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Results of Manned Shelter Testing in Underground Mines

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In the event of a mine emergency that prevents escape, shelter and await rescue may be the best option. Shelter systems have been used in numerous applications over the decades; fall out shelters, control room shelters, and submarine escape compartments to name a few. This paper will report the atmosphere control capabilities of manned shelter tests conducted at the Logan, West Virginia coal mine in September 2007 and at the Cameco McArthur River uranium mine in August 2008. Micropore teamed with Mine Lifeline LLC to support the Logan test and with Cameco Corp. to conduct the McArthur River test.

For these manned tests, carbon dioxide was controlled by deploying ExtendAir® brand CO2 absorbent lithium hydroxide curtains manufactured by Micropore, Inc.. Oxygen was supplied into the shelter from high pressure cylinders via pressure regulators. The ExtendAir® lithium hydroxide curtains and the make-up oxygen were set out based on a predetermined schedule. A common goal of these tests was to demonstrate the proper function of the atmosphere control system and validate the deployment schedule for carbon dioxide control curtains and make-up oxygen.

This paper will report the carbon dioxide concentrations and ExtendAir® absorbent curtain performance over the course of the test. Ambient oxygen concentration and oxygen supply rate will also be reported. Both tests were completed successfully. The refuge chambers maintained a life supporting atmosphere with comfortable ambient temperature and humidity.

INTRODUCTION

This paper reports the results of manned shelter testing conducted at the Logan West Virginia coal mine in September 2007. Micropore teamed with Mine Lifeline to supply and conduct this 96 hour test. The testing was conducted with an average of 10.7 people present, with eight 12 hour shifts. Specifically 1027 man hours were spent inside the chamber over the 96 hour test. The shelter was typically sealed and shift change was via the lock-in/lock-out portal. The McArthur River uranium mine test was conducted over a shorter duration, 36 hours. This is due to the Canadian experience that miners in non-coal applications will be rescued within 36 hours. The Cameco McArthur River mine test shelter was located in the mine's Shaft 3 Refuge Station. This shelter is a permanent facility mined into the rock 530 meters underground. The chamber measures approximately 6.3 meters by 5.3 meters by 4.2 meters high and has an enclosed volume of 140 cubic meters. Cameco selected the Shaft 3 Refuge Chamber for this test because it is located in a relatively inactive area of the mine and can remain sealed for the test duration. This chamber is rated for 8 miners The fact that it includes an airlock permitted the test to be conducted in 3 back-to back 12 hour shifts, with a hot swap where shelter population would double for a short period of time. Specifically 291 man hours were spent inside the chamber over the 36 hour test. The Findings section of this paper will report the detailed results of the two mine shelter tests.

FINDINGS

MINE LIFELINE, LOGAN WV TESTING

A refuge station was constructed inside the Logan, West Virginia coal mine. This shelter was built into a cross-cut and sealed with cinder block and cement. A Mine Lifeline air lock (yellow metal door with person entering shown in Figure 1) was installed in the shelter's block front wall. A Mine Lifeline breathable air system was installed to provide atmosphere control within the shelter.

FIGURE 1
MINE LIFELINE BREATHABLE AIR REFUGE

FIGURE 2
MINE LIFELINE BREATHABLE AIR REFUGE

(Oxygen cylinders (green) in foreground; ExtendAir® Curtains can be seen in background)

OXYGEN

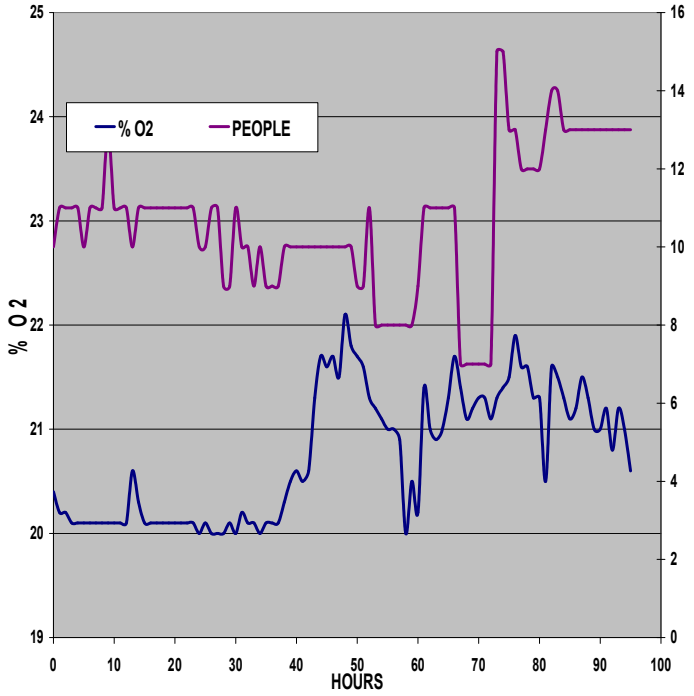
Goals for Oxygen Concentration

The Mine Safety and Health Administration (MSHA) set the allowable oxygen concentration at 19.5% to 23.5% (reference 1). The normal ambient atmosphere contains 20.9% oxygen. Healthy people can comfortably exist with oxygen concentrations over 18% surface equivalent (oxygen partial pressure of 140 Torr). The range of 18 to 21% oxygen surface equivalent is approximately the variation in oxygen partial pressure from sea level to Denver, Colorado. Oxygen concentrations above approximately 21% increase the intensity of fires (reference 2). Additionally, increasing oxygen concentrations from 21 to 25% lowers the ignition temperature of materials (reference 3).

Methods for Providing O2

The Mine Lifeline breathable air refuge uses compressed oxygen cylinders to supply life supporting oxygen. Figure 2 shows the oxygen cylinders deployed in the sealed shelter. Oxygen was released into the shelter on a scheduled basis to replenish the metabolized oxygen.

FIGURE 3 OXYGEN CONCENTRATION



Results for Oxygen Control

Figure 3 plots the shelter oxygen concentration (left axis in percent oxygen) over the 96 hour test. As can be seen in the plot, the oxygen level was maintained between 19.9 and 22.1%. The average oxygen concentration was 20.8% over the 96 hours. The number of personnel in the chamber (right side axis) fluctuated from 7 to 15 but that had no significant impact on the oxygen control.

CARBON DIOXIDE

Goals for Carbon Dioxide Concentration
United States safety standard's for general working conditions inside the mine require atmospheric CO2 concentrations of 0.5% time weighted average (reference 4). For this simulated emergency, the refuge chamber CO2 concentration was set to a maximum of 0.5% to conform to the 2007 MSHA requirement (reference 1). This is a very low concentration to control to and challenges some carbon dioxide control systems.

Method for Controlling Carbon Dioxide

ExtendAir® CO2 absorbent lithium hydroxide curtains, part number OM-0608K, were used to control the build up of carbon dioxide in the chamber. ExtendAir® curtains are a non-powered carbon dioxide absorbent system requiring no electricity or fans to work. This same technology has proven effective for submarines awaiting rescue and is authorized for use in submarine navies worldwide. Without a method to control the shelter's carbon dioxide concentration, the level would constantly rise over the 96 hours to approximately 10%. This greatly exceeds the shelter's maximum allowable limit, 0.5% and also greatly exceeding the immediately dangerous to life and health (IDLH) limit of 4% (reference 4).

The passive carbon dioxide absorbing curtains work by reacting the ambient carbon dioxide and converting it to a solid carbonate. The overall chemical reaction is shown below.

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O$$

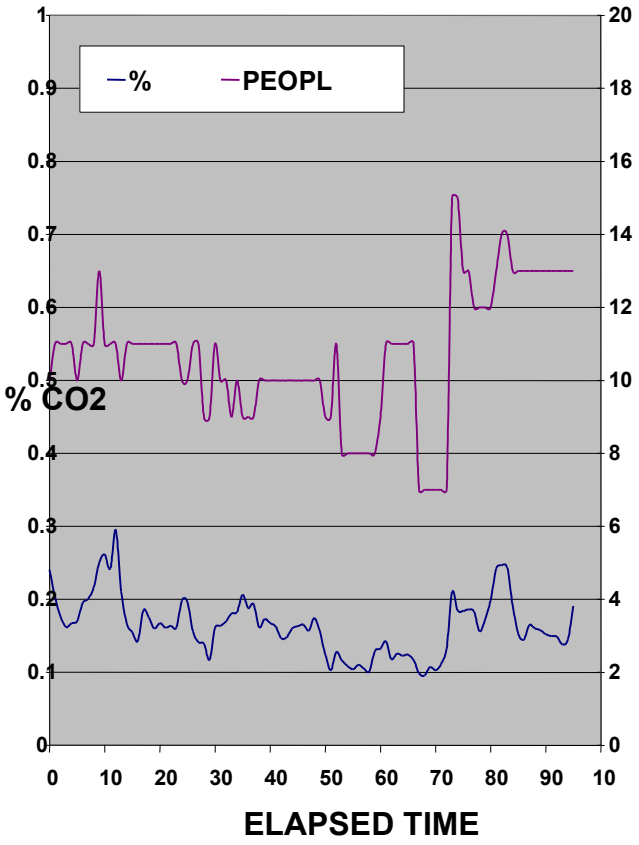
Deployment Method
Each box of ExtendAir® absorbent (5.7 pounds minimum pure lithium hydroxide per box), contains 8 curtains approximately 49 inches long by 11 inches wide, as well as 4 clip style hangers. The curtains are hung side by side with approximately ½ to 1 1/2 inch spacing (see Figure 4). By hanging the curtains in close proximity, an air current is created. This air current is produced by the slight amount of heat generated by the chemical reaction. This airflow produces a "convective engine" that draws the carbon dioxide to the curtains, flows up though the material, and then spreads out across the roof of the chamber. Obviously the natural diffusion of carbon dioxide from an area of high concentration to low concentration also plays a part in moving the carbon dioxide to the curtains. The properties of this "convective engine" allow the curtains to be hung in a variety of locations, typically away from the rescuees and out of the normal traffic flow. As can be seen from Figure 2, the curtains for this test were hung on the far side of the chamber, in the corner near the external wall. In practice the ExtendAir® curtains are deployed at a fixed rate depending on the number of inhabitants and at predetermined frequency. Over the course of testing 84% of maximum stoichiometric efficiency was achieved. For the 96 hour shelter

FIGURE 4
DEPLOYED EXTENDAIR® CURTAINS

test, curtains were hung at time zero and at 12 hour increments. Curtains were left exposed for 48 hours; they are left hanging as there is still some low level of unreacted lithium hydroxide absorbent after 36 hours. The curtain deployment schedule used 6 boxes initially deployed at time zero and 4 boxes deployed at subsequent 12 hour intervals; for a total of 34 boxes.

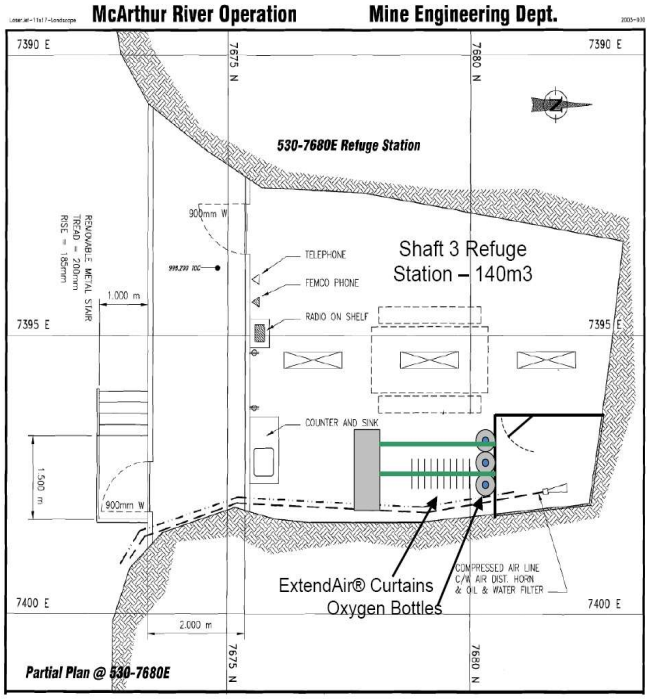
Carbon Dioxide Level in Shelter
Figure 5 is a plot of carbon dioxide concentration over the 96 hour test. The left side axis reports carbon dioxide levels in percent. The x axis is time in hours and the right side y-axis is people within the chamber. The ExtendAir® curtains were deployed to support 10 rescuees and the trial averaged 10.7 people over the entire 96 hours. Carbon dioxide concentrations never exceed 0.3% (3,000 ppm) and the average concentration was 0.16% (1640 ppm). Review of the carbon dioxide profile (Figure 5) during this test shows the rapid decline in carbon dioxide concentrations when fresh curtains are deployed at 12 hour increments. Looking at the second curtain deployment (12), the carbon dioxide level is reduced by 50% in 3.25 hours. This rapid decline was previously observed in laboratory shelter tests.

FIGURE 5 CARBON DIOXIDE CONCENTRATION



The oxygen flow is set by adjusting the oxygen cylinder regulator and is indicated on the cylinder regulator low pressure gage. Note this pressure gage is calibrated in liters per minute of oxygen

FIGURE 6 REFUGE STATION SCHEMATIC



McARTHUR RIVER TESTING

The McArthur River Uranium mine is operated by the Cameco Corp. The mine is located in Northern Saskatchewan, Canada. The Shaft 3 Refuge Station is a permanent shelter measuring approximately 6.3 meters by 5.3 meters by 4.2 meters high with an enclosed volume of 140 cubic meters. Over the 36 hour test a total of 291 man hours were spent inside the chamber. The chamber was manned over three consecutive 12 hour shifts. The shelter was sealed utilizing clay seals molded around the metal door frame; and resealed after each shift change. See Figures 6 and 7.

<u>OXYGEN</u>

Goals for Oxygen Concentration

The goal of the test was to maintain oxygen within the range of 19% to 23%. Each cylinder contains approximately 6800 standard liters of oxygen and 3 of these cylinders are designed to support 8 rescuees for a minimum of 36 hours. A high pressure oxygen cylinder regulator is included in the shelter supplies.

FIGURE 7 REFUGE STATION AIRLOCK

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Results for Oxygen Control

The oxygen flow into the shelter was established very shortly after the shelter was secured (time zero on figure 8). Initial oxygen flow was set to 4.5 standard liters per minute (slpm) based on shelter instructions to establish oxygen flow of 0.5 slpm per miner (and 9 subjects in the chamber at that time). As shown in Figure 8, the oxygen concentrations varied from 20.8% to 21.9% over the 36 hour test. This is well within the pre-established limits of 19 to 23%. Table 1 lists the oxygen cylinder flow rates over the test and the approximate total flow of oxygen provided into the chamber.

Allowing for the slight oxygen addition into the shelter atmosphere (260 standard liters), 8426 liters of oxygen were consumed over the 291 man hours. This equates to an average oxygen consumption of 0.48 liters of oxygen per man per minute (0.45 slpm); in close agreement with the design operating point of 0.5 lpm. In looking at the oxygen concentration from Figure 8, it can be noted that oxygen consumption is not consistent. From the 18th hour to the 28th hour, oxygen concentration is increasing even at reduced oxygen supply rate. This period of time also equates to a period in the test when more subjects were resting. Over the last 2 hours of the test the very minor increase in oxygen concentration is attributed to analyzer drift.

FIGURE 8
OXYGEN MEASUREMENTS IN SHELTER

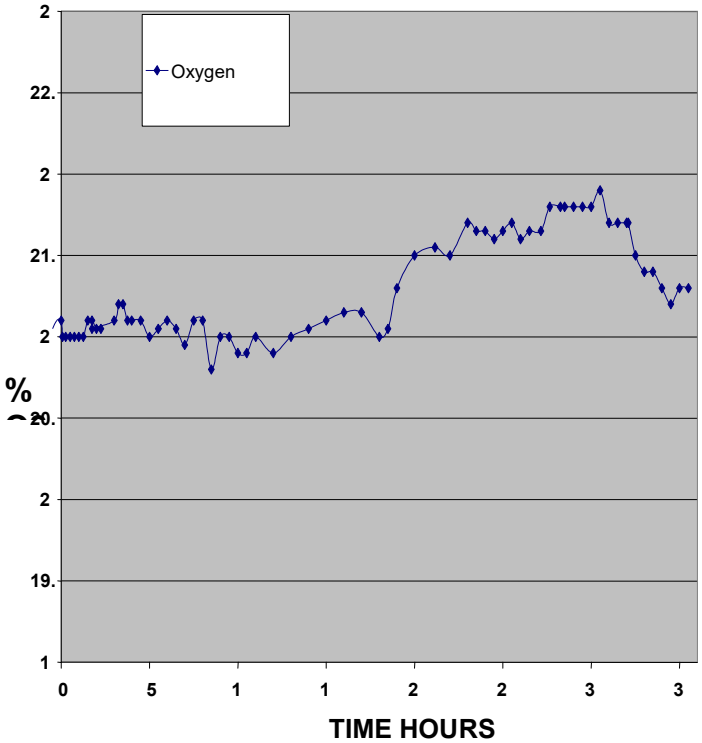


Table 1. Oxygen Consumption

ELAPSED TIME (HOURS)	OXYGEN CYLINDER FLOW (SLPM)	ESTIMATED OXYGEN SUPPLIED[1] (SL)	REMARKS
0	4.5	0	1st cylinder ON
18.5	4.5	4270	Switched to 2nd cylinder
21.5	3.5	-	Reduced flow
32	0	4410	Secured flow
36	0	-	Test ended
Total oxygen supplied		8680	

1. Based on pressure decrease in cylinder

Carbon Dioxide

Goals for Carbon Dioxide Concentration

Identical to the United States, Canadian safety standard's for general working conditions inside the mine require atmospheric CO2 concentrations of 0.5% time weighted average. For this simulated emergency, the refuge chamber CO2 concentration was set to a maximum of 1%; a level safely below the concentration that could be expected to create adverse medical reactions among participants.

Method for Controlling Carbon Dioxide

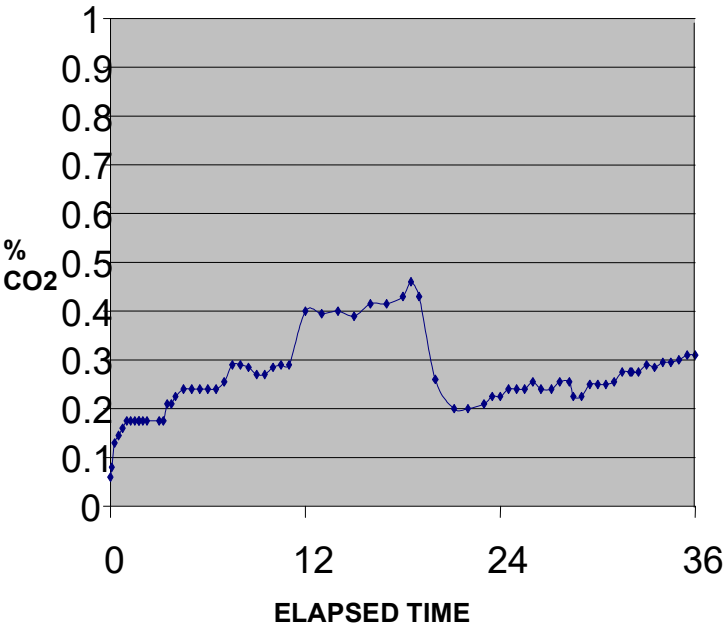
With no control the shelter's carbon dioxide, concentration would exceed the 1% maximum in the first 6.8 hours, and constantly rise over the 36 hours to 6%. Like the Mine Lifeline test, ExtendAir® CO2 absorbent curtains, part number OM-0608K, were used to control the build up of carbon dioxide in the chamber.
As can be seen from Figure 9, the curtains for this test were hung on the far side of the chamber, near the external wall and close to the center-line. For the 8 man shelter, the fixed deployment rate was 3 boxes of curtains (2.7 kilograms per box) at time zero; 3 additional boxes of curtains after 12 hours; and 2 boxes of curtains after 24 hours. The basic deployment equates to one box for 36 man-hours.

The carbon dioxide build-up in the chamber was easily controlled by the deployed ExtendAir® CO2 absorbent curtains. Figure 10 is a plot of carbon dioxide concentration over the 36 hour test. At the12 hour shift change CO2 levels had not yet risen to 0.4% Because of triple redundancy in CO2 detection, it was decided to modify the test protocol to delay the second deployment of curtains until 18 hours or 1% CO2, whichever came first. The carbon dioxide concentration rose consistently for the first 18 hours. The rate of change over the first 8

hours is higher than the following 10 hours. This can be explained by the increased carbon dioxide removal rate as the ambient concentration increases. At 18 hours CO2 concentration was 0.45% and the second batch of curtains were deployed. The carbon dioxide concentration rapidly decreased from 0.45 to 0.19%. From this point on the concentration slowly rose. As can be seen from figure 10, at no time during the test did carbon dioxide levels exceed 0.45%. These results are very similar to the carbon dioxide control in the Mine Lifeline testing.

FIGURE 9
INSTALLING CURTAINS IN SHELTER

FIGURE 10
CARBON DIOXIDE CONCENTRATION



The metabolic conversion of oxygen to carbon dioxide varies depending on diet and work rate. Normal metabolic rate ranges from a minimum of 0.7 to a maximum of 1.0. A useful average is 0.9, reference 4. The 12 hour deployment cycle is conservative and allows for higher than anticipated metabolic rates. Using an estimated 8680 liters of oxygen consumed, an exposure of 291 man hours and a metabolic conversion rate of 0.9 produces 0.45 liters of CO2 per person per minute (or 0.42 standard liters per person per minute). This is a reasonable value and is in close agreement with the Canadian Navy average value of 0.4 standard liters of CO2 per minute and the US Navy average of 0.38 slpm.

CONCLUSION

The awaiting rescue atmosphere control system is remarkably similar whether in a disabled submarine on the bottom of the ocean; in a tethered submersible fouled on cables; or in a mine shelter awaiting rescue. Carbon dioxide is controlled by reaction with alkaline absorbents. Oxygen is supplied by high pressure gas cylinders or the decomposition reaction of oxygen containing chemicals. In the case of the two discussed mine shelter tests Micropore's ExtendAir® passive absorbent curtains were used for carbon dioxide control and high pressure cylinders supplied oxygen. The Cameco McArthur River test had an oxygen consumption of 0.45 slpm per person. If you assume a metabolic conversion of 0.9, the carbon dioxide generation rate was 0.42 slpm per person. This value is in reasonable agreement with the submarine Navies design value of 0.38 to 0.40 slpm. If the metabolic conversion rate is assumed to be 0.85 (the value assigned by the US submarine Navy, reference 3) there is strong agreement between the Mine test and the submarine design guidance.

In the Mine Lifeline test, Micropore's ExtendAir® curtains used to control carbon dioxide were deployed at a rate of 0.2 pounds of curtains per man-hour (based on an extremely conservative MSHA requirement of 0.51 slpm per person) and CO2 concentration remained below 0.3%. For the Cameco test the curtains were deployed at a rate of 0.14 pounds of curtains per man hour (based on 0.4 slpm per person) and CO2 levels remained below 0.45%.

REFERENCES

1. Mine Safety and Health Administration Performance Information Bulletin P07-03
2. Naval Ships Technical Manual, Chapter 550, revision 4, 15 April 2003
3. Oxygen Increases Flammability, P.J.H. Evans, Defence Procurement Agency, UK, August 2005
4. NIOSH Guide to Chemical Hazards, Publication No. 2005-149
5. United States Nuclear Powered Submarine Atmosphere Control Manual, Revision 3
6. United States Navy Diving Manual, Volume 1

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