4. Atmosphere Management

In any closed environment containing humans, a safe breathing atmosphere is critical. This issue has been studied and researched extensively, and this section will document some of these findings. The remainder of this section is organized as follows:

4.1 Literature Review of Atmosphere Standards

4.1.1 Human Respiration

In basic terms, human breathing consumes oxygen and expels carbon dioxide and water vapor. Therefore, any closed system needs to replace the oxygen consumed and remove the carbon dioxide (because it becomes toxic at elevated concentrations).
Table 1 shows oxygen consumption rates and carbon dioxide production, as published from several sources:

Table 1. Human Oxygen Consumption and Carbon Dioxide Production Rates

O_2 Consumption (cfm)	CO_2 Production (cfm)	Activity	Source
0.022	0.019	Average	Foster-Miller, 1983
0.022	0.018	Average	MSHA PIB 07-03
0.011	0.009	Sitting	NAVSEA TS500, 2006
0.042	0.040	Walking (4 mph)	NAVSEA TS500, 2008
Note: Foster-Miller and MSHA are for blended rate of 80% resting and 20% moderate exertion. To convert cfm to liters/minute, multiply by 28.3			

There are several noteworthy items about human respiration:

- The above data represents oxygen consumed and CO2 produced. These flow rates **should not be confused** with breathing rates (technically, the "minute volume"), which of course are much greater. Only about 4% of each breath is actually "consumed" in the respiratory process.

- The ratio of carbon dioxide produced to oxygen consumed is known as the "respiratory quotient", which usually varies from about 0.8 at rest up to 1.0 with vigorous exertion. See Appendix F for more details.
- The above data are averages and can vary depending on the test population age, health, etc. The most significant variable is the degree of exertion of the population as can be seen by the difference between sitting and walking in the NAVSEA data.
- In a closed environment where there is no new oxygen supplied or carbon dioxide removed, human life is threatened by the buildup in carbon dioxide before oxygen depletion. This is discussed in more detail in the next section ("Limits for Survivability")

Based upon the above information and other comparable studies in the literature, we recommend that for design purposes, breathing supplies should be sized to provide .022 CFM of oxygen delivery capacity per occupant and .019 CFM of carbon dioxide removal capacity per occupant. It should be noted that we believe that this is a slightly conservative recommendation and allows a small safety factor. Precise determination is impossible for reasons outlined above including age, health, and level of activity.

4.2 Limits for Survivability

4.2.1 Gas Concentrations

The previous section discussed oxygen consumption and carbon dioxide production, which can be used in determining the quantities of oxygen which must be supplied and carbon dioxide which must be removed. But it is not just a matter of the proper flow rates—the concentrations in the enclosed volume also need to be within limits to prevent debilitating or even lethal conditions.

In addition to oxygen and carbon dioxide, the fact that shelters are used because of fires and/or explosions means that there is potential for significant concentrations of carbon monoxide. There is some potential for the production of other toxic gases in fires (hydrogen sulfide, etc.), but they are not a subject of this report.

There is a large body of work about safe working levels. Table 2, Table 3, and Table 4 show recommended levels from a number of international sources for oxygen, carbon dioxide, and carbon monoxide.

~~3 tables from sean~~

Table 2. Oxygen Limits

Gas	Literature Reference Values	Source
Oxygen, O2	(Not provided)	MSHA PIB 07-03, "Methods for Providing Breathable Air"
	19.5% limit	West Virginia State Technical Rules, Title 56, series 4, section 8
	17% limit	Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983
	above 24% increased risk of fire	Health and safety Exec .gov. UK
	Below 17%, breathing faster and deeper, possible impaired judgement	Pennsylvania State, Deep mines safety training
	Above 18% recommended for portable refuge chamber	Venter et al, South Africa, man test for 24 hrs
	19.5%, 8 hr avg	Sakatchewan Mining regulations, ref, OSHA 1996 regs
	For open systems (Compressed air: 19% O2 emergency working limit). For Closed systems: 18% O2	Brake et al, Australian report "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine", 1999
	O2 upper limit 23.5%	Oregon, OSHA 215
	O2 upper limit 23%	MASHA manual,"Guidelines for Rescue Refuge Stations(Mines and Aggregates Safety and Health Assoc.) Ontario.
	At Min. 18% O2, slight increase in breathing rates	Rimer Alco North America, Manitoba, "Respirable Air Handbook"

Table 3. Carbon Dioxide Levels

Gas	Literature Reference Values	Source
Carbon dioxide CO2, scrubbing target level	(Not provided)	MSHA PIB 07-03, "Methods for Providing Breathable Air"
	0.5% limit	West Virginia State Technical Rules, Title 56, series 4, section 8
	0.5 -1.0% limit	Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983
	Below 0.5% recommended for portable refuge chamber	Venter et al, South Africa (Report: Portable Refuge Chambers: Aid or Tomb in Underground Escape Strategies)
	Ceiling 1.5%, IDLH level 50,000 ppm	Pennsylvania State, Deep mines safety training
	5000 ppm 8 hr avg, 30,000 15 min limit, 40,000 IDLH level	Sakatchewan Mining regulations, ref, OSHA 1996 regs
	For open systems (Compressed air: 0.5% CO2 emergency working limit). For Closed systems: 1.25% CO2	Brake et al, Australian report "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine", 1999
	U.S. Navy recommends 1.5% CO2 limit, or 2% for emergencies	"Living and Working in the Sea" Miller & Koblick, 2nd edition
	American Bureau of Shipping recommends max. 1% CO2 for long term exposure	"Living and Working in the Sea" Miller & Koblick, 2nd edition
	TWA: 0.5%, ST: 3%, IDLH: 4%	NIOSH REL

REL: Recommended Exposure Limit
TWA: Time Weighted Average

Table 4. Carbon Monoxide Limits

Gas	Literature Reference Values	Source
Carbon monoxide CO, scrubbing target level	25 ppm limit	MSHA PIB 07-03, "Methods for Providing Breathable Air"
	50 ppm limit	West Virginia State Technical Rules, Title 56, series 4, section 8
	100 ppm limit	Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983
	25 ppm 8 hr avg	Saskatchewan Mining regulations, ref, OSHA 1996 regs
	190 ppm 15 min limit	Saskatchewan Mining regulations, ref, OSHA 1996 regs
	30 ppm 8 hr avg	Queensland, Australia, mining regulations
	50 ppm 8 hr avg	Pennsylvania State, Deep mines safety training
	200 ppm 15 min limit	Pennsylvania State, Deep mines safety training
		20 ppm is the max. level permitted in diver's breathing gas for depths to 800 ft, per NAVSEA TS500-AU-SPN-010
	"1-70 ppm, Most people no symptoms"	U.S. Consumer Product Safety Comm. Website: www.cpsc.gov/cpscpub/pubs/466.html
	35 ppm for 8 hr TWA exposure, ceiling limit of 200 ppm not to exceed	NIOSH REL
	25 ppm, 8 hr TWA, TLV	ACGIH, American Conf. of Govt. Industrial Hygienists
	50 ppm 8 hr TWA	OSHA PEL
	15 ppm, based on 24 hrs a day, 90 day TWA exposure	National Research Council
REL: Recommended Exposure Limit **PEL: Permitted Exposure Limit** **TWA: Time Weighted Average** **TLV: Threshold Limit Value**		

There are several noteworthy issues regarding concentration limits for gases:

- Note that there is an upper limit on oxygen concentration (23 to 24%) as well as a lower limit. The upper limit is primarily due to the increased risk of fire or explosion. For example, electrical permissibility standards are based on the most explosive mix of methane and air (approx. 10% methane and normal atmospheric oxygen of approx. 21%). Higher concentrations of oxygen will change the basis of permissibility.

- Note that the limits can vary depending upon the length of exposure. It might therefore be desirable to permit short exposures above a baseline. This would be a useful design tool for developers of atmosphere control systems. For example, if a carbon dioxide scrubber is changed out when reaching a limit of 0.5%, there might be a brief spike above that until the new scrubber is operating at full efficiency. As long as the levels do not exceed a short-term limit, the system could still meet a time-weighted average standard.
- Most of the recommendations cited in the tables are based on normal working conditions, and most of the literature is based on 8 hours total exposure, all in non-emergency circumstances.

Based on many sources, including the ones summarized in the tables, we recommend the following:

Oxygen levels of 19 to 23%. The reasons for an upper limit were described previously. The lower limit has no effect on the total amount of oxygen that will require being stored in a closed system (which is dependent on the respiration of occupants; see previous section), and thus imposes no additional burden on designers or manufacturers.
System testing to verify the ability to maintain oxygen levels can be easily accomplished through both simulated (ie, mechanical removal of oxygen) or human subjects testing (see Section 4.5).

Maximum carbon dioxide concentration of 0.5%, with short (less than 1 hour in 8) excursions no greater than 1.0%. This level will not be debilitating to occupants, and several scrubber technologies currently exist that can meet this standard. Just as in the case of oxygen, the total required capacity for a closed system is a function of the respiration of the occupants and not the required concentration limit. For an open system which depends upon dilution for carbon monoxide control, the required diluting airflow is a direct function of both respiration rate and the desired maximum concentration. That is, to dilute the occupants' carbon dioxide production to 0.5% instead of 1.0% will take twice as much air flow (see Section 4.4). This should not be a significant issue for the large quantities of air from a borehole but might be a factor in a compressed-air-supplied system. For such systems, 1.0% CO_2 might be considered.
System testing to verify the ability to maintain carbon dioxide levels can be easily accomplished through both simulated (ie, mechanical introduction of carbon dioxide) or human subjects testing (see Section 4.5).

Maximum carbon monoxide concentration of 25 ppm for life of chamber, 50ppm max for 8 hours. Other higher limits might be possible for shorter exposures. The major issue here is that it is not at all clear that a test can be devised to verify that this specification is being met. We expect that the primary source of carbon monoxide would be from the fire or explosion. How much carbon monoxide is introduced into the chamber depends on leakage, on entrance through the man-door as miners enter and exit the chamber, on gas carried in on miners clothing, even in smokers' breath and/or other hard-to-quantify ways. The technology to control carbon monoxide inside a sealed environment is not well developed (see section 4.5). The alternative is to purge the chamber if carbon monoxide builds up. In a worst case assumption, the purging reduces the carbon monoxide by dilution, meaning that a 1 times volume purge would reduce CO levels by 50%. While this could be readily accomplished with supplied air systems (borehole or compressed air), it could require major quantities of stored air (compressed air bottles). Again, precise levels cannot be quantified, nor is there a baseline scenario to allow testing.

4.2.2 Temperature and Humidity

Heat and humidity will have a direct effect on occupants of an enclosed refuge area. The concept of "apparent temperature" combines the effects of heat and humidity into a single number. Figure 1 explains the concept, and shows apparent temperature numbers for a wide range of temperature and humidity.

Apparent Temperature:

REL	TEMPERATURE (F)													
HUM (%)	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**
0	64	69	73	78	83	87	91	95	99	103	107	111	117	120
5	64	69	74	79	84	88	93	97	102	107	111	116	122	126
10	65	70	75	80	85	90	95	100	105	111	116	123	131	
15	65	71	76	81	86	91	97	102	108	115	123	131		
20	66	72	77	82	87	93	99	105	112	120	130	141		
25	66	72	77	83	88	94	101	109	117	127	139			
30	67	73	78	84	90	96	104	113	123	135	148			
35	67	73	79	85	91	98	107	118	130	143				
40	68	74	79	86	93	101	110	123	137	151				
45	68	74	80	87	95	104	115	129	143					
50	69	75	81	88	96	107	120	135	150					
55	69	75	81	89	98	110	126	142						
60	70	76	82	90	100	114	132	149						
65	70	76	83	91	102	119	138							
70	70	77	84	93	106	124	144							
75	70	77	85	95	109	130	150							
80	71	78	86	97	113	136								
85	71	78	87	99	117	140								
90	71	79	88	102	122	150								
95	71	79	89	105	126									
100	72	80	90	108	131									

Explanation

The apparent temperature is a measure of relative discomfort due to combined heat and high humidity. It was developed by R.G. Steadman (1979) and is based on physiological studies of evaporative skin cooling for various combinations of ambient temperature and humidity. The apparent temperature equals the actual air temperature when the dew-point temperature is 57.2F (14C). At higher dew-points, the apparent temperature exceeds the actual temperature and measures the increased physiological heat stress and discomfort associated with higher than comfortable humidities. When the dew-point is less than 57.2F, on the other hand, the apparent temperature is less than the actual air temperature and measures the reduced stress and increased comfort associated with lower humidities and greater evaporative skin cooling.

Apparent temperatures greater than 80F are generally associated with some discomfort. Values approaching or exceeding 105F are considered life-threatening, with severe heat exhaustion or heatstroke possible if exposure is prolonged or physical activity high. The degree of heat stress may vary with age, health, and body characteristics.

Figure 1. Apparent Temperature Chart, (Dry Bulb Temp. vs Relative Humidity)
Reference: University of Virginia Climatology Office, courtesy of Climate Analysis Center

The temperature which is maintained inside a shelter will be determined by the heat liberated by the occupants, which will be dissipated by the heat transfer characteristics of the shelter. This heat transfer will be strongly influenced by the mine temperature. Typical mine ambient air temperatures in North American coal mines have been measured by MSHA during ventilation surveys, and a chart of wet and dry bulb temperatures, and relative humidity results from 12 such surveys is given in Table 5.

Table 5. Representative Mine Temperatures and Humidities, MSHA

Reference: Charles D. Campbell, MSHA, Pittsburgh Safey & Health Technology Center

	State	Month of Survey	Dry Bulb Temperature, deg F			Wet Bulb Temperature, deg F			Relative Humidity, %		
			Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum
Coal Mines											
A	Illinois	February	62.3	55	67	59.8	53	67	87.1	76	95
B	Illinois	October	65.6	61	68	62.6	60	65	85.3	81	95
C	Illinois	December	64.6	59	70	61.4	53	68	83.3	63	95
D	West Virginia	January	62.0	55	69	59.5	48	67	86.7	60	100
E	West Virginia	November	63.6	62	66	62.6	60	66	95.0	90	100
F	Kentucky	December	65.0	59	71	62.0	52	68	84.9	57	100
G	Virginia	June	71.0	67	75	67.6	65	70	84.4	70	95
H	Alabama	June	79.2	77	87	75.8	74	80	86.7	64	100
Silver Mine											
I	Idaho	August	78.6	67	92	76.5	65	92	91.9	39	100
Copper Mine											
J	Arizona	March	74.3	66	81	64.4	50	73	58.4	28	71
Gold Mine											
K	Nevada	December	65.0	48	80	58.6	42	74	67.8	60	76
Talc Mine											
L	New York	April	49.0	43	52	---------	---------	---------	---------	---------	---------

Note that the mine temperature directly influences the temperature inside the shelter; however, the humidity inside the shelter will be determined by a complex interaction between moisture produced by the occupants, moisture absorption by carbon dioxide scrubbers (if present), condensation, evaporation, etc. Testing may be the only reliable method to quantify the inside humidity levels (see Section 4.5).

We conclude from the previous table that most mine temperatures are low enough to allow heat transfer out of the shelter. The one exception is in parts of Alabama. For that location, auxiliary heat transfer may be required (such as forced air flow from outside).

As shown previously in Figure 1, apparent temperatures above 80F are uncomfortable, and above 105 are life-threatening. Other sources use different temperature indices in their recommendations, as shown in Table 6. Based upon this information, we recommend a maximum apparent temperature 95F.

Table 6. Recommended Maximum Apparent Temperatures

	Heat Tolerance Levels	Sources
1	Apparent temp. of 95F maximum	West Virginia Mine Safety Technology Task Force report" Mine Safety Recommendations", 2006
2	Apparent temp. greater than 80F: Some discomfort, at or above 105F can be life threatening.	University of Virginia, Climatology Office, web site: http://climate.virginia.edu/apparent.htm
3	Workers in temps. At or above 27.5C Wet Bulb, or 37C Dry Bulb, need heat stress management	South Africa Dept. of Minerals and Energy, Mine Health and Safety Inspectorate, "Guideline for the Compilation of a Mandatory Code of Practice on Mnimum Standards of Fitness to Perform Work at a Mine" 2001
4	Max. temp. 85F, max humidity 75%, for 28 day emergency	NASA Man-Systems Integration Standards, Vol. I, Standards, Section 5.8.3.1, Temperature, Humidity, and Ventilation Requirements, Figure 5.8.3.1.1
5	Effective temp.* range for persons at rest: 78-82F most people will tolerate,	MASHA, Mines and Aggregates Safety and Health Association, Ontario. "Guidelines for Mine Rescue Refuge Stations", 1998, p. 48
6	Effective temp. 82-90F physiological stresses can be tolerated by most people for several hours and some hardy individuals for 24 hrs	MASHA, Mines and Aggregates Safety and Health Association, Ontario. "Guidelines for Mine Rescue Refuge Stations", 1998, p. 48
7	Effective temp. 90F and above: Severe physiological stresses can be tolerated without injury for only a few hours	MASHA, Mines and Aggregates Safety and Health Association, Ontario. "Guidelines for Mine Rescue Refuge Stations", 1998, p. 48
8	Hyperthermia is a potential risk any time air temperature exceeds 90F	NAVSEA TS500-AU-SPN-010, NAVY spec. for diving and hyperbaric equipment.

	Heat Tolerance Levels	Sources
9	35C Wet Bulb limit for emergency refuge stations, 39C. Body core temp. maximum 39C	Brake, R., et al, "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine" AusIMM Journal, 1999
10	28-32.2C tolerable for 24 hrs most people. 32.2C and above severe physiological stresses, only a few hours without injury	Venter et al, South Africa (Report: Portable Refuge Chambers: Aid or Tomb in Underground Escape Strategies)
*Effective temperature is an empirical sensory index that takes into account the effects of temperature, humidity and air movement. It is a function of DB, WB and air velocity		

4.3 Closed Systems

Closed systems comprise a sealed volume with no outside life support. The simplest form of a self-contained shelter is a barricade, in which miners erect emergency (usually brattice cloth) stoppings across an entry or crosscut to seal off an area to prevent intrusion of toxic gases, as further discussed in the next subsection (Section 4.3.1).
More sophisticated self-contained shelters will be pre-fabricated and contain atmosphere control systems for life support, as discussed in Section 4.3.2.

4.3.1 Barricades

In a closed environment with no life support systems, the occupants will consume oxygen and generate carbon dioxide. In this scenario, the increase in carbon dioxide will be debilitating and then fatal sooner than the decrease in oxygen. The useful life of such a shelter depends on the volume, the number of occupants, and the breathing rate.
MSHA PIB 07-03 develops the methodology for determining the relationship between these variables, using the design breathing rates as previously defined in Section 4.1.1. PIB 07-03 calculations show that a single miner in an 1800 cubic foot volume would reach 3% CO2 concentration (not good, but survivable in an emergency) in 49.5 hours. These numbers scale with number of miners and size of volume: 10 miners would reach 3% in 1/10 the time; doubling the volume doubles the time, etc. Other sources cite different values. According to MASHA’s “Guidelines for Mine Rescue Refuge Stations”, the US Navy uses a formula:

Time (hours) to reach 3% CO2=.04 x shelter volume(ft^3) / number of occupants

This formula assumes a significantly slower breathing rate (see section 4.1), and thus will show longer times to reach 3% CO2.

4.3.2 Self-contained rescue chambers or shelters

Oxygen supply is well-understood and quite straightforward. Typically, medical-grade oxygen bottles are supplied with gauges, regulators, and flow meters. An initial flow rate is set (according to instructions) based upon the number of miners in the chamber. This flow rate can then be adjusted up or down over time depending upon the observed oxygen concentration in the chamber.

Carbon dioxide scrubbing is somewhat more involved, but state of the art solutions do exist and are available commercially. The two major scrubbing technologies are soda lime and lithium hydroxide. Both these materials react with with ambient air when exposed. Water vapor from humid air and carbon dioxide from breath fuel the reactions, liberating water, heat, and converting CO_2 into a solid waste product. Both soda lime and lithium hydroxide are caustic, and must be packaged to prevent free floating particles while at the same time having large surface area contact with the air.

Soda Lime: Has been used for many years and is well understood. A passive version is available which can be just hung up in a sealed area without any forced air flow, relying on natural air currents to provide exposure. Other types are available in bulk form, in discrete cartridges or bags, and this type needs powered air flow through it to provide full exposure to the air. The bulk form has a range of scrubbing capacities, related to the starting moisture content of the material. Grades with higher moisture content are best suited to powered air scrubbing, to avoid drying out. Particle size and shape affects performance, and best function is obtained with low particle nesting, and max. surface area to avoid channeling. The material is moisture sensitive in that it functions best in warm, humid environments –typical for a mine refuge station. Scrubbing flow rates are critical to performance. Some soda lime curtains currently available have a life of up to 96 hours. Bulk forms may have service life in the realm of 6-12 hours.

Lithium Hydroxide: Provided in curtain form most commonly, it tends to be more efficient at CO_2 scrubbing, with a corresponding higher heat level produced. This material is three to six times more expensive than soda lime, but takes up less volume in a refuge station. Lithium curtains typically have a service life of approximately twelve hours.

4.4 Open Systems (Fresh-air supplied)

Fresh air can be supplied to a shelter via a surface borehole (preferred) or suitably protected compressed air lines. Boreholes as small as 6” diameter will when suitably force fed with air from surface compressors, provide a continual supply of fresh air, and can also provide an overpressure protection to avoid leakage of toxic gases into the refuge station. Borehole air may also assist in temperature and humidity control. No oxygen supply is necessary, no CO_2 scrubbing is necessary, and there is also the potential for the borehole to provide communications, food and water if necessary.
Oxygen is of course supplied by the fresh air flow. Carbon dioxide control is provided by dilution with the fresh air. Table 7 shows the recommendations provided by several sources for the dilution of carbon dioxide. Based on this information, we conclude that an airflow of 1.9 scfm per miner will be required to maintain a carbon dioxide concentration of 1%; 3.8scfm would be required for 0.5%.
Note that the total airflow requirement may also be influenced by the desire to maintain a small overpressure inside the shelter.

Table 7. Required airflow for CO2 dilution

	Flow rates	Conditions and Notes	Reference Source
1	3 CFM / man (85 L /min/man)	Compressed air flow to keep CO2 below 0.5%. (Conservative to allow extra capacity in chamber)	Brake, R., et al, "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine" AusIMM Journal, 1999
2	12.5 CFM/ man (750 CFH/ man)	Compressed air line flow, or borehole flow from surface compressor. CO2 % unspecified	MSHA PIB 07-03 "Methods for Providing Breathable Air"
3	Approx. 3 CFM / man	150 CFM (9 CFH) at 1.3 "wg, Forced air feed, 6" borehole, 4100 ft^3 refuge station, 30 man (136ft^3 / man). CO2 % unspecified	Kielblock A.J., et al, "The Functional Performance of Formal Gold Mine and Colliery Refuge Bays, with Special Reference to Air Supply Failure". Journal of the Mine Ventilation Society of South Africa", May 1988
4	Approx. 2.5 CFM / man	1-10 man 25 CFM (1500 CFH), 10-20 man 50 CFM (3000 CFH), 20-30 man 75 CFM (4500 CFH), 30-50 man 100 CFM (6000 CFH) Compressed air flow for 0.5% CO2 level.	Rimer Alco North America, Manitoba, Canada. "Respirable Air Handbook"
5	1.87CFM / man (112 CFH / man)	Airflow to dilute CO2 to 1% level, (and apply some overpressure)	Foster-Miller report to USBM, "Development of guidelines for Rescue Chambers, Vol. I", 1983

4.5 Special Considerations

There are several areas that cannot be fully resolved at this time. Two of them are:

- Carbon monoxide control
- Atmosphere life support testing

These are discussed in more detail in the following paragraphs

4.5.1 Carbon Monoxide control

There is a critical need to reduce or remove toxic levels of CO that may enter the portable refuge chambers or bulkhead based stations in many ways, including:

- Leakage of the post explosion atmosphere CO through the refuge structure
- Leakage through the mandoor during ingress and egress
- CO from the miner's contaminated clothing,
- CO added from smokers' breath

All of these factors are difficult to quantify. However, one study (Rex, et al, "The Use of Tracer Gas in Assessing the Functional Performance of Refuge Bays", South Africa

Chamber of Mines, 5th International Mine Ventilation Congress, October 1992) found that when a full complement of miners entered a shelter from a contaminated area, 6% of the contaminant concentration reached the shelter. In other words, if the adjacent area had 1500 ppm of CO, the shelter would reach 90ppm. When the shelter had an overpressure from a compressed air line, the contamination was reduced to zero. It should be expected that the infiltration could also by reduced substantially by some sort of airlock, “air knife”, or even a small brattice cloth or plastic hanging strips such as used on commercial freezer rooms or delivery-truck bays.

A variety of opinion has been expressed as to the efficacy of purging CO from refuges. It may be impractical for a larger area such as a bulkhead station, and even for a smaller, portable shelter it may be difficult to achieve safe levels by dilution methods. An alternative to purging is to manage the CO as it occurs by scrubbing. Several methods have proven useful in the past, such as the British Navy’s use of Hopcalite; however it produces large amounts of heat, and in a humid environment it loses most of it’s efficiency. The added problem of needing a non-powered system for the refuge shelters / stations adds to the difficulty of finding a useful CO scrubbing system.
Some new approaches to CO management are emerging and need to be investigated for possible refuge application, including:

- A novel catalyst system has been developed for use in a face mask CO filter, as part of a next generation SCSR device currently undergoing testing and evaluation by NIOSH, developed by Technical Products MFG (TPMFG), Ayer MA. This catalyst is fully active at room temperature, very efficient at scrubbing CO, and has good potential for a refuge station scrubber.
- New NASA spin-off technology has produced a system already utilized by NASCAR drivers to reduce CO fumes, using noble metal / reducible oxide (NMRO) catalysts. This catalyst has been developed by STC Catalyst Inc., and also has potential for use as a refuge station scrubber.
- Methyl Organic Frameworks (MOFs)are a new material which can be “tuned” to filter out almost any compound of choice. This material is just emerging from research laboratories.

4.5.2 Testing of Atmosphere life support systems

At the time of this report writing, testing of refuge chamber life support is at an early stage of development. The following paragraphs summarize the current state of the art.

Simulated testing of portable refuge chambers was conducted by NIOSH in the Fall of 2007. A total of 5 commercially available chambers were tested, using a draft protocol developed on an expedited basis by NIOSH with comments from interested parties.
Human occupancy was simulated as follows:
Oxygen consumption—the oxygen supply was ported directly out of the chamber
Carbon dioxide-- was injected directly into the chamber
Body heat was simulated by light bulbs
Human moisture was introduced via a standard vaporizer

Further details may be found in the draft protocol. The NIOSH report is due out at approximately the same time this report is published.

Human subjects testing has to date only been conducted somewhat informally by equipment manufacturers, either on a complete system or one design feature (eg, CO_2 scrubbing). Some of this information is proprietary and therefore cannot be published. The most interesting test to date was performed by an independent operator, Rick Abraham and a volunteer crew, at the R10 Group Coalburg #2 coal mine, West Virginia in Sept. 2007. The test utilized a concrete block stopping to form a bulkhead-based rescue shelter. The oxygen supply was bottled oxygen and the CO_2 scrubber was lithium curtains. A crew rotated through the shelter over a 96-hour period, keeping 10 miners inside at a time. Oxygen and carbon dioxide remained within the norms at all times, and the temperature did not rise above 72F. See Appendix G for more details.

Human subjects testing at a formal level requires peer-reviewed protocols and many other policies and procedures. NIOSH is currently evaluating the feasibility of developing such protocols.

4.6 Recommended Design Life for Refuge Stations

The likely timeframe required for mine rescuers to reach miners inside a refuge station varied widely in the disasters studied. In at least one disaster, it could have taken rescuers up to 96 hours to reach trapped miners through a borehole. In many other cases it took substantially less time to reach trapped and injured miners. Part of the process of establishing a refuge station design life is to examine the fixed and variable costs associated with keeping a chamber viable for longer periods. The fixed cost of installing a portable or bulkhead-based station is a large majority of the overall cost. The variable costs for supplies related to atmosphere and subsistence is significantly less. The largest single item is the CO_2 scrubbing system whose cost increases directly with design stay time. For example, the incremental cost for increasing CO_2 scrubbing protection 48-hr to 96-hr is about $10,000. This represents a small fraction (less than 10%) of the total refuge cost which is in excess of $100,000 per installation (see Section 7.1). Although many rescues were performed in less than 48 hrs we conclude that the small incremental cost to increase station design life is clearly warranted. This permits stations be equipped to handle stays of up to 96 hours to accommodate the outside range of the rescue timeline and to account for the potential for stations to be overloaded (over designed capacity) at minimal additional cost.