the airlock, and the specified contamination level.

[10] 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 tested 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 and the details of entry procedures into the airlock to reduce the level of CO contamination.

Acknowledgements

The authors would like to acknowledge the assistance of OMSHR technicians Mary Ellen Nelson, Al Cook, and Jon Hummer during the fabrication, equipment procurement, and testing and data collection phases of the research. The analysis of air samples by Cindy Hollerich and Andrew Mazzella, OMSHR technicians from the Fires and Explosions Branch, was an integral part of the research and is greatly appreciated by the authors. The authors would also like to thank the numerous OMSHR employees who graciously volunteered to enter the airlocks and collect data during the air inflow testing and purging experiments. Finally, thanks to the refuge chamber manufacturers for their assistance in making refuge alternatives available.

References

CFR. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

ASTM [2011]. Standard E741-11, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution. ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/E0741-11. [http://www.astm.org/search/fullsite-search.html?query=Standard%20E741&].

ATSDR [2012]. Toxicological profile for carbon monoxide. Atlanta, GA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention (CDC), Agency for Toxic Substances and Disease Registry, June, p. 35. [http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=1145&tid=253].

Hofer LJE, Giardino DA, Zeller LF [1996]. The evaluation of gases from mine explosions by elemental balancing. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration. IR 1231, March, 31 pp.

Lagus, P Dr. (plagus@tracergas.com) [2013]. Use of SF_6 tracer and the ability of the tracer gas to simulate exactly other contaminant gas, such as CO. Multiple e-mail and telephone calls in September 2012 between Edward Thimons (ebt7@cdc.gov), Senior Technical Advisor, URS Corporation, NIOSH Office of Mine Safety and Health Research (OMSHR), and Dr. Peter Lagus, Lagus Applied Technology, Inc., 457 Corporate Drive, Escondido, CA 92029. [http://www.tracergas.com/].

MHS&T [2010a]. Interview Transcript I-0045 of interview of Virgil Brown, May, 24, 2010. 84 pp. Charleston, WV: West Virginia Office of Miners' Health, Safety and Training. [http://www.msha.gov/PerformanceCoal/Transcripts/May2011/I-0042%20.pdf].

MHS&T [2010b]. Interview Transcript I-0024a of interview of Barry Fletcher, May 17, 2010. 51 pp. Charleston, WV: West Virginia Office of Miners' Health, Safety and Training (MHS&T). [http://www.msha.gov/PerformanceCoal/Transcripts/May2011/I-0024b.pdf].

MHS&T [2012]. Interview Transcript I-0259 of interview of Jim Aurednik, December 1, 2012. 50 pp. n the matter of: the investigation of the April 5, 2010 Mine Explosion at Upper Big Branch Mine. Charleston, WV: West Virginia Office of Miners' Health, Safety and Training (MHS&T). [http://www.msha.gov/PerformanceCoal/Transcripts/May2011/I-0259.pdf].

MSHA [2001]. Report of Investigation, Underground Coal Mine Explosion, July 31 – August 1, 2000, Willow Creek Mine. MSHA ID No. 42-02113, Plateau Mining Corporation, Helper, Carbon County, Utah. Arlington, VA: United States Department of Labor, Mine Safety and Health Administration, Coal Mine Safety and Health, July 17, 45 pp. [http://www.msha.gov/disasterhistory/WCREEK2000/willowcreekfinal/WCfinalcvr.htm].

MSHA [2007]. Report of Investigation, Fatal Underground Coal Mine Explosion, January 2, 2006, Sago Mine. MSHA ID No. 46-08791, Wolf Run Mining Company, Tallmansville, Upshur County, West Virginia. Arlington, VA: United States Department of Labor, Mine Safety and Health Administration, Coal Mine Safety and Health, May 9, 198 pp. [http://www.msha.gov/FATALS/2006/Sago/sagoreport.asp].

MSHA [2010a]. Command Center Log for 4/5/2010 to 4/12/2010, Upper Big Branch Mine Disaster. State of West Virginia, D-0042A, 120 pp. [http://www.msha.gov/PerformanceCoal/Logs/D-0042A%20Command%20Center%20Log.pdf].

MSHA [2010b]. Command Center Log for 4/5/2010 to 4/13/2010, Upper Big Branch Mine Disaster. State of West Virginia, D-0105, 99 pp. [http://www.msha.gov/PerformanceCoal/Logs/D-0105%20Command%20Center%20Log%20from%20State%20of%20WV.pdf].

MSHA [2010c]. Mine Emergency Operations (MEO) Log Book, D-0032A. Upper Big Branch Mine Disaster, April 2010, 68 pp. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration. [http://www.msha.gov/PerformanceCoal/Logs/MEO-Blue%20Goose%20Log/D-0032A%20MEO%20Log%20Book.April%202010.pdf].

NIOSH [2012]. National Survey of the Mining Population Part I: Employees. By McWilliams LJ, Lenart PJ, Lancaster JL, Zeiner JR Jr. Pittsburgh, PA: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2012-152, IC 9527. [http://www.cdc.gov/niosh/mining/works/coversheet776.html].

NIOSH [2013]. NIOSH Pocket Guide to Chemical Hazards. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. [http://www.cdc.gov/niosh/npg/pgintrod.html].

NMA [2011]. Profile of the U.S. Coal Miner – 2010. National Mining Association, 101 Constitution Ave. NW, Suite 500 East, Washington, DC 20001, 1 p.

Trackemas J [2013]. Conversation in October 2013 between Jack Trackemas, Mining Engineer, NIOSH Office of Mine Safety and Health Research (OMSHR), and Eric Bauer, Mining Engineer, NIOSH OMSHR. Topic of conversation was Jack Trackemas' personal experience in the fire recovery efforts at the Willow Creek Coal Mine in 2000, including the CO concentrations that were measured by the recovery teams.

Wallace JM, Hobbs PV [1977]. Atmospheric Science: An Introductory Survey. 1st ed. New York: Academic Press, p. 13.

Ward CL [1967]. Body volume of adult men. Unclassified, AD 657 316, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas, June, 5 pp. [http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=AD0657316].

Wharry MJ (wharry.matthew@dol.gov) [2013]. MSHA borehole monitoring data from mine disasters. E-mail message on February 21, 2013 from Matthew J. Wharry, General Engineer, U.S. Department of Labor, Mine Safety and Health Administration (MSHA), Pittsburgh Safety and Health Technology Center, Pittsburgh, PA, to Ed Thimons, Senior Technical Advisor, URS Corporation, NIOSH Office of Mine Safety and Health (OMSHR).

Appendix A – Diffusion and Tracer Gases

The dilution of a contaminant in an enclosed volume where only fresh air is injected and no contaminated air is exhausted follows the principle of dilution which is:

$$C_1\,V_1 = \; C_2\,V_2 \tag{A1}$$

where: C_1 = Initial concentration, ppm;

V_1 = Initial volume, cu ft;

C_2 = Ending concentration, ppm; and

V_2 = Ending volume, cu ft.

In the sealed volume case, one volume of air will reduce the concentration level by 50%. However, RA airlocks are not sealed volumes; they are a ventilated fixed volume, having exhaust relief ports designed to maintain a slight positive pressure in the airlock and main chamber and prevent any overpressure that might damage the RA. To determine the diffusion and/or airflow rates when using tracer gas, or any contaminant within a ventilated enclosure, appropriate equations are found in ASTM Standard E741-11, "Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution" [ASTM 2011].

To interpret data resulting from tracer gas methods, the mass balance of the tracer gas released within a volume under test is used. Assuming that the tracer gas mixes thoroughly within the test volume, the mass balance equation is

$$V\frac{dC(t)}{dt} = S(t) - Q(t)C(t) \tag{A2}$$

where: V = the test volume, cu ft;

$C(t)$ = the tracer gas concentration (dimensionless);

$dC(t)/dt$ = the time derivative of concentration;

$Q(t)$ = the volumetric airflow rate out of the test volume, cfm;

$S(t)$ = the volumetric tracer gas injection rate, cfm; and

t = time, min.

The air exchange or infiltration rate, A, is given by

$$A(t) = Q(t)/V \tag{A3}$$

where: A = air changes per unit minute (min-1 or ACM).

In the simplest case, the value of A represents the flow rate of "dilution air" entering the volume during the test interval. This analysis could be used to analyze the purging efficiency of actual RA airlocks when CO is the contaminant.

Appendix B – Protocol for Airlock Contamination Research

1. Tests will be conducted in the NIOSH OMSHR reverberation room, Bldg. 154 (see Figure 14). The reverberation room is 60-ft long x 33.8-ft wide x 22-ft high. The 44,602 cu ft of room volume will represent the ambient atmosphere in a coal mine following a mine explosion or fire.
2. Sulfur hexafluoride (SF_6) tracer gas will be released into the reverberation room to create an ambient SF_6 concentration of approximately 100–150 ppb. The SF_6 ambient concentration in the reverberation room will be used to simulate a CO concentration resulting in the ambient air of a coal mine following a mine disaster when miners might need to enter a refuge alternative (RA). SF_6 is a colorless, tasteless, and odorless tracer gas that has a NIOSH recommended exposure limit (REL) and OSHA permissible exposure limit (PEL) of 1,000 ppm. This gas has been used for many years to study mine and building ventilation systems. The range of 100 to 150 ppb was selected because this is within the upper range of detection of the NIOSH OMSHR chromatograph.
3. Initially, two types of RAs will be tested. The first is an inflatable tent-type RA. NIOSH was able to obtain a 35-person chamber designed for groups of 7 miners to enter the airlock. The airlock is partly inside of the steel portion of the RA and partly inside the inflatable portion of the RA. The total volume of the airlock is approximately 57 cu ft with the inflatable portion pushed up to its full potential height. The second RA NIOSH obtained was a solid steel RA designed to hold 8 miners. This is actually a test RA developed by the manufacturer, but is similar to the RAs provided to mines. The area inside the airlock in this RA is 153.5 cu ft and is designed to hold all 8 miners during purging and prior to entering the main chamber. These RAs will be located inside the reverberation room during the testing. In addition, NIOSH may build mock-up airlocks to test contaminated air inflows.
4. Figure 14 shows the reverberation room and the locations of the inflatable and steel RAs during the tests. Prior to the start of a test, all doors to the reverberation room will be opened and five mixing fans located around the room will be operated for at least one hour. Two reverberation room exhaust fans will also be operated during this time period. During this time the large garage door located at the outside entrance to the building containing the reverberation room will also be opened. The airlock door to the RA will be open and a fan will be directed into the airlock. This is done to insure that there is no, or minimal ambient SF_6 in the reverberation room or the airlock at the start of the testing. After the one hour of fan operation, all doors to the reverberation room will be closed, the garage door to the building will be closed, and the two reverberation room exhaust fans will be turned off.
5. With the reverberation room sealed (all doors and vents closed or sealed), the five mixing fans will be located around the room to effectively mix the air. After 5 minutes baseline SF_6 vacutainer tube samples will be taken using 15-ml vacutainer bottles at a height of approximately 4 ft at each group of four sample locations when only one chamber is being evaluated, or at all seven (7) sampling locations shown in Figure 16 when simultaneous testing is being conducted. At least one additional baseline sample will be taken inside the airlock. These samples should show that no SF_6 is present in the reverberation room or the airlock at the start of the testing. The airlock door will then be closed.

6. All collected SF_6 vacutainer sample bottles will be labeled on the sample bottle as to date, time, and location where sample was collected.
7. One MIRAN SapphIRe Portable Ambient Air Analyzer, 205B-XL Series (Serial No. 205B-75043-378, Calibration Date: July 30, 2012), SF_6 analyzer will be placed at a specific location in the reverberation room to provide continuous real-time SF_6 analysis and concentrations during all testing and to serve as a check for the chromatograph results. This will provide additional confirmation of the ability to establish and maintain a constant ambient SF_6 concentration in the reverberation room and as a method for insuring that there are no excursions into higher than desired SF_6 concentrations. This analyzer will be located next to sampling location 3 in Figure 16 when conducting tests on the inflatable chamber and at location 7 when conducting tests on the rigid steel chamber.
8. Following the baseline sampling, approximately 1 gm of SF_6 will be released from an SF_6 lecture bottle into the reverberation room by releasing it into the flow in front of one of the fans. Upon completion of the release, the release person will place the SF_6 lecture bottle into a plastic bag and seal the plastic bag to insure against any additional SF_6 being accidentally released into the room due to a leak in the lecture bottle or valve fittings. The researcher releasing the SF_6 will not represent any miner entering into the airlock during testing just to insure that no trace amount of SF_6 is carried on the release individual's clothing. This person may serve as data recorder or sample collector.
9. At intervals of 10 min, 20 min, and 30 min after release of the SF_6, ambient SF_6 concentration samples will be taken at one or both groups of four sample locations shown in Figure 16 at approximately 4-ft height off of the floor. This will result in a total of 12 or 24 samples. These samples will be taken to insure that a uniform ambient SF_6 concentration is established around the reverberation room before subjects representing miners enter the purging room.
10. Following the collection of these ambient room concentration samples, the 5 room fans will be turned off and subjects representing miners (1, 3, 5, or 7 individuals in the inflatable tent-type RA and 1, 3, 5, 7, or 8 individuals in the rigid steel RA) will then open the RA airlock door and enter the airlock. Once all subjects are in the airlock, they will close the airlock door. The total time for the subjects to open the airlock door, enter the airlock and close the airlock door will be recorded. The entering subject(s) will have 6 vacutainer sampling bottles with them. This will require a total of 7 tests (4 with the tent-type RA airlock with 1, 3, 5, and 7 subjects entering and 5 with the rigid steel RA airlock with 1, 3, 5, 7, or 8 subjects entering). It may be possible to run simultaneous tests on both the RAs if enough research personnel are available to enter the airlocks.
11. Once inside the airlock, with the airlock door closed for 15 sec, airlock SF_6 samples will be collected with vacutainers at 3 locations somewhat equally spaced within the airlock. Another set of 3 samples will be collected five minutes later at the same locations. This will be a total of 6 samples. The sampling will be divided among the subjects representing miners in the airlock. If only one subject enters, that individual will take all 3 samples. If more than one subject enters the sampling will be divided up as is most appropriate. At the same times that the samples are collected inside the airlock (15 seconds after closing the airlock door and 5 minutes later), samples will be taken just outside of the airlock door. This will result in an additional 2 or 4 samples. SapphIRe analyzer readings will also be recorded at these sampling intervals.

12. Following the collection of the 5-min post-entering SF_6 samples both inside and outside of the airlock, the airlock occupants will open the airlock door, and exit the airlock.

13. All reverberation room doors will be opened as well as the garage door to the outside of the building. The two reverberation room exhaust fans will be turned on and all of the five mixing fans in the reverberation room will continue to operate for several hours. In addition, one of the fans will be directed into the airlock through the open airlock door. This is done to remove all residual SF_6 from the reverberation room and from the airlock. Previous testing has shown that a minimum of one hour of ventilating the reverberation room and the RA airlock will remove all SF_6 and prepare the reverberation room and the RA airlock for the next test.

14. All collected SF_6 vacutainer sample tubes will be analyzed using the OMSHR SF_6 chromatograph located in Building 118 at OMSHR Pittsburgh. This SF_6 type of testing has been a standard analysis tool used in OMSHR research for many years. All SF_6 vacutainer bottle samples will be analyzed on the chromatograph within one week of testing. Samples may also be sent for analysis to an independent outside testing firm.

15. The ratio of the SF_6 concentration in the RA airlock to the ambient SF_6 concentration in the reverberation room can be used to determine what CO concentrations might occur in an airlock during the entry of miners in a mine disaster situation. For example, if it is found that the reverberation room SF_6 concentration is 200 ppb and the airlock concentration after miners enter is 10 ppb, then the ratio of airlock SF_6 to reverberation room SF_6 is 0.05. If it is assumed that the post-disaster mine ambient CO concentration is 15,000 ppm (a concentration similar to what was found in the first borehole near the RA at Upper Big Branch), then the airlock CO concentration would be 0.05 X 15,000 ppm = 750 ppm CO following the entry of the miners.

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DHHS (NIOSH) Publication No. 2014-116

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