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# Refuge Alternatives in Underground Coal Mines

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## Table of Contents

**List of Figures**

**Figure**                                                                                    **Page**

**List of Tables**

## Foreword

    This report was prepared by Foster-Miller, Inc., Waltham, MA under NIOSH contract 200-2007-20276.  The contract was initiated in response to the requirements of the Mine Improvement and New Emergency Response Act of 2006.  It was administered under the technical direction of the Pittsburgh Research Laboratory, National Institute of Occupational Safety and Health with Dr. Eric Bauer as Technical Project Officer.  Cynthia Mitchell was the Contracting Officer.  This report covers the research, findings, and recommendations completed in fulfillment of the contract requirements during the period 15 April 2007 to 15 December 2008.  This report was submitted by the author on 15 December 2008.

    All cost information in this report is stated in 2007 dollars.

    The technical effort was performed by the Power Systems Technology Group under the direction of Douglas Ounanian as Program Manager with support from engineers Sean O'Reilly and James Murray.  Steven Kokkins developed the blast resistance criteria and the Universal Fixed Bulkhead Refuge design.  Charles Babbitt conducted the research of the mining disasters.  Randy Berry acted as senior technical advisor to the program. Terry Muldoon served as technical advisor for mine disaster studies.  John McCoy served as technical advisor for life support.

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## Executive Summary

The recent tragic events at a series of coal mines in West Virginia and Kentucky have highlighted the need to reevaluate safety protections for miners subsequent to fires and explosions. The recent passage of the Mine Improvement and New Emergency Response Act of 2006 (MINER Act) [1] has enacted legislation that mandates the addition of several specific safety requirements [2]. Among the many new provisions, the Act requires that NIOSH conduct research to evaluate various refuge alternatives including portable refuge chambers.

In response to the requirements of the MINER Act, NIOSH initiated this project to develop engineering guidelines associated with the location, construction, and general application of various refuge alternatives. The project goal is to facilitate the mining industry's rapid implementation of viable refuge concepts by addressing technical barriers or knowledge gaps that are hindering the rapid diffusion of refuge technologies throughout the underground coal industry. The overall objective of the project is to solve engineering problems or develop engineering guidelines associated with the location, construction and general application of various refuge alternatives.

The project has been organized into three phases:

- Phase I – Development of Recommended Refuge Station Criteria.
- Phase II – Design, Selection, and Location Criteria.
- Phase III – Users Guidance Document.

The specific objectives of the work are:

- Evaluate the impact, i.e., lives saved, that refuge stations could have made in the outcome of coal mine explosions, fire emergencies, and mine inundations that have occurred since 1970.

- Establish common design criteria for fixed and portable mine refuge stations.

- Develop a selection guide for type, size and location of refuge stations.

- Develop type-specific performance specifications.

- Develop a practicable mine refuge station bulkhead design.

- Develop a user's guide to select, purchase, or construct and install each refuge station for U.S. coal mine operators.

Phase I was completed in June 2007 and a report [3] was provided to NIOSH. Phase II was completed in December 2007 and a report [4] was provided to NIOSH.

The end result of Phase III is the generation of a guidance document to assist mine operators in the selection, installation, and provisioning of refuge stations in underground coal mines in addition to providing detailed design and construction instructions for the universal fixed bulkhead refuge, a refuge station that is applicable to almost all mine configurations as well as this final report documenting the work performed over the entire project. The duration of Phase III was twelve months beginning in January 2008.

Major work conducted under this program includes:

*Phase I*

- Review and analysis of mining disasters from 1970 to 2006 with emphasis on the role refuge stations would have had if they had been available at the time of the disaster

- Development of the refuge station design parameters in preparation for establishing design criteria. This includes both portable refuge chambers and bulkhead-based stations (ones that are constructed to form a room or station underground within the section).

*Phase II*

- Detailed analysis of a subset of mining disasters where refuge stations may have had significant benefit leading to recommendations for location and use of refuge stations.

- Analysis of atmosphere management requirements for refuge stations, current and near-term technologies to meet these requirements, and recommended values for atmosphere management design criteria.

- Review and analysis of methane explosion research leading to a characteristic blast pressure-time curve to be used as a basis for blast resistant refuge stations.

- Development of two design concepts for bulkhead-based refuge stations.

- Cost estimates and comparisons of alternative refuge stations.

*Phase III*

- Develop a tool to aid in determination of refuge station type, location, and size.

- Develop a matrix for determining life support supplies and infrastructure required based on size, occupant load, and length of stay.

- Develop a matrix for determining general supplies and infrastructure.

- Develop a matrix for use of the Universal Refuge Bulkhead.

- Develop guidelines for the inspection, testing, and maintenance of the Universal Refuge Bulkhead.

- Provide draft and final guidance documents.

This report documents all of the research, findings, and recommendations performed and developed under this program.

**Conclusions and Recommendations**

The major conclusions and recommendations developed during this program comprise the following:

Mine Disaster Analysis

- The results of the mine disaster study show that refuge stations can a have positive impact in cases where miners barricaded and perished or when they perished trying to escape. This represents about 29 percent of the fatalities from fires and explosions since 1970. The primary benefit of refuge stations is providing a breathable atmosphere to miners since in most of these outcomes miners died from lack of breathable air.

- Location and positioning of stations is an important consideration.

- We provided input to the atmospheric testing protocol under development by NIOSH. Ideas and debate regarding atmosphere control testing (both simulated and man-tested) and structural (explosion) testing will likely continue.

Regulation Review

- It is likely that recommendations for station use to be developed may comprise a combination of several regulations from both state and federal agencies. This could be a meld of different but key aspects of regulations covering somewhat disparate applications such as breathable air supply locations, station placement guidelines, seal requirements, and SCSR cache locations. Ideally, the end result would be to gather those points that would provide the best solution for rescue station applications.

Refuge Station Design Parameters

- Blast resistance is a key design parameter for chambers and bulkheads.

- Locate refuge stations "out of the line" of potential projectiles.

- General atmosphere management:
  - Boreholes are the gold-standard for rescue station atmosphere control.
  - Air-supplied systems (borehole, compressed air lines, and/or bottle-supplied) provide oxygen, dilute carbon dioxide, and can maintain a positive overpressure in the station.

- In closed systems, $CO_2$ must be absorbed and oxygen supplied.
- Dangerous $CO_2$ buildup occurs before oxygen depletion.
- Effects of initial spike loading (when miners first enter) must be analyzed.
- Effects of overloading (more miners than specified capacity) on systems must be evaluated.
- Interlocks and purging procedures require careful review.
- Atmosphere measuring instrumentation must be kept in calibration.
- High $O_2$ environment and permissibility of electrical devices requires evaluation.

- Transport of portables must ensure that they are not damaged and that post transport inspection is conducted and documented.

- Construction of bulkhead-based stations should be performed under direct supervision with appropriate record keeping.

- Bulkhead sealing and anchoring must be adaptable to a variety of in-situ conditions.

Refuge Location Analysis

   Our analysis resulted in the following conclusions and recommendations for the placement of refuge stations within underground coal mines.

- Refuge stations should be located at nominal locations that prescribe a location within a range of 1000 to 2000 ft from the faces. Locations closer to the faces may be required depending on coal seam height or other factors making travel to a station difficult.

- At least one station must be active for a working section at all times.

- In sections such as longwall sections where miners are spread widely throughout the face area and alternate escape routes are provided (as in headgate and tailgate escapeways), stations should be provided within each of the main escapeway routes where feasible. This may be difficult in tailgate entries due to obstructions.

- Stations should be located within crosscuts (preferably stubs) off standard designated intake escapeways.

- We recommend establishing an initial station within a dead-ended working section (a section advancing which has not yet connected to any other mine workings) as soon as possible after the section has advanced deeply enough to accommodate it. This will provide refuge to miners trapped within the dead-ended section by fires or explosions either inby or outby in the adjoining main entries. This is in agreement with research by others [9].

- We recommend that stations be equipped to handle stays of up to 96 hr.
- We do not recommend maintaining additional outby stations; however, it may be desirable to maintain borehole fed stations.

- Stations should not be located within escapeway crosscuts that are close to belt drives or other potential fire hot spots. Stations near overcasts should also be avoided. Stations should not be positioned within or off track entries.

Atmosphere Management

We recommend that for design purposes, breathing supplies should be sized to provide 0.022 cfm (0.623 l/min) of oxygen delivery capacity per occupant and 0.019 cfm (0.538 l/min) of carbon dioxide removal capacity per occupant.

We recommend the following criteria related to atmosphere management:

*Oxygen levels of 19 to 23 percent.* Note that there is an upper limit on oxygen concentration as well as a lower limit. The upper limit is primarily due to the increased risk of fire or explosion. Electrical permissibility standards are also affected.

*Maximum carbon dioxide concentration of 0.5 percent,* with short (less than 1 hr in 8) excursions to no greater than 1.0 percent.

*Maximum carbon monoxide concentration of 25 ppm* over the design life of the chamber and 50 ppm maximum in any 8 hour period. Other higher limits might be possible for shorter exposures. A significant concern is that it may not be possible to devise a test to verify that this specification is being met. To date, the technology to control carbon monoxide inside a sealed environment is not well developed. The alternative is to purge reducing the carbon monoxide concentration by dilution. While this could be readily accomplished with a borehole, it would require large quantities of stored air (compressed air bottles) for chambers without boreholes.

Note that the limits for both $CO_2$ and CO vary depending upon the length of exposure. It might therefore be allowable to permit short exposures above a baseline threshold.

*Apparent temperature* should not exceed 95°F. This value is in agreement with or comparable to results from a number of studies listed in Table 10. While formulas have been developed for calculating apparent temperature, we recommend using the table developed by Steadman [51] (see Figure 2) rather than a formula, since Steadman's table is the most accurate reference source, is commonly accepted, and is easy to use since no calculations are required.

Most mine temperatures are low enough to allow heat transfer out of a refuge station. The one exception is in parts of Alabama. For that location, auxiliary heat transfer may be required. The following approaches have been identified for atmosphere management.

*Oxygen supply* is typically, medical-grade oxygen bottles supplied with gauges, regulators, and flow meters.
*Carbon dioxide* scrubbing can be accomplished using state of the art commercially available systems. The two major scrubbing technologies are soda lime and lithium hydroxide.

*Fresh air* can be supplied to a shelter via a surface borehole or suitably protected compressed air lines.  Boreholes as small as 6" diameter will 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 supplied air can also simplify temperature and humidity control. No separate O2 supply and no $CO_2$ scrubbing system are necessary.  We conclude that an airflow of 1.9 cfm (53.8 l/min) per miner will be required to maintain a carbon dioxide concentration of 1 percent; 3.8 cfm (107.6 l/min) would be required for 0.5 percent.

*Carbon monoxide control* is critical but no large-scale commercial systems exist.  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.

- 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.

- Metal-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.

*Testing of atmosphere life support systems in refuge chambers* 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.  The report was released in December, 2007.

- *Human subjects testing* has to date only been conducted informally by equipment manufacturers.

*Recommended design life* for refuge stations is 96 hr.

Blast Loading Characterization

Literature was reviewed and key findings used to develop blast loading characterization.  Eleven significant reports were examined that covered work and experimental testing conducted during the past 40 years.  We conclude that the transient gage pressure applied to a bulkhead will in most cases be at or below the 15 psig transient trace shown in Figure ES-1.  This 15 psig/

**Design Basis Pressure Pulse--Mine Blast**
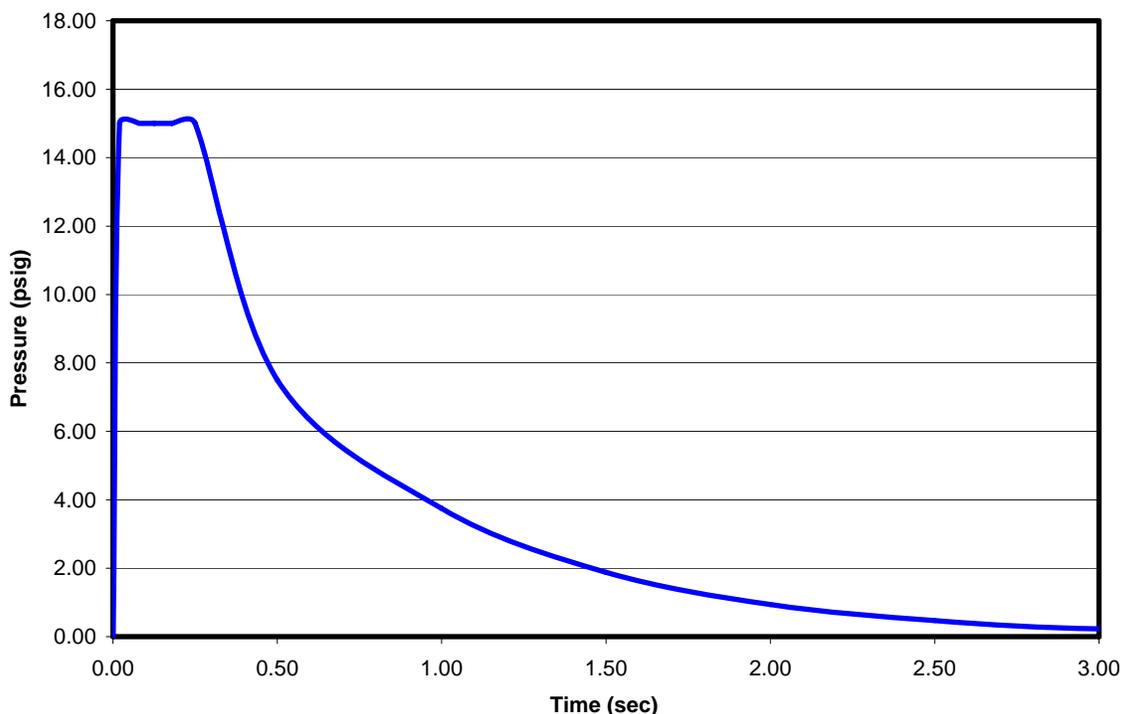


*Figure ES-1.  Mine blast pressure-time "design pulse" at potential refuge station bulkhead locations, developed by Foster-Miller Inc.*

0.3 sec load transient equals or exceeds the great majority of blast situations, and therefore represents a reasonable design basis for the refuge bulkhead.  While magnitudes exceed this in rare circumstances, the many tests at Lake Lynn Experimental Mine (LLEM) have shown that the maximum pressure peak time durations from methane explosions are no longer than ¼ or 1/3 sec, so that this transient nature of the load for methane-only explosions is well accepted.

The effects of flame fronts on refuge stations is based on the blast characterization analysis which showed that the flame front and resultant pressure wave last for a small fraction of a second.  We believe that MSHA's existing flame-resistance requirement (30 CFR 7.24) will govern the design of the exterior components of the refuge station.

Bulkhead Design Concepts for Bulkhead-Based Stations

Two concepts were developed.  Both concepts follow the approach of having a dynamically-acting, shock absorbing system element in front, with a sealed, fiber reinforced hollow concrete block wall with manway (entry) system behind, secured to floor, ribs and roof.  The area behind the block wall is stub ended or otherwise protected.

- The first layer would initially be encountered by a potential blast front. This layer reduces blast pressure and absorbs energy, while surviving the nominal or "working level" design

pulse. This layer would not be relied upon to withstand more than the working level load, but would reduce higher loads on the second stage in the short transient load peak time duration.

- The second layer would withstand the working load pressure in the unlikely event that the first stage of protection above is overpowered. This secondary wall system would also provide the necessary "hard seal" and entry/exit capability to form the actual refuge station itself.

The two options considered for the primary layer were an Energy-Absorbing Chute System and a Panelized Blast Reduction Media System.

The Energy-Absorbing Chute System (EACS) utilizes a large, lightweight parachute-like "chute" that is positioned such that an incoming pressure wave would quickly "inflate" it thereby protecting the solid refuge wall behind it at least up to the level of the working level design pulse. Using a strong fabric similar to ordinary automotive airbag material, it would withstand and dissipate the blast wave via energy-absorbing shrouds.

The Panelized Blast Reduction Media System uses BlastWrap$^{TM}$ packets that absorb the energy from the blast. The blast panel approach is simpler and less expensive than the chute option but for the same transient pressure load, the pressures on the wall behind the blast reduction panels would be somewhat higher. However, in an overpressure situation, due to the progressive crushing nature of the panelized blast media material, the blast protection panel layer provides a greater reduction of pressure on the secondary wall.

We selected the Panelized Blast Reduction Media System for the Universal Refuge Bulkhead design because it is easier to maintain in a ready condition for an extended duration in a mining environment.

The second layer would consist of a sealed structural wall with manway system. This wall would survive the working loads without any damage or compromise in operation.
This wall system would also provide the necessary hard seal and entry/exit capability to form the actual refuge station itself.

An 8 in. thick mortared concrete block wall with the rear (tension side) face reinforced with a standard fiberglass/composite layer was selected as the secondary layer for the bulkhead refuge station. This wall would be supported at the roof and ribs by steel angles anchored with standard roof bolts. The wall would be set into the floor via a concrete-filled trench. The wall system would incorporate a manway (door) and support structure and be sealed on the front (outer) face to prevent entry of contaminating gases

The 8 in. fiber-reinforced concrete block wall was preferred over the Omega block type thick wall mainly due to less volume of construction material (8 in. versus 40 in. thick plus pilasters). The thinner section can also accommodate a greater variety of manway access systems.

*Conclusions from the Bulkhead System Design*

- The behavior under the 15 psi/0.3 sec design pressure pulse shows that all sections remain undamaged. The structural integrity of the complete bulkhead system was evaluated dynamically using several LS-DYNA finite-element simulations of the secondary wall, the chute, and the panelized blast media subsystems.

- A limited number of higher loads were also evaluated for each of the two approaches and concluded that at 150 percent of design load the bulkhead wall system remained intact.

- The two-layer bulkhead systems as proposed are designed to withstand the "working level" 15 psi/0.3 sec transient design pulse with no significant damage and would be functional post-blast in all aspects.

- Under 150 percent of design load there would be damage of the first layer, but survival of the secondary wall with some limited damage but likely retaining function using its reserve strength.

Cost Estimates/Comparisons for Refuge Station Types

Cost estimates including installation for portables are $81,000 to $100,000. Cost estimates including installation for bulkhead stations based on the design concepts presented in Section 9 are $74,000 to $86,000. Total costs for installation and 5 redeployments are $92,000 to $112,000 for portables and $154,000 to $176,000 for bulkhead-based stations.

For an initial bulkhead-based station within a dead-ended working section, the provision for a borehole-fed station is advantageous if depth and surface conditions permit. Unlike other refuge stations, this refuge would likely remain as a permanent installation. The incremental cost for adding a borehole (assumed at 700 ft length) would bring the cost estimate for a bulkhead-based station to approximately $76,000 to $88,000 including the cost reduction from eliminating the stand-alone atmosphere control system which would no longer be required.

In general, cumulative costs will be greater for bulkhead stations when compared to portable refuge chambers as mining advances; however, bulkhead systems offer advantages of greater strength and permanence in certain situations and may be the more viable option under some mining conditions, such as low coal, where use of portable chambers may not be as feasible.

Guidance Document

Based on the research performed for this program, Foster-Miller developed a comprehensive guidance document for the coal mining industry for the selection, installation, and provisioning of refuge stations in underground coal mines.

The guidance document provides an introduction to the basic types of refuge alternatives. It provides guidance on selecting the locations, sizes, and types of refuges as well as on providing life support equipment and general equipment and supplies. The guidance document concludes

with detailed instructions for the design and construction of the Universal Refuge Bulkhead. The final guidance document was delivered to NIOSH in November, 2008.

**Recommendations for Further Study**

In furtherance of the goals of the MINER Act and this program we submit our recommendation for additional work that is offered for NIOSH's consideration. These topics comprise:

- Further study of the MSHA mine disaster data base to include incidents in which there were zero fatalities but potential for use of refuge stations. This will provide additional insight into the appropriate and safe use of refuges during emergencies.

- Response of the bulkhead system to blast loadings. Limited trial evaluations of the structural behavior under extreme loading and testing of a selected configuration.

- Diffusion/leakage test for non-pressurized refuge stations to provide better understanding of the potential for gas ingress if positive pressure is not available or practical.

- CO scrubbing device development and testing (active or passive systems). Three approaches:
  - Develop Metal-Organic Framework (MOF) material for CO scrubbing.
  - Coordinate efforts underway with TPMFG on active CO scrubbing.
  - Coordinate with STC Catalyst on active CO scrubbing.

- Fire resistance and blast tests on BlastWrap.

- Tests with alternative coatings for tension, sealing, and strength, e.g., Line-X and Defend-X polyurea spray coating.

- Improvements on the NIOSH test protocol for shelter evaluation.

- Development of a web-based guidance tool for the NIOSH website. This tool would be accessible by mine operators and would efficiently lead them through the guidance information based on their specific needs.

# 1. *Introduction*

The recent tragic events at a series of coal mines in West Virginia and Kentucky have highlighted the need to reevaluate safety protections for miners subsequent to fires and explosions. The recent passage of the Mine Improvement and New Emergency Response Act of 2006 (MINER Act) [1] has enacted legislation that mandates the addition of several specific safety requirements [2]. Among the many new provisions, the Act requires that NIOSH conduct research to evaluate various refuge alternatives including portable refuge chambers.

## 1.1 *Description of Project*

On April 15, 2007, in response to the requirements of the MINER Act, NIOSH initiated this project to "develop engineering guidelines associated with the location, construction, and general application of various refuge alternatives." The project goal was to "facilitate the mining industry's rapid implementation of viable refuge concepts by addressing technical barriers or knowledge gaps that are hindering the rapid diffusion of refuge technologies throughout the underground coal industry." The overall objective of the project was to "solve engineering problems or develop engineering guidelines associated with the location, construction and general application of various refuge alternatives."

The specific objectives of the work were:

- Evaluate the impact, i.e., lives saved, that refuge stations could have made in the outcome of coal mine explosions, fire emergencies, and mine inundations that have occurred since 1970.

- Establish common design criteria for fixed and portable mine refuge stations.

- Develop a selection guide for type, size and location of refuge stations.

- Develop type-specific performance specifications.

- Develop a practicable mine refuge station bulkhead design.

- Develop a user's guide to select, purchase, or construct and install each refuge station for U.S. coal mine operators.

The project was organized into three phases:

- Phase I – Development of Recommended Refuge Station Criteria.
- Phase II – Design, Selection, and Location Criteria.
- Phase III – Users Guidance Document.

Program activity for each phase is described below.

Phase I Program Activity

- Review of fatal mine disasters from 1970-2006 to determine if refuge stations could possibly have saved lives in some of these incidents.

- Review of existing regulations for their applicability to refuge stations.

- Meetings with mine operators who either had installed or planned to install refuge stations in the near future to develop an understanding of current practices.

- Researched existing refuge stations and previous work and developed a set of design parameters for refuge stations for consideration during our bulkhead design effort in Phase II.

Phase II Program Activity

- Further study of twelve disasters identified in Phase I where we determined that refuge stations could have saved lives.  The purpose of this study was to determine where refuge stations might have been located so that the affected miners could have reached them and taken shelter.  From this research and existing regulations, we developed recommendations on refuge station locations within a mine.

- Researched and recommended atmosphere management design criteria as well as refuge blast and flame front resistance design criteria.

- Development of two concepts for a Universal Refuge Bulkhead that could be used to construct bulkhead based refuge stations.

- Developed and presented cost estimates for portable and bulkhead based refuge stations

Phase III Program Activity

- Development of a worksheet-based decision tool to help mine operators determine the location, type, and size of refuge stations for use in their mines.

- Development of life support systems and supplies matrices and general supplies matrices to help operators determine sizes and quantities of supplies required to provide safe refuge based on the number of station occupants.

- Down selection to a single bulkhead concept and development of design specifications and construction guides for the Universal Refuge Bulkhead which can be used to create refuge stations in almost all mine configurations.

- Assembly of all of this information into a guidance document for the mining industry.

Phase I and Phase II results have been documented in previous reports [3][4] created under this program.  Phase III culminates in the development of a guidance document for use by mine operators in selecting, procuring, installing, and equipping refuge stations appropriate to their mine environment.  This report documents all of the work conducted under this program in all three phases including the guidance document.

## 1.2    Organization of the Report

This report is presented in three volumes.  Volume I documents the research conducted under this program and the results achieved.  Volume II contains appendices to the report.  Volume III contains the guidance document produced in Phase III of the program.  Volumes I and II are organized into sections as follows:

*Volume I*

- The Executive Summary provides a high level overview of the work done under this project.
- Section 1 contains an introduction to the project including goals, objectives, and approach.

- Section 2 presents an overview of refuge station concepts include portable chambers and bulkhead-based refuge stations.

- Section 3 presents an analysis of past mining disasters including data collection procedures, analysis, and results.

- Section 4 presents additional research conducted which includes visits to coal mines to discuss station use; and, provides a review of current state and federal regulations and guidelines that are related to chambers and seals.

- Section 5 presents the high level design criteria for refuge stations.

- Section 6 examines twelve mine disasters where refuge stations might have saved lives. Specific location and use recommendations are presented.

- Section 7 provides design criteria recommendations for atmosphere management systems in refuge stations.

- Section 8 contains research and analysis of the effect of mine explosions on refuge station bulkheads as well as design criteria recommendations for explosion and flame resistance.

- Section 9 provides cost comparisons for four different types of refuge stations including two portable chambers and two bulkhead-based stations based on the design concepts presented in Section 10.

- Section 10 presents two design concepts for bulkhead-based refuge stations with primary focus on blast resistance.

- Section 11 describes the guidance document developed under this program.

- Section 12 contains a summary of recommendations and conclusions developed in this report.

- Section 13 contains a list of references cited in this report.

- Section 14 contains a bibliography for all of the report except the mine disaster analysis.

*Volume II*

- Appendix A contains a summary of detailed reports of mine disasters from 1970 to 2006.

- Appendix B provides extensive details from the analyses of the twelve mining disasters presented in Section 6.

- Appendix C contains the bibliography for the mine disaster study.

- Appendix D provides brief overviews of current refuge chambers both portable and fixed position.

## 2. *Concept of Refuges*

### 2.1 Types of Refuge Alternatives

The term refuge alternatives encompasses all of the types of underground locations or shelters where miners can go to seek safe haven. The use of refuges includes serving as the following:

- Temporary way station for a short-term stay to gather information, communicate, and plan an exit strategy.

- Location where miners too injured to travel may await help or medical attention.

- Location of last resort when mine conditions following a disaster are too hazardous or impassable in conditions such as bad atmosphere, poor visibility, and blocked egress as a result of fire or explosion.

The primary role of refuge alternatives is to provide a breathable atmosphere for miners who may be subjected to bad air conditions as a result of explosion, fire, or noxious gas inundation. Without a viable atmosphere, the miner's chance for survival is low.

While the details of the use of and training for refuge alternatives have not been fully developed it remains unchanged that miners should always try to escape as a first response. As part of this first response, miners may find it useful to gather at or use a refuge location to coordinate the immediate steps to take and when available, use communication systems that are planned for implementation with the refuge, such as a wireless communication network. If escape is not possible or is identified as dangerous (e.g., as a result of communication with the surface) then refuges can be used as a short-term (several hours) or longer-term (several days) safe haven.

There are two basic types of refuge alternatives:

- Portable devices that contain all of the necessary systems and equipment to support life for a specified timeframe. These devices are moved as mining advances. Some refuge chambers are fully assembled while others are stored in a protective enclosure until they are needed at which time they are automatically or semi-automatically erected. A list of currently available portable equipment is provided in Appendix D.

- Permanent or semi-permanent installations that are constructed underground using a bulkhead or wall to form a room which is equipped with portable life-supporting equipment or outfitted with a borehole to provide atmosphere, water, food, and communication equipment. In these types of refuges it is desirable that portions of the constructed bulkhead and seal forming the room can be dismantled and re-used at subsequent locations as the working face advances. All service equipment (e.g., atmosphere management equipment) would be moved as well. These systems are built to suit, that is, they are designed and constructed in place based on the particular mine conditions and are not prefabricated as an entire system; however, portable atmosphere management equipment is

available and the specification of one type is provided in Appendix D.  Presentations of two bulkhead concepts are provided in detail in Section 10.  A detailed design specification for construction of a universal bulkhead refuge station is presented in Volume III.

## 2.2  Definition of Terms

There are several terms associated with refuge alternatives that are used to describe various components and arrangements. We provide below a list of common definitions of terms that are used in this report.  In general, they are consistent with generally accepted terminology used in the industry at present.  The terms are somewhat arbitrary but for the purposes of this report they are applied consistently.

- *Refuge Alternatives* - Encompasses all forms of refuge locations including refuge chambers and bulkhead-based stations.

- *Refuge Stations* - Includes both refuge chambers and bulkhead-based stations.  It is used synonymously with refuges and is the most general term used to encompass all forms.

- *Refuge Chamber* - A portable prefabricated unit that is shipped to a mine site ready for use.  They comprise both hard-sided and soft-sided shelters.  Some refuge chambers are deployed automatically from their stored configuration while others are ready to enter.  Refuge chambers are self-sufficient - they contain all supplies and atmosphere control and maintenance systems.  Refuge chambers are built to be portable so that they can be moved as the working face advances.

- *Bulkhead-based Refuge Station* - A room built directly into the coal seam (preferably a blind or stub-end crosscut) that uses the existing ribs, roof, and floor plus an in-place constructed bulkhead system on the remaining face to form a space to serve as a safe refuge from potentially toxic environment.  The bulkhead based station may be borehole fed, compressed air fed, or include its own atmosphere management system.  A bulkhead-based station can be constructed to a desired size by selecting the proper position for the bulkhead.

- *Bulkhead* - The structure that forms the front face of the bulkhead-based station. The bulkhead may comprise one or more elements or stages and contains a manway for access.  Bulkheads are generally built in place but may use pre-fabricated components.  Some bulkheads are capable of disassembly for reuse as the working face advances.

- *Way Stations* - Way stations are synonymous with refuge stations but imply use for a short period and not necessarily as a long-term refuge location.  They include both portable refuge stations and bulkhead-based refuge stations.

# 3. _Analysis of Past Disasters_

## 3.1 Introduction

As a first step in developing recommended design criteria for refuge stations, an extensive study of past mining disasters from 1970-2006 involving fires, explosions, and inundations in which fatalities occurred was conducted. MSHA reports [R3-12, R3-13, R3-14, and R3-15] were reviewed and data collected on the type of incident, number of survivors, and the number and type of fatalities. The potential effect of refuge stations on both survivors and fatalities was estimated.

## 3.2 Data Collection Procedures

The first step in the data analysis was to determine the scope of past disasters to be analyzed and to prioritize them according to their impact on the analysis. From 1970 through 1994, there were over 2,000 reported ignitions or explosions in US coal mines regardless of whether persons were injured or killed [5]. Given the urgency of this study, detailed reviews were performed on ignitions, explosions, fires, and inundations where at least one miner was killed. Clearly, if there were no fatalities in an incident, then refuge stations would at best not improve the outcome (not considering improvement in miner relief and comfort of those in likely duress). Although stations could possibly have served as way stations to provide comfort to escaping miners or injured miners in such situations, the existence of the stations would not have affected the outcome of zero fatalities in a large majority of cases; therefore, we elected to confine the study to incidences where fatalities occurred and the stations might have made a positive difference. At a later date it may be advisable to study selective cases in which the impact of stations could be negative or detrimental. This might be the case when miners would be able to escape with significant difficulty but elect instead to stay behind in a station. In this case, if the miners are eventually rescued then the outcome is neutral (survived either way); however, if a fire gets out of control or if there is a secondary explosion, then the integrity of the station and timeliness of rescue become even more important. We have provided comments on the studied disasters during which a negative impact is possible, but we have not incorporated these possibilities in our analysis.

### 3.2.1 Description of Data

Data collection began with analysis of *major disasters*, defined as disasters in which five or more miners perished. Major disasters could obviously have benefited the greatest from stations (i.e., a greater number of lives saved) and they are typically reported in greater detail by MSHA. Following analysis of the major disasters, analysis continued with disasters with fatalities in which less than five miners were killed. In all, 19 major disasters and 22 other disasters from 1970 through 2006 were studied. In addition, one disaster in which no miners were killed was reviewed, the July 2002 inundation at Black Wolf Coal Company's Quecreek No. 1 Mine in which all nine miners trapped in a flooded mine were rescued.

19

Because MSHA is the organization charged with investigation of mining accidents and disasters in the US coal industry, and has prepared reports for virtually all of the accidents and disasters through the designated study period (i.e., from 1970 to 2006), the analysis focused entirely on the reports available through MSHA. Sources for these reports included:

- The "Fatal Accident Archive Database" found on the Internet website of MSHA's National Mine Health and Safety Academy library in Beckley, WV (this was the site of many of the full MSHA reports of the major disasters) [6].

- MSHA's National Mine Health and Safety Academy library, which provided copies of reports not readily available electronically on the website [see bibliography for extensive list].

- "Fatalgrams and Investigation Reports" of coal mine fatalities provided on MSHA's website [7].

- MSHA's compendium of historical data, "Historical Summary of Mine Disasters in the United States; Volume II – Coal Mines – 1958 to 1998" [5].

A list of each disaster or accident for which MSHA full investigation reports and summary reports were reviewed for this project is provided in Appendix A. Each of the full investigation reports provides extensive detail in a standard format covering all aspects of the accident or disaster under some or all of the following topics as applicable to each investigation.

- Overview.
- General Information.
- Events Leading to the Accident.
- Description of the Accident.
- Rescue and Recovery Operations (if applicable).
- Investigation of the Accident.
- Discussion.
- Root Cause Analysis.
- Conclusion.
- Enforcement Actions.

It is important to note that it was Foster-Miller's express intention to accept the information and data presented in the MSHA reports at face value. We take no position on the accuracy of the information presented in the MSHA reports and therefore on the accuracy of the information retrieved and provided in this report to NIOSH. We have made every attempt to portray all information and data as presented by MSHA and to avoid any conflicts or judgments on MSHA's findings or conclusions. Any such conflicts are entirely unintentional and MSHA's statement of the facts would govern in any such cases.

There are some situations in which the details relevant to the usefulness of stations are hard to discern. In these cases we clearly identify that we are making an assumption. In other cases we may suggest that in addition to refuge stations that miners would have benefited from the use of

directional lifelines or sooner use of self-rescuers. This is not done to point out deficiencies or to challenge the escape methodology used by the miners at the time of their peril, rather it is included to identify various ways that the miners could have been helped. We do not assume to predict that these suggestions would have necessarily changed the outcome.

### 3.2.2  Data Collection Methods

The approach to our review of the MSHA reports of coal mine disasters was to scan the full report, noting sections within the report containing data relevant to an analysis of the potential impact of refuge stations on the outcome of the disaster. Specifically, we were interested in the following:

- Time and description of the first indication of the fire, explosion or inundation.

- Total number miners underground at the time of the accident.

- Timeline information on the deaths of each miner killed.

- Time and description of the first knowledge of the accident outside the mine and also elsewhere inside the mine.

- Times and description of the actions and movements of those miners inby (downstream) of the accident and those miners outby (upstream) of the accident.

- Distance from the site of the accident to the surface of the mine.

- Extent of flame and explosion forces in the cases of methane ignitions or explosions of methane and coal dust.

- Time and description of any action by the miners to barricade within the mine.

- Time that the first rescue team entered mine and the time that they reached miners barricaded or in need of rescue.

- Time that all miners and rescue teams were out of mine.

The above information was culled from the reports and added to an Excel spreadsheet to collect and categorize all of the pertinent information related to each accident in one database. In some cases, depending on the depth of information provided, the events or actions and their times had to be approximated and were estimated based on the details of the accident or engineering judgment.

From the data above we were able to distill the following information important to our assessment of refuge stations and to the development of the event tree analyses:

- Location of miners at time of incident.

21

- Number of miners impacted by the accident versus not impacted.
- Of those miners impacted, number immediately killed.
- Of those miners impacted, number that escaped and evacuated.
- Of those miners impacted, number that barricaded.
- Number of barricaded miners rescued alive.
- Number of barricaded miners that died.
- Timeframe of escape for miners that escaped.
- Timeframe of death for miners that died.
- Timeframe of rescue for miners that were rescued.

### 3.2.3   Use of Collected Data

Finally, from all of the above information, we were able to assess the potential benefit rescue stations might have provided for each of the accidents studied.  Answers to the following assessment questions were provided in each case:

- Would refuge stations have helped in this disaster?  If so, why?  If not, why not?

- How many miners could have been *positively* versus *negatively* versus *neutrally* affected by stations?

- If stations were a viable option for the miners, would they have needed to be explosion-proof?  If so, why?  If not, why not?

- If stations were viable, is there reason to believe that placement according to WV guidelines or coincident with locations for breathable air supplies per MSHA requirements would have worked?  If so, Why?

The results of the data gathering and assessments of the potential benefits of refuge stations for each of the mine accidents studied is provided in Appendix A.

### 3.3   Data Analysis Procedures

### 3.3.1   Analysis

As discussed above, the data collected and collated for each of the mining accidents analyzed were reviewed to assess the potential impact of refuge stations on the outcome of these accidents. Preliminary conclusions were drawn directly from the facts of each case using engineering judgment.  These conclusions are summarized in Section 3.4 and are presented individually for each accident in the compilation of reports provided in Appendix A.

Some basic "rules" were used in drawing conclusions from the accident data:

- Where affected miners were killed instantly, the use of stations would obviously not have helped to save them and the potential impact of stations on them was considered "*neutral.*"

- Where affected miners survived an explosion and made obvious attempts to escape but later died in the process, the use of stations was considered likely to have helped save them and the potential impact of stations on them was considered "*positive.*"

- In the three cases where miners attempted to barricade and either survived or perished in the process, the use of stations was considered likely to have helped save them and the potential impact of stations on them was considered "*positive.*" Although it could be argued that the effect of stations on survivors might be "*neutral*" since they survived anyway, stations certainly would have provided significant relief to those injured and could have greatly mitigated those injuries through first aid supplies. Hence the potential impact of stations in such situations was considered "*positive*" rather than "*neutral.*"

- In some cases, affected miners survived an explosion but died very close to their assumed locations at the time of the explosion. Some reports provide information (or speculation) on the distances the miners likely traveled and the times they may have survived, though not all reports were able to do so. In these cases, it is more difficult to conclude whether stations would or would not have affected the outcomes. Depending on details provided in the reports, we either concluded that stations "might" have helped to save them if the stations had been located fairly close to their locations at the time of the accident or that stations would "probably not" have helped to save them because of the very short distances they traveled before dying. In most of these cases we assumed the station would not have helped for the purposes of compiling the event tree analysis. The potential impact of stations on these situations was considered "*positive*" or "*neutral,*" respectively.

- Where affected miners were able to escape the hazardous area (either to fresh air or to the surface), we concluded that the miners would probably not have used the stations and the potential impact of stations on them was considered "*neutral.*" It is possible that the miners could have used the stations as safe locations to change SCSRs or for short-term rest or sustenance (water, etc.), but we concluded that miners would continue to escape if at all possible per their training.

- In only a few cases, it was possible that if surviving miners had decided to stop at a station rather than forge ahead with an escape, they definitely would have perished in the station due to such situations as high-force secondary explosions or out-of-control fires making it impossible to reach survivors and requiring sealing of the mine. As discussed earlier we felt that at this point of the program it was too early to accurately predict when there would have clearly been a negative impact especially considering the speculation that a negative impact could be mitigated by assuming miners "stranded" in a refuge station could be rescued by emergency borehole (e.g., Quecreek No.1).

- In two cases involving water inundations, the potential impact of stations on the affected miners was considered "*neutral*" whether or not any survived because the stations would have been inundated, unreachable and unusable.

### 3.3.2 Analysis Method

The detailed review of the mine fires, explosions, and inundations described above was used as input to an analysis of these disasters based on an event tree. The goal of this analysis was to determine the extent to which refuge stations would have benefited miners during the incident.

Based on a review of the disaster timelines and miner actions, the event tree shown in Figure 1 was created.

*Level 1 Outcomes*

Beginning with the number of miners underground at the start of the emergency, three initial outcomes were identified:

- Not impacted by event.
- Impacted by event.
- Impacted and killed immediately.

*Not impacted by event* – Miners underground were not affected by the event. Typically these miners exited the mine but in some instances, they remained in the mine and commenced fire fighting and/or rescue operations.

*Impacted by event* – Miners underground were affected by the event. Almost always these miners attempted to escape and were impeded by smoke and debris, noxious air, and injuries.

*Impacted and killed immediately* – Miners died immediately as a result of the event. No attempt was made to escape. These individuals died as a result of explosive forces or were rapidly overcome by noxious air.

Those not impacted by the event and those killed immediately would not have been affected by the availability of refuge stations.

*Level 2 Outcomes*

The following outcomes were then identified for the surviving impacted miners:

- Escape successful.
- Escape attempt unsuccessful.
- Escape not attempted due to injuries.

24

| Initiating Event | Level 1 Outcomes | Level 2 Outcomes | Level 3 Outcomes | Level 4 Outcomes | Refuge Station Impact Assessment |
|---|---|---|---|---|---|

687
Not Impacted by Event

687
Neutral Impact

4
Positive Impact

148
Escape Successful

144
Neutral Impact

0
Negative Impact

4
Positive Impact

7
Rescued

3
Neutral Impact

0
Negative Impact

1
Positive Impact

10
Rescued

9
Neutral Impact

0
Negative Impact

1116
Underground at Event

276
Impacted by Event

101
Escape Attempt Unsuccessful

27
Barricaded

17
Died

17
Positive Impact

0
Neutral Impact

67
Died

57
Positive Impact

10
Neutral Impact

0
Positive Impact

12
Rescued

12
Neutral Impact

0
Negative Impact

27
Too Injured to Escape

0
Positive Impact

15
Died

15
Neutral Impact

153
Impacted – Killed Immediately

153
Neutral Impact

*Figure 1.  Event tree for analysis of mine disasters*

*Escaped successfully* – Miners were able to exit the mine despite injuries and obstacles.

*Escape attempt unsuccessful* – Miners attempted to escape were unable to exit the mine.

*Escape not attempted due to injuries* – Miners were severely injured by the event but survived for a significant time period. Due to their injuries, they were unable to exit the mine or construct a barricade. Typically, they were unable to move.

*Level 3 Outcomes*

The following outcomes were identified for those miners who were too injured to attempt to escape:

- Rescued.
- Died.

*Rescued* – Miners were located by rescue personnel, evacuated, and survived the accident.

*Died* – Miners succumbed to their injuries or to noxious air prior to the arrival or rescue personnel.

The following outcomes were identified for miners whose escape attempt was unsuccessful.

- Rescued.
- Barricaded.
- Died.

*Rescued* – Miners were unable to exit the mine but were located by rescue personnel, evacuated, and survived the accident.

*Barricaded* – Miners were unable to exit the mine but were able to move about within an area of the mine after the accident. Unable to escape and threatened with noxious air, they constructed a barricade.

*Died* – Miners attempted to exit the mine but died in the process typically due to injuries or noxious air.

*Level 4 Outcomes*

The following outcomes were identified for those miners who were unable to escape and constructed a barricade:

- Rescued.
- Died.

*Rescued* – Miners were located by rescue personnel, evacuated, and survived the accident.

*Died* – Miners succumbed to their injuries or to noxious air prior to the arrival or rescue personnel.

For each final outcome, an assessment was made whether those individuals would have been positively, neutrally, or negatively impacted by the availability of refuge stations. For those outcomes resulting in the deaths of miners, negative impact is not possible since if they died because they used a refuge station, the outcome is identical to the outcome without a station, and hence the impact is neutral.

While this assessment is necessarily subjective, the following assumptions were used in performing this assessment. It was assumed that miners who were too injured to escape would not have been able to move to a refuge station. It was assumed that barricaded miners would have entered a refuge station and survived there until rescued. We assumed that refuge stations would have survived an explosion although in most cases, the affected miners did not survive the explosion and a refuge station would not have affected this outcome.

Details of these assessments by incident are presented in Section 3.3.3.

### 3.3.3   Analysis Results

This section presents the results of our analysis of the mine disasters and our assessments of the potential impact of refuge stations had they been available. Tables 1 through 4 show the Level 1-4 outcomes, respectively, for each individual disaster and in total. Tables 5 and 6 show our assessment of the impact refuge stations would have had on each final outcome in the event tree for each individual disaster and in total. Table 7 provides key summary data from the analysis and assessment.

Table 1 presents the number of miners for each of the Level 1 outcomes described in Section 3.3.2. The date, mine, type of accident, total fatalities, and number of miners underground for each disaster are listed followed by the number of miners for each of the three Level 1 outcomes.

Table 2 presents the number of miners for each of the Level 2 outcomes described in Section 3.3.2. These outcomes refer only to those miners affected by the accident who where not killed immediately. Blank table entries indicate that the value for this entry is zero.

Table 3 presents the number of miners for each of the Level 3 outcomes described in Section 3.3.2. These outcomes refer to (1) those miners affected by the accident whose escape attempt was unsuccessful and (2) those miners who were too injured to escape. Blank table entries indicate that the value for this entry is zero.

*Table 1.  Level 1 outcomes*

| | Disaster Information | | | | Outcomes | | |
|---|---|---|---|---|---|---|---|
| **Date** | **Mine** | **Accident Type** | **Total Fatal.** | **No. Under-ground** | **No. Killed Immed.** | **No. Escape Not Impacted** | **No. Escape Impacted** |
| **Disasters with 5 or more fatalities** | | | | | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | Explosion | 5 | 6 | 2 | 0 | 4 |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | Explosion | 12 | 29 | 1 | 0 | 28 |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | Explosion | 13 | 32 | 12 | 16 | 4 |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | Explosion | 8 | 9 | 8 | 0 | 1 |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | Explosion | 10 | 14 | 4 | 0 | 10 |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | Fire | 27 | 80 | 0 | 52 | 28 |
| 6/21/1983[1] | McClure No. 1 Mine, Clinchfield Coal Co. | Explosion | 7 | 30 | 3 | 20 | 7 |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | Explosion | 7 | 7 | 2 | 0 | 5 |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | Explosion | 13 | 56 | 13 | 43 | 0 |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | Explosion | 8 | 8 | 8 | 0 | 0 |
| 4/15/1981 | Dutch Creek No. 1, Mid-Continent Resources, Inc. | Explosion | 15 | 21 | 15 | 0 | 6 |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | Explosion | 5 | 5 | 5 | 0 | 0 |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | Flood | 9 | 81 | 0 | 65 | 16 |
| 3/9/1976[2] | Scotia Mine, Blue Diamond Coal Co. | Explosion | 26 | 119 | 20 | 90 | 9 |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | Explosion | 5 | 121 | 4 | 113 | 4 |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | Fire | 9 | 43 | 0 | 34 | 9 |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | Explosion | 38 | 39 | 33 | 0 | 6 |
| **Disasters with fewer than 5 fatalities** | | | | | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | Explosion | 1 | 7 | 1 | 5 | 1 |

### *Table 1. Level 1 outcomes (continued)*

| | Disaster Information | | | | Outcomes | | |
|---|---|---|---|---|---|---|---|
| Date | Mine | Accident Type | Total Fatal. | No. Under-ground | No. Killed Immed. | No. Escape Not Impacted | No. Escape Impacted |
| **Disasters with fewer than 5 fatalities (continued)** | | | | | | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | Fire | 2 | 29 | 0 | 0 | 29 |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | Explosion | 2 | 9 | 2 | 0 | 7 |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | Explosion | 1 | 17 | 0 | 15 | 2 |
| 3/19/1992[3] | Blacksville No. 1 Mine; Consolidation Coal Co. | Explosion | 4 | 13 | 0 | 12 | 1 |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | Explosion | 2 | 2 | 2 | 0 | 0 |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | Explosion | 3 | 6 | 3 | 0 | 3 |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | Explosion | 1 | 1 | 1 | 0 | 0 |
| 1/8/1987 | Dutch Creek No. 12; Mid Continent | Explosion | 1 | 4 | 0 | 0 | 4 |
| 8/9/1986 | No. 9 Slope William Station Mine; Pyro Mining Co. | Explosion | 1 | 3 | 0 | 0 | 3 |
| 12/11/1985 | No. 2 Slope Mine; MSW Coal Co. | Explosion | 3 | 5 | 2 | 0 | 3 |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | Explosion | 3 | 4 | 3 | 0 | 1 |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | Explosion | 3 | 14 | 3 | 0 | 11 |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | Explosion | 1 | 2 | 1 | 1 | 0 |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | Explosion | 4 | 20 | 4 | 0 | 16 |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | Explosion | 2 | 32 | 0 | 30 | 2 |
| 3/26/1971 | Nemacolin Mine | Fire | 2 | 125 | 0 | 114 | 11 |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | Explosion | 1 | 60 | 0 | 58 | 2 |
| 4/10/1970 | Homer City | Explosion | 1 | 34 | 0 | 19 | 15 |
| 4/2/1970 | Compass No. 2 | Explosion | 1 | 11 | 1 | 0 | 10 |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | Inundation | 0 | 18 | 0 | 0 | 18 |
| **Total** | | | **252** | **1116** | **153** | **687** | **276** |
| (1) Number underground estimated from report. | | | | | | | |
| (2) Summary of multiple explosions. | | | | | | | |
| (3) Four miners died in this incident but all were on the surface. They are not included in the Total Fatalities or in the analysis. | | | | | | | |

*Table 2.  Level 2 outcomes*

| Date | Mine | No. Escape Successful | No. Escape Attempt Unsuccessful | No. Too Injured to Escape |
|---|---|---|---|---|
| **Disasters with 5 or more fatalities** | | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | | 4 | |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | 16 | 12 | |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | 3 | | 1 |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | 1 | | |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | 4 | 6 | |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | 1 | 27 | |
| 6/21/1983 | McClure No. 1 Mine, Clinchfield Coal Co. | | | 7 |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | | | 5 |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | | | |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | | | |
| 4/15/1981[1] | Dutch Creek No. 1, Mid-Continent Resources, Inc. | 3 | | 3 |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | | | |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | 6 | 10 | |
| 3/9/1976[2] | Scotia Mine, Blue Diamond Coal Co. | 3 | 6 | |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | | 3 | 1 |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | | 9 | |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | 1 | 5 | |
| **Disasters with fewer than 5 fatalities** | | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | 1 | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | 27 | 2 | |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | 5 | | 2 |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | 1 | | 1 |
| 3/19/1992 | Blacksville No. 1 Mine; Consolidation Coal Co. | 1 | | |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | | | |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | 3 | | |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | | | |
| 1/8/1987[3] | Dutch Creek No. 12; Mid Continent | 3 | | 1 |
| 8/9/1986 | No. 9 Slope William Station Mine; Pyro Mining Co. | 1 | 1 | 1 |
| 12/11/1985 | No. 2 Slope Mine; MSW Coal Co. | 1 | 2 | |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | | | 1 |

*Table 2. Level 2 outcomes (continued)*

| Date | Mine | No. Escape Successful | No. Escape Attempt Unsuccessful | No. Too Injured to Escape |
|---|---|---|---|---|
| **Disasters with fewer than 5 fatalities (continued)** | | | | |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | 11 | | |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | | | |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | 16 | | |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | | 2 | |
| 3/26/1971 | Nemacolin Mine | 9 | 2 | |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | 1 | 1 | |
| 4/10/1970 | Homer City | 11 | | 4 |
| 4/2/1970 | Compass No. 2 | 10 | | |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | 9 | 9 | |
| **Total** | | **148** | **101** | **27** |
| (1) One miner did not attempt to escape but remained with miners. This miner was classified as a successful escape. (2) Summary of multiple explosions. (3) One miner was injured during firefighting, was evacuated, and later died. This miner is included as "Too injured to escape." | | | | |

Table 4 presents the number of miners for each of the Level 4 outcomes described in Section 3.3.2. These outcomes refer to miners who barricaded. Blank table entries indicate that the value for this entry is zero.

*Table 3. Level 3 outcomes*

| Date | Mine | Escape Attempt Unsuccessful | | | Too Injured to Escape | |
|---|---|---|---|---|---|---|
| | | Rescued | Barricaded | Died | Rescued | Died |
| **Disasters with 5 or more fatalities** | | | | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | 1 | | 3 | | |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | | 12 | | | |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | | | | | 1 |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | | | | | |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | | | 6 | | |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | | | 27 | | |
| 6/21/1983 | McClure No. 1 Mine, Clinchfield Coal Co. | | | | 3 | 4 |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | | | | | 5 |

## *Table 3. Level 3 outcomes (continued)*

| Date | Mine | Escape Attempt Unsuccessful | | | Too Injured to Escape | |
|------|------|------|------|------|------|------|
| | | Rescued | Barricaded | Died | Rescued | Died |
| **Disasters with 5 or more fatalities (continued)** | | | | | | |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | | | | | |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | | | | | |
| 4/15/1981 | Dutch Creek No. 1, Mid-Continent Resources, Inc. | | | | 3 | |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | | | | | |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | 1 | | 9 | | |
| 3/9/1976[1,2] | Scotia Mine, Blue Diamond Coal Co. | | 6 | | | |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | 3 | | | | 1 |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | | | 9 | | |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | | | 5 | | |
| **Disasters with fewer than 5 fatalities** | | | | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | | | | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | | | 2 | | |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | | | | 2 | |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | | | | | 1 |
| 3/19/1992 | Blacksville No. 1 Mine; Consolidation Coal Co. | | | | | |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | | | | | |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | | | | | |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | | | | | |
| 1/8/1987[3] | Dutch Creek No. 12; Mid Continent | | | | | 1 |
| 8/9/1986[4] | No. 9 Slope William Station Mine; Pyro Mining Co. | 1 | | | | 1 |
| 12/11/1985[5] | No. 2 Slope Mine; MSW Coal Co. | 1 | | 1 | | |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | | | | 1 | |

*Table 3.  Level 3 outcomes (continued)*

| Date | Mine | Escape Attempt Unsuccessful | | | Too Injured to Escape | |
|---|---|---|---|---|---|---|
| | | Rescued | Barricaded | Died | Rescued | Died |
| **Disasters with fewer than 5 fatalities (continued)** | | | | | | |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | | | | | |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | | | | | |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | | | | | |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | | | 2 | | |
| 3/26/1971 | Nemacolin Mine | | | 2 | | |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | | | 1 | | |
| 4/10/1970 | Homer City | | | | 3 | 1 |
| 4/2/1970 | Compass No. 2 | | | | | |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | | 9 | | | |
| **Total** | | **7** | **27** | **67** | **12** | **15** |
| (1)   Summary of multiple explosions. | | | | | | |
| (2)   Two additional victims were found outside the barricade but may have originally been inside.  Since the report was inconclusive, we did not include these two miners in the number who barricaded. | | | | | | |
| (3)   One miner was injured during firefighting, was evacuated, and later died.  This miner is included as "Too injured to escape - Died." | | | | | | |
| (4)   One miner was too injured to escape, was rescued, but died later as a result of his injuries.  This miner is included as "Too injured to escape - Died." | | | | | | |
| (5)   The miner who died was attempting to rescue the other miner.  Since this miner was present at the incident and not clearly out of danger, this death was included with unsuccessful escape attempts. | | | | | | |

Tables 5 and 6 present our assessment of the impact refuge stations would have had on the final outcomes of the disasters covered by this analysis.  For miners not impacted by the event and miners killed immediately, refuge stations would have had no impact on the final outcome so these are not covered in the tables.  Table 5 covers the final outcomes of miners impacted by the event who escaped successfully, miners who did not escape and were rescued, and miners who barricaded and were rescued.

Table 6 covers miners who barricaded and perished, miners who died attempting to escape, and miners too injured to escape who were either rescued or perished.  The tables show the number of miners that we estimate would have been positively, neutrally, or negatively affected by the availability of refuge stations during the accident.  As discussed above, negative impacts for fatal outcomes are not considered.  Blank table entries indicate that the value for this entry is zero.

*Table 4.  Level 4 outcomes*

| Date | Mine | Barricaded | |
| | | Rescued | Died |
|---|---|---|---|
| **Disasters with 5 or more fatalities** | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | | |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | 1 | 11 |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | | |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | | |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | | |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | | |
| 6/21/1983 | McClure No. 1 Mine, Clinchfield Coal Co. | | |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | | |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | | |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | | |
| 4/15/1981 | Dutch Creek No. 1, Mid-Continent Resources, Inc. | | |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | | |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | | |
| 3/9/1976[1,2] | Scotia Mine, Blue Diamond Coal Co. | | 6 |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | | |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | | |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | | |
| **Disasters with fewer than 5 fatalities** | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | | |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | | |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | | |
| 3/19/1992 | Blacksville No. 1 Mine; Consolidation Coal Co. | | |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | | |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | | |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | | |
| 1/8/1987 | Dutch Creek No. 12; Mid Continent | | |
| 8/9/1986 | No. 9 Slope William Station Mine; Pyro Mining Co. | | |
| 12/11/1985 | No. 2 Slope Mine; MSW Coal Co. | | |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | | |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | | |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | | |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | | |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | | |
| 3/26/1971 | Nemacolin Mine | | |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | | |
| 4/10/1970 | Homer City | | |
| 4/2/1970 | Compass No. 2 | | |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | 9 | |
| **Total** | | **10** | **17** |
| (1)  Summary of multiple explosions. | | | |
| (2)  Two additional victims were found outside the barricade but may have originally been inside.  Since the report was inconclusive, we did not include these two miners in the number who perished in the barricade. | | | |

*Table 5. Refuge station impact assessment part 1*

| Date | Mine | Escape Successful | | | Escape Unsuccessful and Rescued | | | Barricaded and Rescued | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pos. | Neut. | Neg. | Pos. | Neut. | Neg. | Pos. | Neut. | Neg. |
| **Disasters with 5 or more fatalities** | | | | | | | | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | | | | 1 | | | | | |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | | 16 | | | | | 1 | | |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | | 3 | | | | | | | |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | | 1 | | | | | | | |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | 4 | | | | | | | | |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | | 1 | | | | | | | |
| 6/21/1983 | McClure No. 1 Mine, Clinchfield Coal Co. | | | | | | | | | |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | | | | | | | | | |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | | | | | | | | | |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | | | | | | | | | |
| 4/15/1981 | Dutch Creek No. 1, Mid-Continent Resources, Inc. | | 3 | | | | | | | |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | | | | | | | | | |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | | 6 | | | 1 | | | | |
| 3/9/1976[1] | Scotia Mine, Blue Diamond Coal Co. | | 3 | | | | | | | |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | | | | 3 | | | | | |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | | | | | | | | | |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | | 1 | | | | | | | |

*Table 5. Refuge station impact assessment part 1 (continued)*

| Date | Mine | Escape Successful | | | Escape Unsuccessful and Rescued | | | Barricaded and Rescued | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pos. | Neut. | Neg. | Pos. | Neut. | Neg. | Pos. | Neut. | Neg. |
| **Disasters with fewer than 5 fatalities** | | | | | | | | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | | 1 | | | | | | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | | 27 | | | | | | | |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | | 5 | | | | | | | |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | | 1 | | | | | | | |
| 3/19/1992 | Blacksville No. 1 Mine; Consolidation Coal Co. | | 1 | | | | | | | |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | | | | | | | | | |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | | 3 | | | | | | | |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | | | | | | | | | |
| 1/8/1987 | Dutch Creek No. 12; Mid Continent | | 3 | | | | | | | |
| 8/9/1986 | No. 9 Slope William Station Mine; Pyro Mining Co. | | 1 | | | 1 | | | | |
| 12/11/1985 | No. 2 Slope Mine; MSW Coal Co. | | 1 | | | 1 | | | | |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | | | | | | | | | |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | | 11 | | | | | | | |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | | | | | | | | | |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | | 16 | | | | | | | |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | | | | | | | | | |
| 3/26/1971 | Nemacolin Mine | | 9 | | | | | | | |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | | 1 | | | | | | | |
| 4/10/1970 | Homer City | | 11 | | | | | | | |
| 4/2/1970 | Compass No. 2 | | 10 | | | | | | | |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | | 9 | | | | | | 9 | |
| **Total** | | **4** | **144** | | **4** | **3** | | **1** | **9** | |
| (1) Summary of multiple explosions. | | | | | | | | | | |

36

*Table 6. Refuge station impact assessment part 2*

| Date | Mine | Barricade and Died | | Escape Unsuccessful and Died | | Too Injured to Escape and Rescued | | | Too Injured to Escape and Died | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pos. | Neut. | Pos. | Neut. | Pos. | Neut. | Neg. | Pos. | Neut. |
| **Disasters with 5 or more fatalities** | | | | | | | | | | |
| 5/20/2006 | Darby Mine No. 1, Kentucky Darby LLC | | | 3 | | | | | | |
| 1/2/2006 | Sago Mine, Anker West Virginia Mining Company Inc. | 11 | | | | | | | | |
| 9/23/2001 | No. 5 Mine, Jim Walter Resources, Inc. | | | | | | | | | 1 |
| 12/7/1992 | No. 3 Mine, Southmoutain Coal Co. | | | | | | | | | |
| 9/13/1989 | William Station No. 9 Mine, Pyro Mining Co. | | | 6 | | | | | | |
| 12/19/1984 | Wilberg Mine, Emery Mining Corp. | | | 27 | | | | | | |
| 6/21/1983 | McClure No. 1 Mine, Clinchfield Coal Co. | | | | | | 3 | | | 4 |
| 1/20/1982 | No. 1 Mine, RFH Coal Co. | | | | | | | | | 5 |
| 12/8/1981 | No. 21 Mine, Grundy Mining Co. | | | | | | | | | |
| 12/7/1981 | No. 11 Mine, Adkins Coal Co. | | | | | | | | | |
| 4/15/1981 | Dutch Creek No. 1, Mid-Continent Resources, Inc. | | | | | | 3 | | | |
| 11/7/1980 | Ferrell No. 17, Westmorland Coal Co. | | | | | | | | | |
| 3/1/1977 | Porter Tunnel, Kocher Coal Co. | | | | 9 | | | | | |
| 3/9/1976[1] | Scotia Mine, Blue Diamond Coal Co. | 6 | | | | | | | | |
| 12/16/1972 | Itmann No. 3 Mine, Itmann Coal Co. | | | | | | | | | 1 |
| 7/22/1972 | Blacksville No. 1, Consolidation Coal Co. | | | 9 | | | | | | |
| 12/30/1970 | Nos. 15 and 16 Mines, Finley Coal Co. | | | 5 | | | | | | |
| **Disasters with fewer than 5 fatalities** | | | | | | | | | | |
| 10/23/2006 | R&D Coal Company, Inc. Mine | | | | | | | | | |
| 1/19/2006 | Alma Mine No. 1; Aracoma Coal Co, Inc. | | | 2 | | | | | | |
| 7/31/2000 | Willow Creek Mine; Plateau Mining Corp. | | | | | | 2 | | | |
| 11/30/1993 | Elmo No. 5 Mine; AA&W Coals Inc. | | | | | | | | | 1 |

*Table 6.  Refuge station impact assessment part 2 (continued)*

| Date | Mine | Barricade and Died | | Escape Unsuccessful and Died | | Too Injured to Escape and Rescued | | | Too Injured to Escape and Died | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pos. | Neut. | Pos. | Neut. | Pos. | Neut. | Neg. | Pos. | Neut. |
| **Disasters with fewer than 5 fatalities (continued)** | | | | | | | | | | |
| 3/19/1992 | Blacksville No. 1 Mine; Consolidation Coal Co. | | | | | | | | | |
| 1/16/1991 | No. 1 Mine; Fire Creek, Inc. | | | | | | | | | |
| 7/31/1990 | No. 3 Mine; Granny Rose Coal Co. | | | | | | | | | |
| 12/26/1987 | No. 1 Mine; Double R Coal Co. | | | | | | | | | |
| 1/8/1987 | Dutch Creek No. 12; Mid Continent | | | | | | | | | 1 |
| 8/9/1986 | No. 9 Slope William Station Mine; Pyro Mining Co. | | | | | | | | | 1 |
| 12/11/1985 | No. 2 Slope Mine; MSW Coal Co. | | | | 1 | | | | | |
| 8/19/1985 | No. 3 Mine; R & R Coal Co. | | | | | | 1 | | | |
| 2/16/1984 | No. 1 Mine; Greenwich Collieries | | | | | | | | | |
| 7/3/1983 | Homer City Mine; Helen Mining Co. | | | | | | | | | |
| 7/7/1977 | No. 2 Mine; P & P Coal Co. | | | | | | | | | |
| 9/25/1973 | No. 4 Mine; Oakwood Red Ash | | | 2 | | | | | | |
| 3/26/1971 | Nemacolin Mine | | | 2 | | | | | | |
| 11/30/1970 | Pyro No. 2 Mine; Pyro Mining Co. | | | 1 | | | | | | |
| 4/10/1970 | Homer City | | | | | | 3 | | | 1 |
| 4/2/1970 | Compass No. 2 | | | | | | | | | |
| 7/24/2002 | Quecreek No. 1 Mine, Black Wolf Coal Company, Inc. | | | | | | | | | |
| **Total** | | **17** | | **57** | **10** | | **12** | | | **15** |
| (1) Summary of multiple explosions. | | | | | | | | | | |

Table 7 presents key summary data from the event tree analysis and refuge station impact assessment.

*Table 7.  Summary of refuge station impact*

| Total Miners Underground | Number Impacted by Event | Number Positively Impacted | Number Neutrally Impacted(1) | Number Negatively Impacted | Total Fatalities |
|---|---|---|---|---|---|
| 1116 | 429 | 83 | 193 | 0 | 252 |
| (1) Does not include miners not impacted by event and miners killed immediately. | | | | | |

The outcomes and estimated impacts of the availability of refuge stations during the incident are also included in the event tree diagram in Figure 1.

### 3.4  Conclusions

The results of the event tree analysis indicate that refuge stations would have had a positive impact on the outcomes of 12 (32%) of the 38 disasters studied.  The total number of miners that would have been positively impacted is 83 (19%) of the 429 underground and impacted by these accidents.  A total of 74 (29%) of the 252 fatalities would have been positively impacted and potentially would have survived the accident.  This represents 75% of the 99 fatalities who were not killed immediately.  We caution that these numbers must be viewed in the light of the assumptions that were made during our analysis of the mine disaster reports.  We feel these assumptions are conservative and based on sound understanding of coal mining environments, operations, and procedures.  This analysis is designed to provide insight into the design and use of refuge stations and is not intended to make any statement about the actions and events described in these reports.

By far the greatest single outcome that would have been positively impacted is the case of miners who perished during their escape attempts.  Our assessment indicates that 57 (85%) of the 67 miners might have been positively impacted.

A second outcome that would have benefited is the case of miners who barricaded.  While barricades were used in only two relevant incidents, these incidents combined involved 17 and possibly 19 fatalities.  All of these miners might have been positively impacted by stations.

The primary benefit of refuge stations in these incidents would have been in providing a breathable atmosphere to miners since most in these outcomes died from lack of breathable air.

Refuge stations would not be useful to miners who are too injured to move or be moved following an accident.  They would also not be useful when miners are killed instantly or shortly after an incident from noxious atmosphere who have no time to react to the situation.

Refuge stations would also create a positive impact on miners who escaped successfully.  These individuals might have used stations as way stations on the way out of the mine to safely change SCSRs, rest, and obtain first aid.

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## 4. _Review of Existing Regulations_

Having demonstrated that refuge stations would have saved lives in certain mine disasters, we now consider the design criteria for refuge stations.  For initial guidance, we reviewed existing regulations relevant to construction and use of refuge stations.  These regulations included the West Virginia regulations for portable refuge chambers, MSHA regulations on breathable air, and federal regulations on gob seals and on mine evacuations.  The goal of this review was to determine which MSHA regulations might already impact refuge station design and which state regulations regarding refuge station design should be examined for applicability.

The state of West Virginia mandated that underground coal mines must have portable refuge chambers in place by July of 2007.  The West Virginia legislature commissioned a detailed study of what the chamber requirements should be, which produced guideline rules for initial chamber development within a short time span.  Since our initial review, MSHA has issued a proposed rule for refuge alternatives [8] based in part on reports produced under this program.

For easy reference, Table 8 shows a summary of current Foster-Miller recommendations, side by side with the MSHA proposed rule, West Virginia [17] and MSHA PIB 07-03[12] latest rules and guidelines. The proposed rule was not available during our initial review of regulations but is included for reference.

### _Table 8.  Rules summary - FMI guideline report, MSHA, WV_

| Category | Sub-Category | Foster-Miller Recommendations | MSHA Proposed Rule; Refuge Alternatives for Underground Coal Mines | West Virginia Technical Rules for Approval (Title 56, Series 4, Section 8) | MSHA PIB Recommendations (PIB 07-03, Breathable Air) |
|---|---|---|---|---|---|
| Life Support Timespan Capability | | 96 hrs | Min. 48 hrs | Min. 48 hrs | Min. 96 hrs |
| Initial Event Survival Standards | | 15 psi overpressure for .3 seconds; flash fire of 300F for 3 seconds | 15 psi overpressure for 0.2 seconds; flash fire of 300F for 3 seconds | Peak overpressure 15 psi ; flash fire of 300deg F for 3 seconds (Per NFPA-2113) | N/A |
| Handling and Transport Readiness | | Universal Refuge Bulkhead design utilizing reusable, modular components | Safely moveable, withstand collisions during transport/handling | Protect for normal handling and mine conditions | N/A |
| Atmosphere Management Capability | Oxygen Level | $O_2$ between 18.5%-23% | $O_2$ between 18.5%-23% | $O_2$ above 19.5% | N/A |
| | Carbon Dioxide Level | $CO_2$ max. 0.5% with excursions to 1% | $CO_2$ 1.0% or less with excursions not to exceed 2.5% | $CO_2$ below 0.5% | N/A |

*Table 8.  Rules summary - FMI guideline report, MSHA, WV (continued)*

| Category | Sub-Category | Foster-Miller Recommendations | MSHA Proposed Rule; Refuge Alternatives for Underground Coal Mines | West Virginia Technical Rules for Approval (Title 56, Series 4, Section 8) | MSHA PIB Recommendations (PIB 07-03, Breathable Air) |
|---|---|---|---|---|---|
| Atmosphere Management Capability (continued) | Carbon Monoxide Level | CO 25 ppm or less | CO 25 ppm or less after 20 minutes | CO below 50 ppm | CO below 25 ppm |
| | Apparent Temperature | Max. 95°F | Max 95°F | Max. 95°F | Max. 95°F |
| | Respiratory Quotient ($CO_2/O_2$) | 0.75 at rest<br>0.9 moderate<br>1.0 very vigorous* | Not specified | N/A | 0.8 |
| | Average Oxygen Consumption Rate | 0.6 CFH (0.283 L/min) at rest<br>4.2 CFH (1.982 L/min) moderate activity<br>6 CFH (2.832 L/min) very vigorous* | 1.32 CFH/Man (0.62297 L/Min/Man) | N/A | 1.32 CFH/Man (0.62297 L/Min/Man) |
| | Assumed Breathing Rate | 4/5 at rest<br>1/5 at moderate activity* | Not specified | N/A | 4/5 at rest<br>1/5 at moderate activity |
| | Average Carbon Dioxide Generation Rate | 1.117 CFH/man (0.527 L/min)* | Not specified | N/A | 1.08 CFH/Man (0.5097 L/Min/Man) |
| | $CO_2$ Scrubbing Provisions | 0.019 CFM/occupant (0.538 l/min/occupant)*. | 1.08 CFH/Man (0.5097 L/Min/Man) | N/A | LiOH curtains : 0.244 lb/Man/hr (or equivalent in soda lime etc) |
| | Chamber Purge Volume Requirement | Not specified | Not specified | N/A | 3 x Chamber volume |
| | Required airflow for $CO_2$ dilution with no scrubber | 1.9 to 3.5 cfm/occupant (53.8 to 107.6 L/min/occupant) | Not specified | N/A | 750 CFH/man |
| | Chamber overpressure required (if the only system of gas incursion protection) | 5 in of water (~0.18 psi)* | 0.25 psi above mine atmospheric pressure | N/A | N/A |

*Table 8. Rules summary - FMI guideline report, MSHA, WV (continued)*

| Category | Sub-Category | Foster-Miller Recommendations | MSHA Proposed Rule; Refuge Alternatives for Underground Coal Mines | West Virginia Technical Rules for Approval (Title 56, Series 4, Section 8) | MSHA PIB Recommendations (PIB 07-03, Breathable Air) |
|---|---|---|---|---|---|
| Gas Monitoring | | $O_2$, CO, $CO_2$ inside; $O_2$, CO, $CH_4$ outside | Monitor inside and out $O_2$, CO, $CO_2$, and $CH_4$ | Monitor inside and out: $O_2$ and CO | Monitor $O_2$, CO, $CO_2$, & $CH_4$ |
| Egress Provision To Maintain Air Quality | | All chambers to have airlocks | Airlock or positive overpressure inside | Provide entry and exit method that maintains inside atmosphere integrity | N/A |
| Powered Subsystem Intrinsic Safety | | Must be permissible system | Must be intrinsically safe | MSHA certified intrinsically safe power, if required | N/A |
| Water Provision | | 9 qt/occupant | Min. 2.25 Qts /person/ Day | Min. 8 Quarts of water/Miner | N/A |
| Food Provision | | 6960 calories of Food/occupant | Min. 2000 calories of food/person/day | Min. 4000 calories of food/Miner | N/A |
| Human Waste Disposal | | Min 2 toilets Add 1 toilet for every 8 occupants over 16 occupants 2 gallons waste storage/occupant | Provide a means to contain human waster and minimize odors | Provide means for human waste disposal outside of chamber | N/A |
| First Aid Provision | | 1 standard MSHA first aid kit/10 occupants | Provide first aid supplies | Provide first aid kit, (Per W. Va. Code Chapter 22A, article 2-59(3)(b) | N/A |
| Inspection Provision | | After initial installation, annually thereafter, after relocation, after mine event, pre-shift checks | Pre-shift checks for damage, tamper resistant seals, activation mechanism, $O_2$ or air availability | Provide means for inspection of shelter and contents | N/A |
| Inside Repairs By Occupants Provision | | Repair materials specified | Provide means to repair. Ensure routine repairs can be completed within 10 minutes. | Contain manufacturer recommended repair materials | N/A |
| Occupant Indicator Light Provision | | Not specified | Not specified | Provide battery powered strobe light visible from outside indicating occupancy | N/A |

*Table 8.  Rules summary - FMI guideline report, MSHA, WV (continued)*

| Category | Sub-Category | Foster-Miller Recommendations | MSHA Proposed Rule; Refuge Alternatives for Underground Coal Mines | West Virginia Technical Rules for Approval (Title 56, Series 4, Section 8) | MSHA PIB Recommendations (PIB 07-03, Breathable Air) |
|---|---|---|---|---|---|
| Surface Communications Provision | | Two way communications with mine areas outside refuge and with surface | Provide two way communication | Provide provisions for communications to the surface and mine's communication system | N/A |
| MSHA Approval of All Items and Materials | | Per existing MSHA regulations | Required | Provide proof of approval for all items and materials subject to MSHA approval | N/A |
| *Value determined from Foster-Miller Inc. 1983 Report, "Development of Guidelines for Rescue Chambers, Vol. 1" [14] | | | | | |

### 4.1.1  Description of New Seal Regulations

The following documents were reviewed to discern the latest legislation as it applies to crosscut refuge station bulkhead overpressure requirement:

- MSHA PIB P07-03 Methods for providing breathable air [12].

- MSHA PIB P07-03 Breathable air Q & A  [12].

- MSHA Program policy letter P06-V-10, Implementation of Section 2 of the MINER Act of 2006  [15].

- Federal register Emergency Mine Evacuation, Final Rule 30 CFR 3, 48, 50 and 75 [16].

### 4.1.2  Background to the New Regulations for Abandoned Area Mine Seals

An Emergency Temporary Standard (ETS) was issued under section 101 (b) of the Federal Mine Safety and Health Act of 1977, as amended by the Mine Improvement and New Emergency Response Act of 2006 (MINER Act), 30 U.S.C. 811 (b) [RES-1 and RES-2].   The ETS establishes or revises standards in part 75 – subpart D – Ventilation.  An ETS serves as both a final rule with immediate effect, and a proposed rule to establish a final rule through the notice and comment process.  The MINER Act states that the ETS is a temporary standard and must be superseded by a final rule within nine months.

Section 10 of the MINER Act requires the government to issue mandatory health and safety standards for gob seals no later than December 15, 2007. On February 8, 2007 NIOSH issued a draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" [18] which provides recommendations for formulating seal design criteria [18]. In a July 2006 Program Information Bulletin (PIB) No. P06-16 [13], MSHA increased strength requirements for new alternative seals to 50 psig from the previous 20 psig requirement.

### 4.1.3  MSHA Proposed Rule

In June of 2008, MSHA released a proposed rule for refuge alternatives in underground coal mines. While the proposed rule endorses many of the recommendations in this report, there are differences. For example, MSHA requires outby refuge stations at one hour travel intervals while our research indicates that such stations may not have significantly impacted miner survival in the disasters studied.

### 4.1.4  Mine Visits

As part of our review of the applicability of existing state and federal regulations to refuge station design parameters, we visited two western United States coal mines that either have already installed refuge stations or will soon have them in place. The purpose of these visits was to gain insights into their current and/or planned practices for the installation and use of refuge stations. Visits were made to the San Juan Coal Company mine near Farmington, NM and to the Twentymile Coal Company Foidel Creek Mine in Routt County, CO. Interviews were conducted with the safety officials at the respective mines. In addition, at the San Juan location a trip underground was made to see the stations first-hand. Of particular interest is that San Juan Coal has constructed a series refuge stations using bulkheads and will provide breathable air through the use of boreholes.

### 4.1.5  Conclusions from the Regulation Review

Our conclusions based on the foregoing sources are as follows:

- There is currently no specific regulation specifying crosscut refuge station bulkhead explosion resistance.

- There is a minimum 50 psi seal requirement if SCSRs are stored in a hardened room and these are part of the mine's Emergency Response Plan.

- SCSRs could be stored in a refuge shelter which does not have 50 psi explosion seal rating, provided the SCSRs are not part of the mine's Emergency Response Plan.

- MSHA has no current requirement for explosion resistance of a portable refuge shelter, however West Virginia rules called for an initial event 15 psi for 3 seconds peak overpressure resistance for portable refuge shelters.

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## 5. Refuge Station Design Parameters

### 5.1 Introduction

To develop refuge station design criteria, we performed a detailed study of design parameters to identify primary and secondary design parameters. Primary design parameters involved the ability of a refuge to survive an event and continue to provide life support to trapped miners. Secondary design parameters cover all other aspects of refuge stations. We identified these parameters as described in this section and studied key issues and considerations for each.

The design parameters are organized as follows. Section 5.2 discusses design parameters common to both portable and fixed position stations. Sections 5.3 and 5.4 cover design parameters specific to portable chambers and design parameters specific to fixed position stations, respectively.

### 5.2 Common Design Parameters

### 5.2.1 Structural Integrity

At the time of this report, West Virginia mandates call for portable refuge chambers to withstand an initial event of 15 psi overpressure for 3 seconds, and a flash fire of 300°F for 3 seconds. All currently approved West Virginia chamber vendors have performed some level of computational analysis to show accordance with this requirement and one vendor (Kennedy Metal Products, Inc.) has done actual explosion tests to validate their chamber. The secondary structural consideration with portable chambers concerns ruggedness for general mine handling and transport, and compatibility with existing mine equipment for towing/lifting etc.

There are two basic types of portable chamber approved by West Virginia to date:

- Those which are rigid walk/crawl in, explosion resistant chambers with all supplies inside.
- Those which are inflatable (post event), but stored pre-event in an explosion resistant container.

There is also one system (Vendor: LifePod) which can be treated as an inflatable chamber for purposes of assessing structural integrity since it has a pre-event explosion resistant container for supplies. This system does not provide an enclosed chamber for miners. Instead, a manifold system of masks is used to provide breathable air for the miners.

Table 9 summarizes the design factors for structural integrity.

*Table 9. Structural integrity design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Blast resistance | Must survive mine explosion. | A portable shelter may need to be constrained from moving during an explosion e.g., with ground anchors. May require local protection of vulnerable elements e.g., door handles, exposed compressed air valves on skid. Locate out of the main entryways. |
| Fire resistance | Must survive blast flame front. | Place shelter out of the main entryways, possibly use a separate heat shield in front of the shelter. Exterior materials must withstand flash fire. |
| Routine damage resistance | Must survive general mine handling and transport | Establish minimum clearance required for each station type to be moved (e.g., by mine scoop or dragging). Create chart of shelter dimensions, mine seam heights (mine map) and mine scoop clearance requirements. |

### 5.2.2  Atmosphere Management

The primary goal of any refuge station is to provide a habitable, breathable atmosphere for miners until they are rescued. The two principal requirements for a breathable atmosphere are supplying oxygen and eliminating $CO_2$ buildup either by absorption (chemically) or by dilution. In a closed environment, toxicity from $CO_2$ levels will occur well before the oxygen levels become dangerously low.

It is to be expected that respiration cycles will vary between occupants of a refuge station and over time for individual occupants. Station atmosphere management systems must be able to adjust for varying conditions that may arise. For example, after an event miners may arrive at a shelter wearing self contained self rescuers (SCSRs) and are likely to be anxious, hot, and possibly injured. Initially respiration rates may be very high and carbon dioxide levels may quickly build up to toxic levels (0.5% or higher) unless scrubbed from the air. The station $CO_2$ removal system must be able to produce a high scrubbing rate at least for an initial period, without failing. As time goes on, miner respiration rates will moderate, requiring less scrubbing capacity. Systems and supplies must accommodate these cycles. Similarly, oxygen will need to be added to the station air to make up for that consumed in respiration. The $O_2$ level must be monitored and flow rate adjusted to maintain safe levels.

There are several $CO_2$ scrubber issues that are of concern:

- Particulate buildup in the air.

- Form of scrubber (canisters versus curtains).

- Impact of overload from initial spike loading; especially handling more miners than the system is designed for.

- Instrumentation reliability and calibration.

- Effects of long-term storage and potential damage as a result of station transport (if applicable).

48

Station air, or at least airlock air, will need to be purged in situations where carbon monoxide enters the station with arriving miners. This purging should be performed as quickly as possible. In stations using a collective protection air management system, the chemical reactions involved (e.g., $CO_2$ scrubbing via soda lime reaction or CO conversion to $CO_2$ via catalyst reaction) may be endothermic or exothermic. These reactions coupled with the human heat output and breath moisture condensation cooling will result in some temperature and humidity variation within the station. Provision or planned design should control these variations to within human tolerable limits.

There are several methods of carbon dioxide scrubbing via chemicals; the two most common options being soda lime and lithium hydroxide (LiOH). Both methods cause a chemical reaction with carbon dioxide gas and generate a solid product thereby eliminating the $CO_2$ from the air. LiOH is generally regarded as the more efficient method and requires less station volume. Soda lime is less efficient, requires more station volume, but is less costly than LiOH. Each system has been shown to work, the choice depends on which system is most suitable to a particular station design. Of the stations approved by West Virginia, some use soda lime, some use LiOH, and one uses a continuous air supply and does not require $CO_2$ scrubbing. All claim to successfully manage the atmosphere within prescribed limits. Carbon dioxide can also be managed by diluting station air with a borehole-provided air supply, compressed air lines, or compressed air bottles.

Because stations may not be used for significant periods after installation it is critical to develop a testing program for the atmosphere support system that can be executed on a regular basis. All supplies, scrubbers, instrumentation, and air sources will require periodic evaluation. This would also include careful monitoring of equipment and supplies that have various shelf lives.

Table 10 summarizes the design factors related to atmosphere management.

### 5.2.3   Location/Positioning

Both state and federal authorities have introduced some guidelines or regulations as of this writing. Current West Virginia rules for refuge station locations dictate that the stations must be located within 1000 feet of the nearest working face in each working section.

The preferred locations of refuge stations are in crosscuts or dead ends perpendicular to the main entryways. It is expected that a methane explosion would propagate pressure waves and flash fire in all directions. The pressure-time characteristics will vary considerably depending on the concentration of methane, the length of the gas zone, the location of the ignition source within the gas zone, and the location of the gas zone within the mine. The influence of intersections and turns on shock wave propagation in a continuous passage tunnel has been studied by Taylor [20], and it has been shown that if an explosive shock wave passes three crosscuts before reaching the refuge station, the peak pressure will be reduced by 50 percent. A second observation is that in the neighborhood of a crosscut, there are high local reflected pressures at short distances down the crosscut. Consequently, it would appear advantageous to

*Table 10. Design factors for atmosphere management*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Oxygen Addition | $O_2$% must be held within limits. Must support station overload. | Control flow rate, constant monitoring and adjust for conditions and/or no. of people. Provide chart of settings |
| Carbon Dioxide Scrubbing | $CO_2$% must be maintained below an acceptable level. | Scrubbing chemicals and air movement must be sufficient to control $CO_2$% |
| | Must be usable by intended occupants. | Protect from toxic chemicals, provide chart of instructions, constant gas level monitoring and adjust for no. of people |
| | Ensure sufficient airflow to achieve required scrubbing. | If passive air flow, ensure natural currents are sufficient or provide manual air mover to ensure safe levels; activate hand crank blower, or compressed air powered fan |
| Carbon Monoxide Removal | Maintain below acceptable level. | If no specific scrubber for CO, must provide sufficient purge capacity. |
| Methane Removal | Maintain below acceptable level. | Purging |
| Hydrogen Sulfide Removal | Maintain below acceptable level. | Purging |
| Humidity | Maintain within safe limits. Maintain within occupant comfort limits. | Actively control humidity in colder ambient temp. mines (with desiccant or other), or collect and divert the condensation moisture away from occupants |
| Temperature | Maintain within safe limits. | Plan for worst case overload heat conditions. Provide blankets in case of low temperature. |
| Airlock | Minimize per man cycle time. Allow entry of injured men on a stretcher. | Design to accommodate a stretcher. Design to accommodate several men at once. Design for minimal empty space during use to reduce air volume required to purge. |
| Atmosphere Integrity | Prevent inflow of air/gasses from exterior | Net result of gas transfer inside station must provide positive pressure. May need pressure relief valve |

place a station or bulkhead even with the crosscut entrance; however, it is important to consider protecting the refuge station from flying debris from the blast wave. Loose items in the entryways such as roof bolts, hand tools, cribbing, and machinery could cause severe damage to a station. In this instance, placing the refuge station some distance down a crosscut has some advantages. The trade-off between these crosscut depths must be examined with these factors in mind.

MSHA provides specific guidance on the placement of breathable air at 2000 ft from the working face. This location along with the requirement to place caches of SCSRs at 30 minutes walking distance must be considered when establishing refuge locations.

The MSHA proposed rule states that refuge alternatives be located between 1000 and 2000 ft from the working face and from locations where mechanized mining equipment is being installed

or removed and spaced within one hour travel distances in outby areas where people work (with exception provisions).

### 5.2.4  Communications

Of the varied communication systems currently used in underground coal mines, there are still wide variations in performance.  Communications have played an important role in the past to help coordinate efforts and intelligence for rescues. However, the nature of coal mines is such that communication networks are either hard wired or limited range wireless networks that require signal transmitters/receivers to be spread liberally throughout the mine.  A more recent technology development are text pagers which can transmit an emergency message to each miner via a device on their helmets; however, this is a one-way communication with no way to acknowledge the receipt of the message.  RFID tags are useful in allowing the above ground control operation staff to know which miners are where at any time, but permissibility of these systems is still a problem.  Any system that uses wires is at risk of disconnection damage due to an explosion, and ideally should have a wired or wireless back up system.  Most recently NIOSH initiated a major thrust into the development of a wireless mesh network for underground communication.  In addition, all the stations being built now must carry at least the provision for installation of a system later, and provide for gas tight cable holes should they be required. Table 11 shows a summary of the design criteria for refuge station communications systems.

*Table 11.  Communications design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Wired systems | Must provide communications to other parts of mine and to surface.<br><br>Stations must provide airtight hole seals for cables.<br><br>Cables must survive an event. | Use standard OTS gas tight seals and hardware. |
| Wireless systems | Must provide communications to other parts of mine and to surface. | Systems in development |

### 5.2.5  Inspection and Maintenance

A system of inspection and maintenance is vitally important for each refuge station type. Refuge stations are either be fixed bulkhead type or portable chamber.  Specific inspection and maintenance issues are discussed for refuge bulkhead stations in Section 5.4.8, and for portable chambers in Section 5.3.4.  Each station type has unique elements, and they may sit on stand-by for weeks, months or years.  A specific inspection plan should be established to monitor system components, ensure that inventory is maintained and any degradable supplies kept in date. Components subject to calibration or safety checks should be charted and recorded (e.g., hydrostatic tests on pressure cylinders).  An important consideration when inspecting is to record the station location and verify that it falls within the guidelines of distance from the working face.  Station orientation should be verified to permit proper operation such as inflatable deployment or unblocked hatch access.

Regardless of refuge station type (portable chambers or bulkhead-based stations) it may be useful to develop and maintain a registry of the location and type of shelter in the event of a product or component recall or field service experience that uncovers operational problems or defects. The registry could be agency-maintained (e.g., MSHA) and could be managed online to minimize cost. In the event of a problem, notification and subsequent compliance with any recommended changes could be readily tracked and verified minimizing the probability that an issue was not communicated to those affected. This would help maintain miner confidence that refuge shelters will function as designed when they are needed.

Table 12 is a summary of the inspection and maintenance design factors. Note that not all system elements, concerns, and possible remedies are applicable to all types of stations.

### 5.2.6  Secondary Design Parameters

*Water and Food* - The advances in technology for rescue operations and borehole drilling have led to a reduction in the expected length of stay in a refuge station during an emergency. The current expectation is for a rescue to happen in shorter periods (e.g., no more than four days). In a breathable atmosphere, humans can generally survive for extended periods without food. The more immediate need is for water to stay hydrated. Whether or not food affects survival over a short period, the provision of food is mandated since it will increase comfort levels, maintain energy, and improve morale of the occupants. Potable water will be provided and is easily stored for long periods.

Table 13 summarizes the design factors with regard to food.

*Waste management* - Human waste in an enclosed environment will emit strong odors and gasses, and must be either ejected from the station without contaminating the station air or placed in a valve sealed area for later disposal. Modern equipment for camping, for example, allows for simple dry chemical toilets which contain catalysts for breaking down the waste and reducing odors, while providing discrete sealed bags. This is a typical system used in the newer stations. Table 14 summarizes the design factors for human waste management.

*Operational supplies shelf life* - Most systems for life support rely on various chemicals and catalysts for atmosphere management and waste management. If items have a shelf life it should be tabulated with expiration dates so that inspection procedures can determine when something is out of date. If batteries are included as part of a permissible powered subsystem, it is important to establish an interval beyond which they may need to be charged. Any perishable items that are in sealed containers to prevent premature degradation, e.g., food packaging, should have a proven seal, and be clearly identified with expiration dates for inspection/replacement. A thorough inventory and chart of station contents will indicate the item with the shortest shelf life and ensure supplies are always fresh. Table 15 shows a summary of design factors concerning supplies shelf life.

*Table 12.  Inspection and maintenance design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Gas monitor status | Maintain in operational state. | Gas monitor(s) should be mounted securely at breathing level in the station as applicable, calibration checks per MSHA or mine quality rules, check battery levels separate from the unit; don't just switch on unit. |
| Oxygen cylinder status | Ensure cylinders are operational and structurally sound. | Operate the valves briefly to check. Check $O_2$ levels in all cylinders, and inspect the hoses. Check log to determine if hydrostatic testing due. Check for physical damage. |
| Compressed air cylinder status | Ensure cylinders are operational and structurally sound. | Operate the valves briefly to check. Check air levels in all cylinders, and inspect the hoses. Check log to determine if hydrostatic testing due. Check for physical damage. |
| Powered blower | Maintain in operational state. | Check battery levels separately; don't just switch on unit to check. |
| Station structure | Ensure station is structurally sound. | Inspect exterior and/or interior of the shelter, is there any sign of damage to structure, controls, and signage?  Repair/replace parts as necessary |
| Perishable/degradable supplies | Ensure all supplies are within expiration dates. | Maintain supply log.  Check for expired items.  Check for items that will expire prior to the next inspection. Replace/order supplies as necessary |
| Communications systems | Maintain in operational state. | Establish contact with the surface, and a random station underground to verify connections |
| Station supplies | Ensure required supplies are stock in station. | Periodic inventory of station supplies. Use check off list, make sure supplies are properly sealed. |
| Station location | Ensure station is in correct location. | Verify current station position.  Refer to mine map and ERP to determine required location. |
| Storage locations of station contents. | Ensure station contents are properly stored and restrained. | Check for play in the restraints on supplies and gas cylinders, tighten as necessary |
| Access to activation controls for inflatable shelters, clearance for operation | Ensure any station activation controls are accessible.  Ensure sufficient clearance is available for station deployment if required. | Ensure hatches can be fully opened. Ensure there are no physical items near shelter that would obstruct inflatable deployment (if applicable).  Clear the area or reposition as necessary |
| Condition of inflatable systems stored in explosion proof boxes | Maintain in operational state. | Verify system readiness.  Ensure inflatable (soft-sided) will function as expected. Consider equipment check during periodic in-mine training |

*Table 13.  Design factors for food and water provision*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Water | Provide sufficient potable water to maintain health. | Use OTS products. <br> Reference well established numbers, e.g. <br> FMI: 9 qt/miner total, 2.25 qt/miner/day <br> West VA.: 8 qt/miner <br> MSHA: 2.25 qt/miner/day |
| Types of food provisions | Provide food with extended shelf life | Cull from existing OTS space capsule/submarine type foods, e.g., dried, MRE's, canned, pouches, boxes, individual kits of food and water or bulk, vacuum packs, pills |
| Calorie count | Provide sufficient calories to maintain health | Reference well established numbers, e.g. <br> FMI: 6960 cal/miner total, 1740 cal/miner/day <br> West VA: 4000 cal/miner <br> MSHA: 2000 cal/miner/day |

*Table 14.  Waste management design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Toilet waste disposal method | Isolate station occupants from waste. | Provide suitable gas tight waste storage if not expelling waste from station, with possible relief valve to outside |
| Toilet location in station | Ensure sufficient number of toilets for station occupants. <br> Ensure usable in existing seam height. | Position toilet near to disposal valves or airlock to prevent having to transport waste. FMI guidelines recommend 2 toilets per station. (Army manuals indicate 1 toilet per 8 men) |
| Toilet chemicals shelf life | Ensure any required chemicals are within their specified shelf life | Use well tested OTS systems, e.g., Army/camping toilets.  Shelf life must be validated |

*Permissible electrical components* – Currently one vendor approved by West Virginia for a refuge station (Modern Mine Safety Supply) is planning to use a dry cell battery powered blower system in its atmosphere management system.  The battery system must be housed in an explosion proof container to be permissible under current MSHA regulations and approval is awaiting the results of testing.  Other approved vendors may in the future adopt permissible battery systems, as they expressed in conversations with Foster-Miller.  Some of these systems are currently in development, while these vendors use compressed air to power their blowers for now.  As with all battery systems that sit uncharged, there will be some decay in charge over time, which needs to be planned for and recharging scheduled as necessary.  These batteries in the stations are being used primarily for moving the air, either to force it into contact with scrubbing chemicals or to disperse an injected gas stream.  Some sort of back-up power for air movement should be provided in case of battery failure or complete discharge. This could be in the form of spare batteries or possibly a hand crank blower to move the air as dictated by the gas monitor levels.  Note that due to the potential for high oxygen concentration within a station, the MSHA intrinsic safety approval requirements and approval processes may need to be reviewed. Table 16 summarizes the design factors for permissible electrical components.

*Table 15. Supplies shelf life design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| $CO_2$ scrubbing, Soda Lime | Maintain viable supply | Approximate 10 yr shelf life |
| $CO_2$ scrubbing, Lithium Hydroxide curtains | Maintain viable supply | Approximate 10 yr shelf life |
| CO scrubbing, catalyst | Maintain viable supply | Establish the shelf life spec for proprietary catalyst |
| Potable water | Maintain viable supply | Add 1 teaspoon of liquid bleach per 5 gals water to extend life, or replace per water packaging co. recommendations |
| Food | Maintain viable supply | Establish shelf life for specific type of food/packaging used |
| Toilet chemical catalyst | Maintain viable supplies | Establish shelf life from specific manufacturers |
| First aid kit chemicals | Maintain viable supplies | Establish shelf life from specific manufacturers |
| Repair kit chemicals | Maintain viable supplies | Establish shelf life from specific manufacturers |
| Chemical snap-lights | Maintain viable supply | Shelf life is 1 to 4 yrs depending on manufacturer |
| Batteries for permissible blower system | Maintain viable supply | Establish a test interval, and recharge as necessary. Allow for extra battery capacity as back up |
| Chemical cooling packs | Maintain viable supply | Establish shelf life per manufacturer. Protect for storage if snap-activated |
| Desiccants for humidity control | Maintain viable supply | Establish shelf life from specific manufacturer |

*Table 16. Design factors for permissible electrical components*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Blower lubrication | Any gas pumps managing $O_2$ only should not have any oils or lubricants as they can spontaneously combust in $O_2$, | $O_2$ introduced should be blended with compressed air, or added directly from cylinder. |
| Back up system | Provide sufficient backup systems. | Back-up battery power or manual hand crank air pump should be provided as a back up. |
| Heat addition | Ensure heat production within safe limits. | Measure heat output, add chemical cooling methods if required |

*Security and storage of emergency supplies* - The life support components and supplies in the station must be secured and restrained so that moving the station frequently does not damage or dislodge them. Space may also be at a premium in the occupied stations, so efficient storage of supplies is important while maintaining easy access to supplies. In the case of soda lime cartridges used for $CO_2$ scrubbing, many of these are required in the station taking up a lot of space; however, they may be stored under the seats or stacked high in one corner to free up space for the occupants. Table 17 summarizes design factors for security and storage of emergency supplies.

*Psychological factors* - Design factors regarding psychological issues consider personal space, privacy issues, and provisions that reduce panic and improve morale. These issues can be fairly easily incorporated to a station, and should not be discounted considering the situation. The

*Table 17. Design factors for security and storage of emergency supplies*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Cylinder storage | Must be safely restrained. Must be easily reached. Minimize space required. | Cylinders are allowed to be stored vertically or horizontally in refuge stations, but should be restrained to prevent relative movement during transport. Place cylinders in dedicated pockets or rigid frame cages. |
| $CO_2$ scrubber cartridges/curtains storage | Prevent exposure to air. Prevent impact damage. Minimize space required. Must be easily reached Provide storage for used components. | Provide drawers or stackable structural containers that can restrain motion. (Suggestion: restraints designed for some no. of G's force in any direction) Store packages so as to minimize space required, and allow for storage of used scrubber packages as they accumulate. |
| Food/water storage | Minimize space required. Must be easily reached Must remain sealed until used. | Stackable containers with a small footprint are ideal. |
| Chemical snap lights | Prevent prematurely activation due to impact. | Protect the airtight packaging, place in rigid tubes or restrain in boxes for storage. Provide more than minimum anticipated to allow for extra duration or extra light when needed. |

miners may have arrived at the station already injured, burned, and in shock. Current opinion is that station occupancy duration is expected to be in a range of 4 days versus up to 2 weeks, the criteria specified in the earlier Foster-Miller 1983 report [14]. For a duration of 4 days, serious, long term psychological issues are of less concern. Design factors here mainly address improving quality of existence and comforting those injured. Table 18 summarizes the design factors pertaining to psychology.

*Table 18. Design factors pertaining to psychology*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Personal space | Provide sufficient space. | FMI 1983 Guidelines report recommends 15 sq. ft per person |
| Privacy | Provide sufficient privacy for toilet use. | FMI 1983 Guidelines report recommends 2 toilets per shelter. Several shelter designs offer a screened off area for toilet use, some are located in the airlock |
| Information and instruction | Provide information and instructions usable by station occupants. | Provide charts of shelter operation procedures, gas ppm level charts to consult, first aid procedures, phone No.s for all mine areas and mine surface contacts |
| Entertainment provisions | Provide appropriate activities. | Provide paper and pencils, books, modeling clay, chess game, trivia questions etc. |
| Lighting | Provide sufficient lighting for station operation and maintenance. | The chemical snap lights start out bright and slowly fade. Provide several sources of light for reassurance. Cap lamp light can be rationed, but a single stationary light source may be preferred. |

### 5.3    Portable Chambers Design Parameters

### 5.3.1    Damage Resistance

General handling of the chambers may be done by equipment such as a mine scoop, which will need to be able to reach under the chamber and pick it up enough to proceed down mine crosscuts and entryways.  Skids provided under the chambers must be sized for compatibility, and designed to withstand the impact forces applied.  Typically a mine scoop will require at least 1 to 2 feet of clearance to successfully pick and move an object in the mine.  Since head room will be at a minimum, chambers should be strong enough to withstand impacts to the roof and sides of the container as well as the base skids.  In some cases, the chambers may not be picked up but dragged from location to location.  All protruding exterior controls/handles should be suitably armored for handling damage as necessary, or shielded by a chamber exoskeleton
.

### 5.3.2    Anchorage

Of the portable refuge chambers currently approved by West Virginia, the fully stocked weights are roughly in the range of 10,000 lb to 20,000 lb.  These chambers are heavy due to the structural integrity requirements, but still light enough to be moved around by mine equipment. The forces generated in any given explosion within a coal mine may mean that portable refuge chambers are subjected to forces large enough to move them during a blast. If this should occur, collision damage to exterior hardware, access doors and controls may render the chamber unusable, or in the case of a soft-sided deployable chamber forces may move it to a position which prevents deployment.  For this reason it is necessary to consider anchoring portable shelters in place each time they are relocated although anchoring may cause more damage under certain conditions.  Typically the approved chambers are rigid box structures mounted on a skid for ease of transport and this type of base could be modified to allow for jack stabilization or bolting if necessary.  Placement of the chambers is also a factor, since any existing raised areas in the floor or ribs may provide opportunity to restrain the portable chamber thus helping to resist movement caused by blast forces.

### 5.3.3    Structural Integrity

The portable refuge chambers are divided into two main categories: rigid and soft-sided deployables.  For the deployable types, they are typically stowed in an explosion resistant container until a post event need arises.  Once the initial explosion or high pressure event has occurred and been resisted by the rigid container, the deployable section can be extended from the container to house the occupants, and this takes the form of an air beam or frame supported tent.  As shown in Table 19, factors of permeability, tear resistance, leakage, and pressure loads must be considered in design.  These soft-sided deployable chambers provide an area of breathable air and a survivable ambient environment for the duration of refuge but are not designed to withstand any large external forces.

*Table 19.  Structural integrity design factors for soft-sided deployable chambers*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Tent Fabric | Should be tear resistant. Should be very low or non-permeable. Should be moisture (humidity) resistant | Establish an acceptable tear resistant specification, and provide rapid repair kit. Overpressure the chamber by any measurable amount to prevent gas incursion.  Materials list should indicate whether moisture will be a problem. |
| Airbeams | Must not leak and deflate. Must not be affected by temperature variation. Must initially deploy from storage successfully. | Airbeams must be capable of maintaining pressure until miners are rescued or provide for a manual air pump to re-inflate.  Specific materials should emulate existing proven airbeams in military uses etc. |

### 5.3.4  Inspection and Maintenance (Portable-Specific)

Portable chambers will have their own atmosphere management system unless they are outfitted specifically with a borehole fed supply.  Atmosphere management and structuralintegrity are the most important functions to maintain.  Along with the common factors mentioned above for inspection and maintenance, the portable chambers may be susceptible to shifting of contents.  Items must be restrained to prevent damage.  Restraints should be checked before and after every chamber relocation.  As mentioned in Section 5.3.2, whenever relocation takes place the chamber must be oriented correctly if it is a deployable type, to avoid restriction of hatches, and provide enough room for the chamber to fully deploy.  Verifying this clearance must be part of the inspection procedure for these chambers, as well as keeping areas in the path of deployment clear and free of debris.  Deployment of inflatable chambers should be considered when developing initial and refresher training instruction.  It may not be necessary to deploy soft-sided chambers or to operate the atmosphere management system as part of a routine inspection; however, controls and systems should be checked thoroughly and attention paid to any developing threats to successful operation such as general corrosion, stuck valves, and frozen hatch covers.  Portable chambers may also encounter damage during transit, and inspections may need to consider this. A summary chart of specific inspections is shown below in Table 20.

*Table 20.  Inspections specific to soft-sided deployable refuge chambers*

| Items to Inspect | Concerns | Possible Approaches |
|---|---|---|
| Check for any shifting of contents in shelter | Are the crucial supplies restrained and intact? | Check for play in the restraints on supplies and gas cylinders, tighten as necessary |
| Check access to activation controls for inflatable shelters, and clearance for operation | Are the hatch covers easily opened? Are there any physical items near shelter that would obstruct inflatable deployment? Is there enough height/width/length for deployment? | Clear the area as necessary |

### 5.4  Fixed Bulkhead Refuge Station Design Parameters

Besides portable refuge chambers, a second method of providing refuge areas in a coal mine is to create an enclosed area by constructing bulkheads to form a chamber or room by either:

1) Blocking off part of a crosscut using two bulkheads, or
2) Sealing off a blind heading with a single bulkhead.

The designs of these bulkheads can vary, depending on the degree of permanence desired:

- Permanent designs, intended to be never moved.

- Reusable designs, in which major components can be disassembled and re-used at a new location.

- Lightweight and/or quickly erected bulkheads.

The major differences between portable chambers and bulkhead style stations are as follows:

- Portable chambers can be more easily relocated, and are therefore best suited for deployment where the required location is constantly changing (e.g., within 1000 feet of working faces).

- Bulkhead-based stations can be much bigger, are more easily adapted to equip with a borehole (the gold-standard for atmosphere control), and can be multi-purpose (storage of supplies, underground lunch room or office).

Ideally these bulkhead-based refuge stations should be constructed around a borehole opening which would supply the fresh air and venting necessary for life support.

Bulkhead seals have been used in mines for two specific reasons:

1) Ventilation stoppings which divide the intake air from return air, ensuring fresh air reaches the working faces without short-circuiting.

2) Gob seals to form explosion-proof bulkheads which seal off unused or abandoned parts of a mine to prevent explosions.

In the case of using a bulkhead to form a refuge station, the intent is to provide a refuge area that can survive an initial event (such as a methane explosion or mine fire) and still be able to provide a life sustaining atmosphere to trapped miners who are awaiting rescue.  Mine gob seals are traditionally very massive structures, laborious to construct, and once built, are left permanently in place.  Directly adapting them for refuge station use is impractical and unnecessary.  Ventilation stoppings are generally considered too weak to serve as refuge

bulkheads.  An optimal approach for refuge bulkheads is be to make them easily constructible and either re-useable or easy to duplicate in a new location.

Current stand-alone portable refuge chambers can generally be readily deployed in a range of mines since they are largely independent of the rock conditions and floor, roof, and rib surface undulations.  Fixed bulkhead refuge stations must be tailored to each specific location in a given mine to achieve a successful structure and seal.  This requires that bulkhead stations be somewhat adaptable to their surroundings.  In a previous Foster-Miller effort ("Design of Reusable Explosion-Proof Bulkheads for a Cross-cut Refuge Chamber," Maser, Kingery and Hoadley, 1975) [21], three types of in mine constructible steel bulkheads were successfully developed which collectively covered the expected range of mine conditions, and the seals in these designs were designed to survive up to 40 psi static pressure.  All three designs were successfully tested in underground methane/air explosions.

Less rigid structures could be deployed after an underground event such as an explosion.  These include alternatives such as inflatables, free-floating curtain seals, or valved openings which may be able to accommodate an initial explosion and then settle into place as an airtight seal for refuge areas.

For any bulkhead expected to withstand an explosion, an overpressure design specification is required.  In Section 8 of this report, we present an analysis and recommendation of 15 psi overpressure for 0.3 seconds.  Currently West Virginia has mandated a level of 15 psi (static, for 3 seconds) for portable refuge chambers.  The MSHA proposed rule specifies 15 psi overpressure for 0.2 seconds.

The remainder of this section discusses the major design considerations for bulkhead-based stations, covering only those topics which differ from those already discussed for portable chambers.

### 5.4.1  Main Structure

Design factors for the refuge station bulkhead structure include:

- Design limit for peak overpressure expected.

- Pressure-time curve of an explosion.

- Structural damping of the system (negative pressure and rebound).

- Reflected pressure based on how far down the crosscut it is located.

- Temperature resistance by the bulkhead in the event of a short term flash fire from an explosion.

Consideration must be given to a mine fire in close proximity to the refuge bulkhead and the duration and extent of a fire must be evaluated when developing the fire resistance criteria.  For example, West Virginia specifies a flash loading of 300°F for 3 seconds.

Verification of structural integrity including full-scale testing must be considered.

Specification of materials must consider:

- Ease of assembly.
- Transportability underground.
- Standard sized structural shapes (economical consideration).
- Material type restrictions, if any.

Table 21 summarizes the design factors related to structural integrity for fixed bulkhead refuge stations.

*Table 21.  Fixed bulkhead structural integrity design factors*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Design limit for peak overpressure | Survive peak overpressure anticipated during a mine explosion | Perform analysis to determine minimum pressure requirement. |
| Pressure-time curve of an explosion | Survive dynamic load/unload from blast wave | Perform analysis to determine pressure-time curves. |
| Structural damping | Provide sufficient damping | Perform analysis. |
| Reflected pressure | Minimize reflected pressure | Perform analysis. |
| Temperature resistance | Prevent damage to the bulkhead and/or seal from flash fire. | Perform material evaluation. |
| Safety Factor | Select appropriate safety factor. | Use engineering judgment.. |

### 5.4.2  Anchorage

Anchorage will affect bulkhead performance. Anchorage parameters include:

- Minimizing labor required to install.
- Adaptability to varying seam conditions.
- Suitability to floor, rib, and roof applications.

The methods of anchorage include:

- *Jacks* – Consider factors related to creep, possible loss of hydraulic pressure in the jacks, and spacing.

- *Trenches* – Suitable for some parts of the bulkhead perimeter.  Trench edge geometry, depth of penetration, width, fill material are all considerations.

- *Rock Bolts* – Suitable for different parts of the perimeter.  Requires anchorage mechanism or bonding agents.

- *Bearing Supports* – Dependent on bearing strength of host strata.

### 5.4.3  Sealing

All bulkheads require some form of seal or sealing material to bridge the gap between the edges of the bulkhead and the surrounding roof, ribs, and floor.  The seal has several functions including:

- o  Preventing gas transfer.
- o  Surviving an initial overpressure event.

In developing the design criteria for sealing the bulkheads several factors were considered:

- Structural analysis of the seal between bulkhead and surrounding rock surfaces including flexural, compressive and shear loads at the rock-seal interface.

- Minimizing the number and size of joint to be sealed.

- Consideration of the size of air gap in to be sealed, including surface irregularities and warp.

- Accommodation of surface irregularities.

- Seal strength required depending on the size of the gap.

- Flame and temperature requirements.

- Degree of resilience and expected deformation to accommodate movement.

The following factors were also considered in developing the seal design criteria with regard to sealing materials and their application:

- Sealant type.
- Sealant composition.
- Method of application.
- Temperature specifications.
- Physical properties.

Table 22 summarizes the design factors for sealants for fixed bulkhead refuge stations.

*Table 22.  Fixed bulkhead refuge station sealant design factors*

| Factor | Criteria | Possible Approaches |
|--------|----------|---------------------|
| Sealant type | Must meet performance requirements. | Well trusted materials should be used if they meet specifications. |
| Sealant composition | Compatible with other bulkhead materials. | Material should be analyzed/tested for compatibility, joint integrity. |
| Method of application | Suitable for in-mine construction use. | Select a practical set time based on mine logistics. |
| Temperature specifications | Material must meet temperature requirements | Analyze/test materials for temperature limits if not clearly understood. |
| Physical properties | Optimize material properties for requirements | Investigate to determine range of material options. |
| Gap size range | Must perform in anticipated gaps. | Materials should be analyzed/tested to determine range. |

### 5.4.4   Site Preparation

There are several factors to consider in site preparation.  It is necessary to look for problems such as floor heave, rib slough, bedding separation, and signs of convergence.  Analysis may be required to estimate what the future convergence potential is before proceeding with construction.  In addition, choosing the exact underground location must be coordinated with other factors, such as access from the surface.

The site selected for a seal must allow loose rock removal down to stable strata for a specified depth.  Plans for all objects passing through the seal location such as roof mesh, straps, rails, pipes and wires must be developed.  The use of keys may be required and their size and specification established.  The need for supplemental roof support should be determined on both the inby and outby sides of the seals.  Specific plans for site inspection at various steps during the installation process such as after the preparation phase and prior to the bulkhead construction are necessary.

### 5.4.5   Ease of Assembly, Equipment Required

Assembly should primarily require common mining tools for construction, such as continuous miners, cutting machines, hand and post mounted augers, jackhammers, small electric drills, roof bolting machines, and small hand tools.  Use of electric or compressed air power should be consistent with mining procedures and environments.  The required placement accuracy should not exceed what is normally required for routine mining operations.

### 5.4.6   Consideration for Station Entry, Exit, and Airlocks

Use of airlocks, purge capacity, or both may be used to rid the station of noxious gases that may enter with the miners.  Measuring instruments are necessary to monitor gas levels and adjust air systems as necessary for survival.  These factors are similar to those required for portable chambers.

Bulkhead refuge station location dictates the number of bulkheads required (e.g., two bulkheads to enclose the station in a crosscut, or one bulkhead in a blind entry). Bulkheads require an airlock or other method to restrict contaminated air from entering the station. Overpressure can help prevent noxious gas incursion.

### 5.4.7 Atmosphere Management

Atmosphere management can be provided using either a borehole, compressed air line or self-sufficient supply and scrubbing systems.

- *Boreholes* (with a surface-mounted fan) are the gold standard for refuge stations. Oxygen is assured, carbon dioxide and other noxious gases are controlled by dilution with fresh air, and communication and even food and water can be provided via the borehole. Borehole size and supply flow are determined based on station size and maximum number of occupants.

- *Compressed air lines* provide the same air benefits as boreholes. If the air lines are in the mine, they must be protected from damage from an explosion.

- *Breathable air sealed systems:* If a borehole or external compressed air supply is not provided, an atmosphere management system must be provided and will be similar to the systems used in stand alone portable refuge chambers described in detail in Section 5.2.2. All the same criteria applied to portable chamber air systems apply to bulkhead refuge stations, including provision for maintaining oxygen levels, scrubbing $CO_2$, and systems for scrubbing or purging CO. Apparent temperature must be maintained to a tolerable level. Survivable conditions must be maintained in the station until the miners are rescued.

### 5.4.8 Inspection and Maintenance (Bulkhead-Specific)

Inspection and maintenance of a bulkhead-constructed station is similar to the requirements for portable chambers (especially as they relate to inspection of stores and equipment inside), and will not be repeated here; however, portable chambers arrive prebuilt and certified from a vendor. Bulkheads are built on site, and therefore have unique issues of supervision and sign-off during construction, and then a follow-up inspection of the structure and surrounding strata.

The NIOSH PRL produced a draft report on "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" [18]. It provides detailed design considerations for gob seals. This provides an excellent framework from which to consider the same factors for the bulkhead refuge stations. The following is a summary of gob seal design criteria related to construction and inspection.

The four actions of a Professional Engineer (P.E.) with regard to new gob seals (from Federal Register, 30 CFR part 75, May 22, 2007) [19] are:

1. Determine analysis methods and select materials for seal construction.
2. Perform analysis, prepare drawings and design calculations.

3. Select test methods for the materials, for during and after seal construction.
4. Develop construction procedures.

Furthermore, supervision and signoff requirements include:

- The P.E. must oversee seal installation.

- There must be a mine map showing the location of the seal.

- The site preparation should include an estimate of dimension increases due to site preparation, removal of weak or friable surfaces, consideration of the local geology, and possibly anchorage pull out tests. Convergence is a crucial issue for some designs.

- For maintenance and inspection, there should be a chart of monitoring, training, and approvals.

- Roof and floor rock must be stronger than the compressive strength of the seal, so that the arch is able to resist the compression.

- Removal of metallic objects through or around seal.

- Miners in their normal inspection activities are to perform non-structural repairs only: for air leaks, minor cracks, water drainage systems, and sampling pipes.

Table 23 summarizes the design factors related to inspection and maintenance for fixed bulkhead refuge stations.

*Table 23. Fixed bulkhead refuge stations design factors*
*for inspection and maintenance*

| Factor | Criteria | Possible Approaches |
|---|---|---|
| Inspection frequency | Ensure station is operational. | Daily visual inspections, less frequent inventories and equipment inspections. |
| Material storage | Ensure materials are properly stored. | Materials may need to be protected from moisture or other damage. |
| Seal permeability | Ensure seal is intact and proper gap exists. | Measure local roof height regularly to monitor convergence. |
| Pressure differential | Ensure pressure differential is within specifications | Pressure differential may be measured with existing instrumentation. |
| Air systems | Ensure borehole is operational and unobstructed.<br><br>f non-borehole ensure all supplies are intact and the atmosphere management system is operational. | Inspect borehole for flow rate. Perform supply inventory. Inspect controls. |
| Rock inspection | Ensure rock integrity around the seal area and station roof. | Inspect the local rock for any sloughing or convergence. |
| Water | Station should remain dry. | Any accumulated water should be removed. If water ingress cannot be managed, station should be moved. |

### 5.4.9  Height/Width Adjustability

The bulkhead design should accommodate some adjustable height or width elements, to minimize the seal gap where the passage geometry varies.  Without this adjustability, the seals must be designed for large gaps that may occur.

### 5.4.10  Allowance for Convergence

The action of mining can cause local ground motions including heaving of the floor and sagging of the roof.  These movements can be as much as several inches over the life of a bulkhead.  This convergence movement can cause compressive forces where a bulkhead exists, which must be tolerated by the bulkhead and/or its seal.  Design of the bulkhead seal must include an estimation of the convergence that may be likely.

### 5.4.11  Corrosion Resistance

Normal mine atmosphere tends to be damp and acidic, which can accelerate corrosion.  There is also a possibility of water build up against the bulkhead wall from ground water at low spots in the mine, although ideally the station will be located so as to avoid this.  The materials used in refuge bulkheads must address and provide for adequate protection against corrosion.

### 5.4.12  Roof Support

The roof area of the refuge station must be supported to prevent rock falls due to sloughing, by typical mine methods, such as roof bolting and mesh application.  Roof strata may be adversely affected by moisture build up.  Local support of the roof inby and outby the bulkhead wall is needed especially to protect the integrity of the seal should the rock become loose.

### 5.4.13  Standby Ventilation

Gas levels need to be monitored and vented as necessary to reduce any internal explosion risk or the accumulation of other toxic or noxious gases (blackdamp, etc.) resulting from an enclosed volume with exposed coal and rock.

### 5.4.14  Component Ruggedness, Weight and Size

Components for the refuge station bulkheads must be easily transportable throughout the mines on some form of mine transportation vehicle.  For rapid, efficient assembly by at least two men, no individual component of the bulkhead assembly should weigh more than 150 lb. The mine environment and conditions should be evaluated relative to the storage and use of bulkhead materials.

### 5.4.15  Approaches to Fixed Bulkhead Design for Refuge Stations

In previous work, Foster-Miller developed three steel bulkhead designs for refuge stations [21].  These designs were reviewed as part of the bulkhead design effort.

New material technologies such as lightweight composites, reinforced air beams/airbags, and high tensile textile netting are available for use in new bulkhead designs.  Candidate materials include:

- *Inflatable Structures* – Air beams, airbags, and their associated technologies will be evaluated for bulkhead applications.  Larger and higher pressure inflatables have emerged in recent years, and a wider range of shapes is now possible.  Inflatables may need to be coupled with an exo-skeleton structure to guide force vectors and corral their shapes.

- *Composites* – Blast resistant composite panels have been successfully employed in many military and industrial applications, (e.g., aircraft carrier jet thrust drop barriers).  Only nonflammable materials can be used.

- *Frag-Bags* – These bags have been shown to perform well in containing explosive materials or as armor protection and have possible bulkhead application.

- *High Tensile Netting* – Tough, durable netting using materials such as Spectra and Kevlar may be suitable use for soft bulkheads.

- *Tapered Blocks with Arching Geometry* – Through the use of special geometry blocks it may be possible to take full advantage of the rigid arching that can occur with a transverse load against a bulkhead.

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## 6.  *Refuge Location Analysis and Recommended Use*

### 6.1   Introduction

In Section 3, we reviewed 42 past mining disasters and assessed the impact refuge stations would have had on the final outcomes of 38 of those disasters most applicable to the project. Section 6 describes a further analysis of these disasters to reach conclusions and recommendations on the placement of stations within underground coal mines to help save miners lives in the event of future disasters.  To do this, we engaged in a two-pronged approach:

1. We conducted an additional review of all 42 disasters to determine if the point of origin of the disaster (fire, explosion, etc.) occurred at a working face or some distance away and how this might correlate with the outcome on miners lives and therefore on the placement of stations.

2. We selected a subset of those disasters that were most relevant for the potential of stations to save miners lives and studied them in greater depth to more accurately pinpoint how stations might have been used in those cases.

Based on these studies, we were able to reach final conclusions and provide a series of recommendations for the use of stations in coal mines.  The following subsections present the results of these studies and our recommendations for the use of refuge stations.  A bibliography listing the resources we used to conduct the analyses on this project is provided in Appendix C. The bibliography also includes contact information for those individuals that either met with us regarding the project or provided us with some of the materials used in the analyses.

### 6.2   *A Study of the Locations of Mine Disasters Within the Mines*

An additional review was conducted of all of the 42 disasters to determine if the point of origin of the disaster occurred at a working face or some distance away.  This was expected to shed light on how the point of origin of a disaster might correlate with the outcome on miner's lives.  In the case of explosions, for example, it was assumed that an explosion right at the working face would instantly either kill or severely injure the miners in the area, limiting the potential ability of a refuge station to have a positive impact.  Explosions elsewhere in the mine, on the other hand, would be expected to have a less dramatic impact on most of the affected miners.

In the case of mine fires or gas inundations, the reverse could be true.  A fire or gas inundation near the working face would likely be discovered quickly and miners on the working section would probably be able to readily escape through an intake escapeway.  Fires or inundations in outby areas, on the other hand, might not be discovered and communicated to inby miners in a timely manner and could contaminate intake airways or belt entries leading into working sections.

Tables 24, Table 25, and Table 26 present the basic data from this review.  Because of their differing impact on disaster outcomes, explosions and fires/inundations are tabulated separately.

For completeness, a third table lists remaining disasters of the total 42 that are not applicable to this review.

*Table 24.  Mine explosions*

|  | Mine | Explosion at Face Area? |
|---|---|---|
| 1 | Darby Mine Explosion | No – 1000 ft away; 2 victims near explosion died instantly; 3 in face died later |
| 2 | Sago Mine Explosion | No – 2300 ft outby; 1 victim near explosion died instantly; 11 in face died later |
| 3 | Pyro No. 9, William Station Explosion (1989) | No – 450 ft inby; 4 victims along longwall face closest to explosion died instantly; 6 further from explosion died later |
| 4a | Scotia Mine Explosion – 1st explosion | No – 800 ft inby; 6 of 15 victims killed instantly; of 9 others near face, 3 likely survived a short time and 6 others died in barricade |
| 4b | Scotia Mine Explosion – 2nd explosion | No – 2500 ft inby; all 11 victims located in an outby area died instantly |
| 5 | Oakwood Red Ash Explosion | No – 6000 ft away; 2 victims near explosion were not killed instantly |
| 6 | Itmann No. 3 Mine Explosion | No – 1000 ft outby; of 8 miners near explosion, 5 were killed (instantly or nearly so) and 3 were injured |
| 7 | Blacksville No. 1 Fire and Explosion (1972)* | No – occurred between mine fire and face area (report is not specific on location); no deaths were related to this explosion |
| 8 | Finley 15 and 16 Mine Explosion | No – 150 to 1500 ft away; 33 of 38 affected miners were killed instantly |
| 9 | Pyro No. 2 Mine Explosion | No – 1 of 2 men surveying old works died; the other escaped; explosion occurred a considerable distance from active areas (data not provided); no other miners affected |
| 10 | Jim Walters Resources, Inc., No. 5 Mine | No – 2 explosions: one (minor) about 400 ft outby the faces; the other (major) about 1,000 ft outby the faces; the major explosion killed 12 of 13 victims instantly, none near faces at the time |
| 11 | Southmountain Coal Co., Inc. -  No. 3 Mine | Yes (or very close); 8 of 9 victims killed instantly |
| 12 | McClure  No. 1 Mine | Yes (or very close); 3 of 7 victims killed instantly; others too injured to escape |
| 13 | RFH  Coal Co.,  No. 1 Mine | Yes; 2 of 7 victims killed instantly; others too injured to escape |
| 14 | Grundy Mining Co.,  No. 21 Mine | Yes (or very close); all 13 victims killed instantly |
| 15 | Adkins Mining Company, No. 11 Mine | Yes; all 8 victims killed instantly |
| 16 | Mid-Continent, Dutch Creek  No. 1 Mine | Yes; all 15 victims killed instantly |
| 17 | Westmoreland Coal Co., Ferrell No. 17 Mine | No – distance from active faces unknown; 5 miners retrieving track in an abandoned area and all 5 victims killed instantly |
| 18 | R&D Coal Company, Inc. Mine | Yes; all 1 victim killed instantly |

## Table 24.  Mine explosions (continued)

| | Mine | Explosion at Face Area? |
|---|---|---|
| 19 | Plateau Mining Corp., Willow Creek Mine | Yes; all 2 victims killed instantly |
| 20 | A.A. & W Coals Inc. Elmo  No. 5 Mine | No – one miner alone in old works died instantly or very soon after igniting methane; explosion was about 2,000 ft inby active section; only one miner on the active section was injured |
| 21 | Fire Creek Inc.  No. 1 Mine | Yes (but no active mining in progress); all 2 victims killed instantly |
| 22 | Granny Rose Coal Company, No. 3 Mine | Yes; all 3 victims killed instantly |
| 23 | Double R Coal Co.,  No. 1Mine | Yes (or very close; victim alone in mine) |
| 24 | Mid Continent Inc., Dutch Creek  No. 2 Mine | Yes; none killed instantly; all escaped and one died in hospital |
| 25 | Pyro No. 9, William Station Explosion (1986) | Yes; none killed instantly but 2 of 3 injured; one died one week later |
| 26 | M.S.W. Coal Company, No. 2 Slope Mine | Yes; 5 miners in area: 3 died; 2 killed instantly |
| 27 | Greenwich Collieries No. 1 Mine | Yes; all 3 victims killed instantly |
| 28 | Helen Mining Co., Homer City Mine (1983) | No – explosion occurred in a section inactive due to mine vacation; distance to faces unknown (without access to mine maps); victim alone conducting fire patrol ignited methane |
| 29 | P and P Coal Company, No. 2 Mine | No – all 4 miners retrieving equipment from old works died instantly; explosion occurred a considerable distance from active areas (data not provided); 16 miners in other areas escaped |
| 30 | Helen Mining Co., Homer City Mine (1970) | Yes; 5 miners in area: 3 injured and 1 killed |
| 31 | Clinchfield Coal Co., Compass  No. 2 Mine | No – one miner died while traveling alone when his personnel carrier ignited methane; distance to active areas unknown (without access to mine maps); mine was idle at the time |
| | *Note that this explosion occurred some time after a mine fire had developed.  This disaster is also shown in the table below related to mine fires. | |

## Table 25.  Mine fires/inundations

| | Mine | Fire/Inundation At Face Area? |
|---|---|---|
| 32 | Emery Mining Corp - Wilberg Mine Fire | No (about 2,200 ft outby longwall face); 27 victims of 28 miners in face area |
| 33 | Blacksville No. 1 Fire and Explosion (1972)** | No (1,900 ft and 3,500 ft outby two longwall working sections); 9 of 9 victims |
| 34 | Aracoma Coal Co., Inc, Alma Mine  No. 1 Fire | No (about 3,500 outby working section); 2 victims of 12 miners escaping face area |
| 35 | Buckeye Coal Co., Nemacolin Mine Fire | Yes (3 crosscuts - about 300 ft outby faces); 9 of 10 miners in section escaped and 1 died; 2nd victim was found about 1,100 ft outby |
| 36 | Grays Knob Coal Company, No. 5 Mine | Yes (inundation of $CO_2$; 3 miners in face area died; others escaped) |
| | **Note that this fire included an explosion that occurred some time after the fire had developed.  This disaster is also shown in the table above related to mine explosions. | |

*Table 26.  Disasters not applicable to this study*

|    | Mine (not applicable to this study) | Nature of Disaster |
|----|-------------------------------------|--------------------|
| 37 | Black Wolf Coal Co., Quecreek  No. 1 Mine | Inundation of water; no deaths; all 9 miners impacted were rescued |
| 38 | Consolidation Coal Co., Loveridge  No. 22 mine | Suffocation in coal storage bin |
| 39 | Clinchfield Coal Co., Moss  No. 3 Portal A Mine | $CO_2$ inundation 265 ft from surface of mine |
| 40 | Kocher Coal Corporation, Porter Tunnel Mine | Water inundation in multi-level anthracite mine |
| 41 | Jim Walters Resources, No. 4 Mine | CO asphyxiation in an outby area |
| 42 | R and R Coal Company, No 3 Mine | CO asphyxiation near mine surface following a production blast with explosives |
| 43 | Consolidation Coal Co., Blacksville  No. 1 Mine (1992) | Above-ground explosion at production shaft |

### 6.2.1   Analysis and Conclusions

For the 32 mine explosions reviewed (including two separate explosions at Scotia), 16 occurred at a working face area while the other 16 occurred some distance away from a face area or elsewhere in the mine.  Of the 16 explosions occurring at the working face, all of the miners who perished were killed instantly in eight of them.  In four others, some of the miners were killed instantly and others died some time later.  In two other explosions, one miner in each explosion died in the mine but the time of death is unknown.  In the remaining two explosions, one miner in each explosion died after being removed from the mine.

Of the 16 explosions *not* occurring at a working face, only six explosions directly affected miners who were working in face areas at the time of the explosion.  Of these six explosions, three resulted in the deaths of face area miners but none were killed instantly; all were killed later while attempting to escape or awaiting rescue.  In another two explosions, some or most of the face area miners *were* killed instantly due to the violence of the explosion.  In one of the explosions, a face area worker was injured but not killed.

Of the remaining 10 of the 16 explosions *not* occurring at a working face, seven events affected only the miners who were in the vicinity of the explosion.  Miners in face areas were not affected.  In all of these cases except one, all of the miners in the immediate vicinity of the explosion were either killed or injured.  In only one case, a miner in the immediate vicinity of the explosion was able to escape uninjured.  In two additional explosions (the second explosion at Scotia and the explosion at Jim Walter No. 5 Mine), miners some distance outby the point of origin of the explosion were killed (and most of them instantly) by the violence of the explosion.  One explosion (Blacksville No. 1 Mine) was minor and had no effect on any of the miners.

Of the four mine fires that were reviewed, three originated a considerable distance from face areas.  In the Wilberg fire, 27 of the 28 miners present in the longwall face area perished trying to escape the smoke and gasses from the outby fire.  In the Blacksville fire, all 9 of the miners in two face areas perished trying to escape the smoke and gasses from the outby fire.  In the Alma

fire, 2 of 12 miners escaping the fire became separated from the rest of the group and perished. In the Nemacolin Mine fire, which did occur near the working faces, one of 10 miners escaping the fire left the group and perished while another miner attempting to escape separately was not successful.

One gas inundation was represented in the study, occurring right at the active face area. In the Grays Knob $CO_2$ inundation, all but three of the crewmembers were able to escape while three perished.

Generally, the above conclusions supported our expectations. Explosions occurring right at working faces killed all or some of the affected section miners instantly in most cases, while face area miners were *not* killed instantly in most cases of explosions occurring away from the face. In cases of particularly violent outby explosions (Scotia, Jim Walters and Finley, for example), face area miners still died instantly from the explosions.

In the case of the four fires studied, one of them (Nemacolin) originated close to the working faces, was discovered immediately by section personnel and most of the miners were able to escape quickly. The other three fires occurred well away from face areas and two of them resulted in significant loss of life because they were not communicated to face areas in a timely manner and escape routes were blocked.

The results of this study show that in nearly all cases, it is disasters that occur away from the face areas that provide the best opportunity for underground refuge stations to have an impact in saving miners lives. Unfortunately, face area explosions with sufficient forces to kill miners will kill most of them instantly, rendering stations irrelevant in most cases. Explosions away from face areas on the other hand allow surviving miners an opportunity to attempt escape or to seek refuge in stations if escape is not possible. Stations are also very viable in saving miners lives in the cases of fires originating away from face areas where smoke, gasses and heat block the miners escape routes.

### 6.3   Detailed Analyses of Selected Mining Disasters

In Section 3, we assessed whether a refuge station would have had a "positive," a "neutral" or a "negative" impact on the miners affected by the disaster if a refuge station had been present in the mine at the time. We did this for two basic situations:

1.  Situations in which the miners escaped successfully, did not escape but were rescued or barricaded and were rescued.

2.  Situations in which the miners died attempting to escape, barricaded and perished, or were too injured to escape and were either rescued or perished.

Clearly the most important impact that refuge stations might have had on the outcomes of the disasters are those situations in which the stations might have saved miners lives, i.e., in which they would have had a "positive" impact on miners who died (Situation 2 above). There were 12 such mine disasters and a key part of this analysis has been to re-evaluate those twelve disasters in greater detail. It is notable that all but one of these 12 disasters originated well away from

73

face areas, hence correlating well with the conclusions reached in the study of disaster locations discussed in the previous subsection.

The objective of this more extensive study of the 12 select disasters was to determine as accurately as possible, based on the specific situations of each disaster, where the affected miners were located when they died and what environmental or physical conditions they might have been subjected to.  The intent was to help determine where a refuge station might have best been located to provide the greatest chance of saving the miners lives and, to the extent possible based on the information available, the conditions that a station would have had to endure (i.e., fire, explosion forces, etc.).

The twelve mine disasters selected for further study were (in reverse chronological order):

1.  Darby No. 1 Mine Explosion – May 20, 2006.
2.  Aracoma Alma No. 1 Mine Fire – January 19, 2006.
3.  Sago Mine Explosion – January 2, 2006.
4.  Pyro William Station Mine Explosion – September 13, 1989.
5.  Wilberg Mine Fire – December 19, 1984.
6.  Scotia Mine Explosion – March 9 and 11, 1976.
7.  Oakwood Red Ash No. 4 Mine Explosion – September 25, 1973.
8.  Itmann No. 3 Mine Explosion – December 16, 1972.
9.  Blacksville No. 1 Mine Fire – July 22, 1972.
10. Nemacolin Mine Fire – March 26, 1971.
11. Finley No. 15 and 16 Mine Coal Dust Explosions – December 30, 1970.
12. Pyro No. 2 Mine Explosion – November 30, 1970.

For each of these disasters, we attempted to answer a series of key questions:

- Where were the victims found within the mine?  Were they at active working faces, at outby (or inby) areas during an escape from active faces or elsewhere in the mine (at work areas away from active faces, while traveling within the mine, etc.)?

- Where were the miners found with respect to the source of the explosion or fire?

- Where did the source of the explosion or fire occur with respect to working faces?

- If a station had been in place in the mine within 1,000 ft from the face (i.e., per West Virginia regulations [10]), would the affected miners have been able to reach it?

- If a station had been in place in the mine 2,000 ft from the face (i.e., coincident with MSHA's breathable air guidelines [12]), would the affected miners have been able to reach it?
- Would a station at 1,000 ft from the face have been a preferred location compared to a station at 2,000 ft from the face or vice versa?

- Would a station positioned at some location *other* than 1,000 ft or 2,000 ft from the face have been preferred?

- Would flame and/or explosion forces have impacted a station (at 1,000 ft from the face, 2,000 ft from the face or some other location if applicable)?  To what range of explosive forces would a station at each location have been subjected (if such information is available)?

- How long would it have taken mine rescue personnel to reach the affected miners if they were located in a station at 1,000 ft from the face?  At 2,000 ft from the face?

- Would additional outby stations beyond those relative to the face (i.e., at 1 hr travel distances, etc.) have been potentially applicable to the miners?

We focused the above questions on the locations of 1,000 ft from the face and 2,000 ft from the face based on WV regulations and MSHA breathable air guidelines.  Unless there was a compelling reason to choose a station location different than 1,000 ft from the face or 2,000 ft from the face, we preferred to hold the study to a comparison between those two potential locations.  In fact, the results of the twelve detailed studies showed that there was *not* a strong reason in any of the cases to choose an alternative station location.

Table 27 presents a summary of the results of the detailed study of the twelve select disasters and an assessment of the results and conclusions follows the table.  Appendix B provides additional detail related to each of the twelve disasters including a mine map showing the location of the disaster within the mine, locations of the miners who perished, locations where refuge stations would have been positioned at 1,000 ft from the face or 2,000 ft from the face, etc.

### 6.3.1   Analysis and Conclusions

- Of the twelve disasters given further study, eight involved explosions, three involved fires and one involved a fire with an accompanying minor explosion.

- Of the nine disasters involving explosions, none occurred right at a working face.  In the Finley disaster (involving two conjoined mines), the explosion occurred about 150 ft away from one of the working faces but about 1,500 ft away from the other.  In the other eight disasters, the explosions ranged from 450 ft to 2,300 ft away from working faces.

*Table 27. Summary of detailed analyses of 12 select mine disasters from 1970 to 2006*

| # | | Darby Explosion May 20, 2006 | Alma Mine Fire Jan 19, 2006 | Sago Explosion Jan 2, 2006 | Pyro Wm Station Explosion Sept 13, 1989 | Wilberg Mine Fire Dec 19, 1984 | Scotia Mine Explosion Mar 9-11, 1976 | Oakwood Red Ash Explosion Sept 25, 1973 | Itmann No. 3 Mine Explosion Dec 16, 1972 | Blacksville No. 1 Fire & Explosion July 22, 1972 | Nemacolin Mine Fire Mar 26, 1971 | Finley 15 & 16 Mine Explosion Dec 30, 1970 | Pyro No. 2 Mine Explosion Nov 30, 1970 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Where were victims found with respect to working face? | 3 at faces | At face | 11 at face | 4 at face | Various (to 1900' outby) | Mar 9: 13 at face | N/A | 1000' outby | 600-3000' outby | 1 @ face; 1 outby | Various (most @ faces) | N/A |
| 2 | Were some victims in outby areas? | 2 outby (at explosion) | No | 1 outby (at explosion) | 6 at 250' outby | Yes | Mar 11: 11 outby | 2 in old works | Yes, on mantrip | Yes, escaping | 1 at 1100' outby | Yes | 2 in old works |
| 3 | Where were victims found with respect to disaster point of origin? | 3 at 1000' | 3500' outby | 2300' inby | 450-1000' outby (?) | Nearby or inby | 800' outby 2500' outby | At origin | At origin | 500-1200' inby fire | 1 inby; 1 outby | 150-1500' away | At origin |
| 4 | Where did the event occur relative to face (or work area)? | 1000' away | 3500 ft outby | 2300' outby | 450' inby | 2200 ft outby | 800' inby; 2500' inby | 6000' away | 1000' outby | Inby fire; outby face | 300 ft outby | 150-1500' away | Away from face |
| 5 | Would victims have been able to reach a station 1,000 ft away? | Yes | Yes | Yes | Yes (?) | Yes | Yes (some) | Maybe, if present | Maybe, if nearby | Yes (A2&A3) | Yes | Unknown | Yes, if present |
| 6 | Would victims have been able to reach a station 2,000 ft away? | Yes | Yes | Maybe | Maybe (?) | Yes | Yes (some) | Maybe, if present | No | No-A2 Yes-A3 | Yes | N/A | but would not have used |
| 7 | Which station location (1,000 ft or 2,000 ft away) would have been favored? | 2,000 ft | Neither | 1,000 ft | 1,000 ft | 1,000 ft | Cannot say | Cannot say | 1,000 ft (by luck) | 1000 ft-A2 2000 ft-A3 | Neither | N/A | N/A |
| 8 | Would a station at a location other than 1,000 ft or 2,000 ft away have been better? | No | No | No | No | No | Yes (in section) | N/A | No | No | No | No | N/A |
| 9 | Would FLAME have affected a station at 1,000 ft away? | No | No | No | No | No | Yes | Yes, if present | Yes | Yes-A2 No-A3 | No | Yes | No, if present |
| 10 | Would FLAME have affected a station at 2,000 ft away? | No | No | No | No | No (flame) Yes (heat) | No | No, if present | No | Yes-A2 Yes-A3 | No | N/A | No, if present |
| 11 | Would FLAME have affected a station per OTHER guidelines? | N/A | N/A | N/A | N/A | N/A | Yes | N/A | N/A | N/A | N/A | N/A | N/A |
| 12 | Would FORCES have affected a station per at 1,000 ft away? | Yes; 15 to 20 psi | N/A (fire) | Yes; 2-5 psi | No | N/A (fire) | Yes | Yes | Yes; 2-4 psi | Yes (low) | N/A (fire) | Yes | No, if present |
| 13 | Would FORCES have affected a station at 2,000 ft away? | Yes; 2-4 psi | N/A (fire) | Yes; 2-5 psi | No | N/A (fire) | Yes | Yes | Yes; <2 psi | Yes (both) | N/A (fire) | N/A | No, if present |
| 14 | Would FORCES have affected a station per OTHER guidelines? | N/A | N/A | N/A | N/A | N/A | Yes | N/A | N/A | N/A | N/A | N/A | N/A |
| 15 | Time (in hrs) rescuers would have made contact with trapped miners | 1000 ft: 8 to 10 2000 ft: 3 | 48 or less | 1000 ft: 48 2000 ft: 40 | 3 or less | 2-32 (?) | 1000 ft: 10+ 2000 ft: <1 | <21, if present | 1000 ft: 5 2000 ft: 4.5 | 96?-with borehole | <5 (?) | 6.5-21.5 | N/A |
| 16 | Would additional outby stations have been beneficial? | No | No | No | No | No | No | Cannot say | No | No | No | N/A | No |

76

- In nine of the disasters, some or all of the victims were originally located at their working faces when the disaster was first discovered. In the other three disasters (all explosions), miners at outby locations triggered the explosions and they were the only miners affected.

- In nine of the twelve disasters, some or all of the miners were sufficiently healthy to attempt escape for a considerable distance. In the other three disasters, miners were apparently injured severely or overcome quickly and traveled only a short distance. Two of these (Oakwood Red Ash and Itmann) involved cases where outby miners triggered the explosions. The third (Finley) involved a violent explosion that instantly killed 33 of the 38 miners affected and the other 5 were only able to travel 100 to 140 ft before perishing.

- *Stations located at 1,000 ft from the face*: in eight of the twelve disasters, the victims would likely have been able to reach a station located 1,000 ft from the faces. In another of the disasters (Finley), it is not know whether the victims initially surviving the explosion could have reached a station at 1,000 ft because data is not available on the extent of their injuries. In another two of the disasters (Oakwood Red Ash and Itmann), the victims would only have been able to reach a station at 1,000 ft if it were close by due to their injuries. In one of the disasters (Pyro No. 2, in abandoned works), the sole victim could have reached a station at 1,000 ft (if it still existed in the area) but would probably not have stayed because he would have been in fresh air.

- *Stations located at 2,000 ft from the face*: in six of the twelve disasters, all or some of the victims would likely have been able to reach a station located at 2,000 ft from the faces. In two of the disasters (Itmann and Blacksville), all or some of the victims would *not* have been able to reach a station at 2,000 ft due to their injuries or mine conditions. In two of the disasters (Sago and Pyro William Station), it can't be determined for sure if the victims would have been able to reach a station at 2,000 ft based on their injuries or mine conditions. In one of the disasters (Oakwood Red Ash), the sole victim would only have been able to reach a station at 2,000 ft if it were close by due to his injuries. In one of the disasters (Pyro No. 2, in abandoned works), the sole victim could have reached a station at 2,000 ft (if it still existed in the area) but he probably would not have stayed because he would have been in fresh air. In the Finley disaster, a station at 2,000 ft would not have been provided due to close proximity to the mine portals.

- *Stations at 1,000 ft from faces versus stations at 2,000 ft from faces*: for five of the disasters, a station located at 1,000 ft would have been preferred over the 2,000 ft location. In two of the disasters, the station location at 2,000 ft would have been preferred and in another two, neither would have been preferred over the other. In two other disasters, it wasn't possible to say if one would have been preferred based on data available. Finally, in two of the disasters the question was not applicable because stations would not have been used in one of them and a station at 2,000 ft would not have been provided in the other.

- *Alternate station locations*: in only one of the disasters could it be said that an alternate station location would have been preferred over the 1,000 ft or the 2,000 ft locations. In the Scotia disaster, miners within their working section off the main entries were trapped inside their section due to an explosion that occurred out in the main entries inby their location. In

77

such cases, it would have been preferable to maintain a refuge station some distance inside the section away from the junction with the mains.  Although it is not possible to predict ahead of time that a disaster of this nature might occur, it might be a sensible protocol to establish a station within a dead-ended working section just as soon as possible after the section has advanced deeply enough to accommodate it.  The Sago disaster bears this out as well; a location within 1,000 ft from the working faces at Sago would have been inside the section away from the direct firing line of the explosion and an ideal location for a refuge station.  Because the submain was less than 2000 ft long a station at 2,000 ft from the faces at Sago would have been in the main panel and closer to the explosion and much more difficult for the miners within the section to reach.  Note, however, that a station would never have been placed close to a gob seal because of exactly what happened at Sago.

- *Effects of flame on stations at 1,000 ft from faces*: in seven of the twelve disasters, flames *would not* have impacted a station located at 1,000 ft from the faces.  In four of the disasters, flames *would* have impacted a station at 1,000 ft and in one disaster (Blacksville) flames would have impacted a station at 1,000 ft for one working section but not the other.

- *Effects of flame on stations at 2,000 ft from faces*: in ten of the twelve disasters, flames *would not* have impacted a station located at 2,000 ft from the faces, although heat would have been a factor in the Wilberg disaster.  In only one of the disasters (Blacksville), flames *would* have impacted a station at 2,000 ft.  One disaster (Finley) is not applicable because a station at 2,000 ft would not have been provided due to close proximity to the mine portals.

- *Effects of forces on stations at 1,000 ft from faces*: in seven of the nine disasters involving explosions, forces *would* have impacted a station located at 1,000 ft from the faces.  Little numerical data was available as to the extent of the forces but in one explosion (Darby), a station at 1,000 ft would have been subjected to forces of up to 15 to 20 psi.  In the Sago and Itmann explosions, a station at 1,000 ft would have been subjected to forces of about 2 to 5 psi and 2 to 4 psi respectively.  In the Pyro William Station and Pyro No. 2 explosions, forces *would not* have impacted a station at 1,000 ft (and a station may not have even been provided in the Pyro No. 2 case).

- *Effects of forces on stations at 2,000 ft from faces*: in six of the nine disasters involving explosions, forces *would* have impacted a station located at 2,000 ft from the faces.  Again, little numerical data was available but in the Darby explosion we estimate that a station at 2,000 ft would have been subjected to forces of about 2 to 4 psi; in the Sago explosion we estimate it would have been subjected to forces of about 2 to 5 psi and in the Itmann explosion we estimate it would have been subjected to forces of less than 2 psi.  In the Pyro William Station and Pyro No. 2 explosions, forces *would not* have impacted a station at 2,000 ft (and a station may not have even been provided in the Pyro No. 2 case).  Also, a station at 2,000 ft would not have been provided in the Finley explosion due to close proximity to the mine portals.

In most cases (though not all), stations located at 2,000 ft from the faces would have had the advantage of being further from most of the fires and explosions than a station at 1,000 ft and so less likely to be affected by flame and explosion forces; however, miners would have been able

to reach a station at 1,000 ft in more cases than a station at 2,000 ft due to injuries, disorientation, debris in their path and the greater distance to be traveled, so stations at 1,000 ft would have been preferred in more cases as noted above.

- *Time for rescuers to reach miners in stations*: the time that it would have taken rescuers to reach miners taking refuge in a station varied widely across the twelve disasters, ranging from about 2 hr to potentially up to 96 hr where drilling a borehole would be required (see details in the table).  Generally, rescuers would reach a station at 2,000 ft from the faces quicker than a station at 1,000 ft due to its location 1,000 ft further outby.  In some cases, they would have reached a station at 2,000 ft much sooner (as in the Darby and Scotia explosions) while in other cases there would have been little difference.  Obviously it would have depended on the conditions that rescuers would have encountered in the 1,000 ft of advance between the 2,000 ft and the 1,000 ft stations.

- *Additional outby stations*: as to the possible benefits of additional stations located in outby areas (as at 1 hr travel intervals to match MSHA's breathable air requirements), there was only one disaster (Oakwood Red Ash) where an outby station might have possibly helped.  The two victims were working in an abandoned area of the mine, so an outby station could possibly have been their only recourse had one existed in the area and if the extent of their injuries had allowed them to travel to it.  In all eleven of the other disasters, miners either would have used stations at 1,000 ft or 2,000 ft from the faces instead or would not have been able to reach an outby station or would have been in clean air before ever reaching one.

- *Additional recommendations for locating stations*: recommendations related to station positioning are identified as follows:
  - Both the Wilberg and Alma mine fires were associated with conveyor belt systems.  Conveyor belt systems, especially belt drives, are potential friction hot spots and have been sources of mine fires in the past.  Avoid locating stations within escapeway crosscuts that are close to belt drives or other potential fire hot spots.  Past mine fires and explosions have also often destroyed ventilation overcasts so station locations near overcasts should also be avoided.
  - The Blacksville No. 1 mine fire occurred in the track entry on equipment being moved in the entry.  Fires and explosions have occurred in track entries in the past due to the prevalence of equipment, supplies and moving electrical and mechanical systems along the track.  Although MSHA regulations [11] preventing the movement of equipment while miners are located inby will prevent similar disasters in most cases, another suggestion for station positioning would be to avoid locating them within or off track entries when other options are available.
  - The Oakwood Red Ash and Pyro No. 2 mine explosions both suggest that it could be important to maintain stations at either 1,000 ft or 2,000 ft from abandoned or mined out areas of mines as long as there is likelihood that miners will still need to access those areas, even if only occasionally, particularly since they may not be as well ventilated as more active working sections.  Only a single station would be required since the section would no longer be advancing and the 1,000 ft location would be

preferred since the greatest likelihood of an ignition or explosion would be in or near the abandoned face areas.
- Based on the Sago disaster and general mining engineering judgment, stations should not be placed near gob seals.

- *Issues regarding station use and deployment.* It appears that some mines in the country are opting for portable stations (chambers) that have to be deployed for use. The advantage of these stations is that they easier to move; however, our analyses of the mining disasters from 1970 to 2006 have shown that many involved injured miners, most involve poor visibility, and many have miners donning self rescuers. In fact, some miners under the duress of a mine emergency have had trouble opening and donning a self rescuer. This leads to key questions regarding the use of stations that have to be deployed by miners during a disaster:
  - How difficult are such stations to deploy, how long does it take and how much training is required to deploy them?
  - How are injured and disoriented miners going to deploy the refuge stations or the inflatable walls if they barely make it to the station and are in dense smoke or dust when they get there?

  These issues must be considered when developing or revising emergency response plans as they pertain to training for and use of portable refuges requiring post-event deployment.

### 6.4 Recommendations for Placement of Refuge Stations in Underground Coal Mines

Based on the research conducted, following is a summary of our final conclusions and recommendations on the placement of stations within underground coal mines:

- In the cases of many of the disasters studied, stations would have been most effectively located within 1,000 ft from the faces of mining sections while in other cases stations would have been more effective at the 2,000 ft locations, so there are two choices: place stations at both locations or provide one about 1500 ft. It is not possible to maintain consistent distances (e.g., 1000 ft) at all times because the working section is continually advancing as coal is produced. Hence, the station(s) should be situated in *nominal* locations. In the approach using only one station it would be located within a range of 1000 ft to 2,000 ft from the face. Similarly, in the two station option one would be located in range of 500 ft to 1500 ft and the other within 1,500 ft to 2,500 ft from the face.

- It will always be necessary to maintain at least one active station for a working section at all times. A portable chamber cannot be considered "in-service" when it is being moved because its location will be changing and miners will not necessarily know of its in-transit or new final location. In addition, it may be subject to significant damage should an event occur while unanchored or in transit and rendered useless. Therefore, if a one-station system is being used it would require being moved during non-working shifts. If a mine is maintaining a two-station system for a working section, one can be dismantled and moved while the other station remains in service. This would apply whether the stations were portable chambers or bulkhead-based stations. Two basic scenarios that could be employed for this are:

80

1. *Alternating stations*: as the inby station begins to reach a distance of 1,500 ft from the faces (and the outby station approaches 2,500 ft from the faces), the outby station would be relocated to a position approximately 500 ft from the faces and the previously inby station would then become the new outby station.  This cycle repeats as mining advances.  If both portable chambers and bulkhead type stations are used in this scenario, they would alternate in their positioning.
2. *Series station advancement*: as the inby station begins to reach a distance of 1,500 ft from the faces (and the outby station approaches 2,500 ft from the faces), the inby station would be moved up to a position approximately 500 ft from the faces while the outby station remains in service.  Once the inby has been relocated and is back in service, the outby station would then be moved up to a new position about 1,500 ft from the faces.  This cycle also repeats as mining advances.

- The above recommendations would apply to retreat longwall and pillar mining as well as to forward development mining.  In cases of retreat mining, the stations would simply be relocated in the outby direction rather than the inby direction as mining progresses.  Retreat mining could allow the reuse of abandoned bulkhead type stations that had been set up during earlier development mining.

- Note that special consideration has not been given to very low coal seams in this recommendation.  Mines may need to consider placement of refuge stations within ranges closer to the faces on a case by case basis depending on the height of their coal seams or on other mitigating factors that would make travel to a station particularly difficult during emergency conditions of poor visibility and potentially bad atmosphere.

- In sections such as longwall sections where miners are spread widely throughout the face area and alternate escape routes are provided (as in headgate and tailgate escapeways), stations should be provided within each of the main escapeway routes where feasible.  In the case of longwall tailgate entries, this may not be possible given the caved entries from adjacent mined out panels and dense cribbing installed to provide support in those entries.

- Stations should obviously be located within crosscuts off standard designated intake escapeways.  If necessary in some instances, they may be located off designated return escapeways.

- None of the disasters studied suggested a specific station location that would obviate the 1,000 ft, 1,500 ft or 2,000 ft options.  Hence, we are not recommending any specific alternative locations; however, we recommend establishing an initial station within a dead-ended working section as soon as possible after the section has advanced deeply enough to accommodate it.  This will provide refuge to miners who could become trapped within the dead-ended section by fires or explosions that might occur either inby or outby in the adjoining main entries. This is in agreement with research by others [9].

- The likely timeframe required for mine rescuers to reach miners trapped in a refuge station varied widely in the disasters studied.  In at least one disaster, it could have taken rescuers up to 96 hr to reach trapped miners through a borehole.  In many other cases it took substantially less time to reach trapped and injured miners.  We  recommend that stations be equipped to handle stays of up to 96 hr to accommodate the outside range of the rescue

timeline and to account for the potential for stations to be overloaded (over designed capacity).

- Our study has shown that additional outby stations would only rarely be helpful in sustaining miners escaping a mine disaster and we do not consider maintaining outby stations to be a necessary requirement.  However, mines providing boreholes at regular intervals as mining progresses (typically under minimal cover with ready access to all surface areas) might consider maintaining stations at intervals within the mine based on the relative ease in doing so.  In a severe disaster, they could certainly provide temporary refuge to escaping miners to regroup and rest as they continue their escape.

- Stations should not be located within escapeway crosscuts that are close to belt drives or other potential fire hot spots.  Past mine fires and explosions have also often destroyed ventilation overcasts so station locations near overcasts should also be avoided.

- Fires and explosions have occurred in track entries in the past due to the prevalence of equipment, supplies and moving electrical and mechanical systems along the track.  MSHA regulations (initiated based on the Blacksville No.1 fire and explosion) prevent the movement of equipment while miners are located inby.  Nonetheless, stations should not be positioned within or off track entries when other options are available.

- Stations should be maintained at either 1,000 ft or 2,000 ft from abandoned or mined out areas of mines as long as there is likelihood that miners will still need to access those areas, even if only occasionally, particularly since they may not be as well ventilated as more active working sections.  Because mining will not be occurring in such inactive areas, stations will obviously not need to be relocated within those areas.

# 7.   *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:

- Literature Review of Atmosphere Standards (Section 7.1).
- Limits for Survivability (Section 7.2).
- Closed Systems (Section 7.3).
- Open Systems (Section 7.4).
- Special Considerations (Section 7.5).
- Recommended Design Life for Refuge Stations (Section 7.6).

## 7.1   *Literature Review of Atmosphere Standards*

### 7.1.1   *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 28 shows oxygen consumption rates and carbon dioxide production, as published from several sources:

*Table 28.  Human oxygen consumption and carbon dioxide production rates*

| $O_2$ Consumption cfm (l/min) | $CO_2$ Production cfm (l/min) | Activity | Source |
|---|---|---|---|
| 0.022 (0.623) | 0.019 (0.538) | Average | Foster-Miller, 1983 [14] |
| 0.022 (0.623) | 0.018 (0.510) | Average | MSHA PIB 07-03 [12] |
| 0.011 (0.311) | 0.009 (0.255) | Sitting | NAVSEA TS500, 2006 [22] |
| 0.042 (1.189) | 0.040 (1.133) | Walking (4 mph) | NAVSEA TS500, 2006 |
| Note: Foster-Miller and MSHA are for blended rate of 80%resting and 20% moderate exertion. | | | |

There are several noteworthy items about human respiration:

- The above data represents oxygen consumed and $CO_2$ produced.  These flow rates *should not be confused* with breathing rates (technically, the "minute volume"), which of course are much greater.  Only about 4 percent 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.  Table 29 shows a comparison of respiration quotients (volume of carbon dioxide produced/volume of oxygen consumed) found in literature.

*Table 29.  Respiration quotients*

| Respiration Quotient ($CO_2/O2$) | Literature Source |
|---|---|
| 0.75 at rest<br>0.9 moderate activity<br>1.0 vigorous activity | Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I," 1983 [14] |
| 0.85 resting | NAVSEA TS500-AU-SPN-010 (Diver Equipment Spec.[22] |
| 0.8 resting | Brake, R.,  et al, "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine" AusIMM Journal, 1999 [27] |
| 0.8 resting | MSHA PIB 07-03 "Methods for Providing Breathable Air" [12] |
| 0.85 resting | Busby,R.,  "Standard Man" Table for Life-Support System Design Computations, Manned Submersibles, Office of the Oceanographer of the Navy, 1976 [64] |

- 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 0.022 cfm (0.623 l/min) of oxygen delivery capacity per occupant and 0.019 cfm (0.538 l/min) 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.

### 7.2    Limits for Survivability

### 7.2.1    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 30, Table 31, and Table 32 show recommended levels from a number of international sources for oxygen, carbon dioxide, and carbon monoxide, respectively.

*Table 30. Oxygen limits*

| Gas | Literature Reference Values | Source |
|---|---|---|
| Oxygen, O2 | (Not provided) | MSHA PIB 07-03, "Methods for Providing Breathable Air" [12] |
| | 19.5% limit | West Virginia State Technical Rules, Title 56, series 4, section 8 [17] |
| | 17% limit | Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983 [14] |
| | above 24% increased risk of fire | Health and safety Exec .gov. UK [23] |
| | Below 17%, breathing faster and deeper, possible impaired judgment | Pennsylvania State, Deep mines safety training [24] |
| | Above 18% recommended for portable refuge chamber | Venter et al, South Africa, man test for 24 hr [25] |
| | 19.5%, 8 hr avg | Saskatchewan Mining regulations, ref, OSHA 1996 regulations [26] |
| | 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 [27] |
| | O2 upper limit 23.5% | Oregon, OSHA 215 [28] |
| | O2 upper limit 23% | MASHA manual, "Guidelines for Rescue Refuge Stations (Mines and Aggregates Safety and Health Assoc.) Ontario. [29] |
| | At Min. 18% O2, slight increase in breathing rates | Rimer Alco North America, Manitoba, "Respirable Air Handbook" [30] |

There are several noteworthy issues regarding concentration limits for gases:

- Note that there is an upper limit on oxygen concentration (23 to 24 percent) 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 (approximately 10 percent methane and normal atmospheric oxygen of approximately 21 percent). 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 percent, 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.

*Table 31.  Carbon dioxide levels*

| Gas | Literature Reference Values | Source |
|---|---|---|
| Carbon dioxide $CO_2$, scrubbing target level | (Not provided) | MSHA PIB 07-03, "Methods for Providing Breathable Air" [12] |
| | 0.5% limit | West Virginia State Technical Rules, Title 56, series 4, section 8 [17] |
| | 0.5 -1.0% limit | Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983 [14] |
| | Below 0.5% recommended for portable refuge chamber | Venter et al, South Africa (Report: Portable Refuge Chambers: Aid or Tomb in Underground Escape Strategies) [25] |
| | Ceiling 1.5%, IDLH level 50,000 ppm | Pennsylvania State, Deep mines safety training [24] |
| | 5000 ppm 8 hr avg, 30,000 15 min limit, 40,000 IDLH level | Saskatchewan Mining regulations, ref, OSHA 1996 regulations [26] |
| | For open systems (Compressed air: 0.5% $CO_2$ emergency working limit). For Closed systems: 1.25% $CO_2$ | Brake et al, Australian report "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine", 1999 [27] |
| | U.S. Navy recommends 1.5% $CO_2$ limit, or 2% for emergencies | "Living and Working in the Sea" Miller and Koblick, 2nd edition [31] |
| | American Bureau of Shipping recommends maximum 1% $CO_2$ for long term exposure | "Living and Working in the Sea" Miller & Koblick, 2nd edition |
| | TWA: 0.5%, ST: 3%, IDLH: 4% | NIOSH REL [32] |
| REL: Recommended Exposure Limit<br>TWA:  Time Weighted Average | | |

- Most of the recommendations cited in the tables are based on normal working conditions, and most of the literature is based on 8 hr 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 percent.*  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 (i.e., mechanical removal of oxygen) or human subjects testing (see Section 7.5.2).

**Table 32. 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" [12] |
| | 50 ppm limit | West Virginia State Technical Rules, Title 56, series 4, section 8 [17] |
| | 100 ppm limit | Foster-Miller report to USBM, "Development of Guidelines for Rescue Chambers, Vol. I", 1983 [14] |
| | 25 ppm 8 hr avg | Saskatchewan Mining regulations, ref, OSHA 1996 regulations [26] |
| | 190 ppm 15 min limit | Saskatchewan Mining regulations, ref, OSHA 1996 regulations |
| | 30 ppm 8 hr avg | Queensland, Australia, mining regulations [33] |
| | 50 ppm 8 hr avg | Pennsylvania State, Deep mines safety training [24] |
| | 200 ppm 15 min limit | Pennsylvania State, Deep mines safety training |
| | | 20 ppm is the maximum level permitted in diver's breathing gas for depths to 800 ft, per NAVSEA TS500-AU-SPN-010 [22] |
| | "1 to 70 ppm, Most people no symptoms" | U.S. Consumer Product Safety Comm. Website: www.cpsc.gov/cpscpub/pubs/466.html [34] |
| | 35 ppm for 8 hr TWA exposure, ceiling limit of 200 ppm not to exceed | NIOSH REL [35] |
| | 25 ppm, 8 hr TWA, TLV | ACGIH, American Conf. of Govt. Industrial Hygienists [36] |
| | 50 ppm 8 hr TWA | OSHA PEL [37] |
| | 15 ppm, based on 24 hr a day, 90 day TWA exposure | National Research Council [80] |
| REL: Recommended Exposure Limit<br>PEL: Permitted Exposure Limit<br>TWA: Time Weighted Average<br>TLV:  Threshold Limit Value | | |

- *Maximum carbon dioxide concentration of 0.5 percent,* with short (less than 1 hr in 8) excursions no greater than 1.0 percent.  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 percent instead of 1.0 percent will take twice

as much air flow (see Section 7.4). 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 percent $CO_2$ might be considered. System testing to verify the ability to maintain carbon dioxide levels can be easily accomplished through both simulated (i.e., mechanical introduction of carbon dioxide) or human subjects testing (see Section 7.5.2).

- *Maximum carbon monoxide concentration of 25 ppm* for life of chamber, 50 ppm maximum for 8 hr. 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 7.5.1). 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 percent. 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.

### 7.2.2 Temperature and Humidity

**Background**

In order to develop design criteria for temperature and humidity, we reviewed a substantial body of research literature on approaches to measuring the effect of heat and humidity on humans. Effective temperature was developed by Yaglou and Houghton [58] in 1923 (based on wet and dry bulb temperatures and air movement). It was modified in 1932 (Vernon and Warner [81]) to provide a Corrected Effective Temperature (CET), using black-globe temperature instead of dry bulb temperature to account for radiant heat. WBGT was developed in 1957 (C.P. Yaglou and D. Minard [65]) to protect troops in training in South Carolina, based on temperature, humidity, air movement, and radiant heat. It was developed as an approximation of Effective Temperature. The Heat Stress Index (HSI) was devised in the 1950's by H.S. Belding and T.F. Hatch [82]. HSI includes more factors in the calculation of an exposure index than the WBGT and Effective Temperature. It reflects interactions among temperature, humidity, wind, radiant heat, work rate, and sweat production. The ACGIH (2001), "*2001 TLV's and BEI's Threshold Limit Values for Chemical Substances and Physical Agents, and Biological Exposure Indices*" [49] is quoted as saying: *"By providing a heat balance framework, the HSI assesses the effects of metabolic heat production and environmental contributions to heat stress."* It assumes healthy individuals, dressed in light clothes. It is described in the ACGIH report as very complex to calculate and does not appear to be broadly used.

A book by C.S. Leithead and A.R. Lind, "*Heat Stress and Heat Disorders*," F.A. Davis Co., Philadelphia 1964 [67] appears to be a seminal work, discussing the progression of physiological effects towards heat stroke. Briefly, progressive response to heat is given as follows:

- Vasodilation to increase skin temperature.
- Sweating.
- Core temp keeps rising and skin is completely wet.
- Hidromeiosis (reduction in sweating) due to swelling and blocking of sweat glands.
- Core temp rapidly increases to beyond 38 to 39°C (collapse may occur), to above 41°C (rectal temp), where heat stroke may occur.

An Australian report from Brake and Bates "*Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine*," 1999, [27] presents a 35°C wet bulb limit for emergency refuge stations or a deep body core temperature maximum of 39°C. The source referenced by Brake and Bates for this limit is the Leithead and Lind work from 1964. In 1969, the World Health Organization (WHO) recommended a limit on body core temp of 38°C (100.4°F) for sustained exposures to heat stress [63]. From this report, hyperthermia driven by heat stress is a result of the progressive inability of the body to maintain thermal balance. An elevated core temperature greater than 38°C normally indicates a marginal ability to tolerate greater levels of heat stress or a loss of thermal regulatory control.

In the 1970's, R.G. Steadman performed exhaustive research on the effects of heat and humidity on humans and this work was published in the papers: "The Assessment of Sultriness, Parts I and II" Textiles and Clothing Dept., Colorado State University, Fort Collins, CO. 1979 [51] [62]. This research resulted in a list of 20 different parameters contributing to apparent temperature and was later developed into a Heat Index formula by the U.S. NOAA National Weather. This long formula shows errors for temperatures below 80°F and humidity below 40%. (See NCDC website discussion of the formula inaccuracy at http://www.ncdc.noaa.gov/oa/ climate/research/heatstress/ .) Steadman also developed his own formulas in a 1984 paper [52].

In 1986, NIOSH produced a Recommended Standard – Occupational Exposure to Hot Environments [61], using the prior work above to develop an exposure metric for heat stress and to select a threshold to limit body core temperature to below 38°C (since it is not easily measured). REL and RAL were developed. In 1989, the International Standards Organization, Geneva, (ISO) developed an index to predict core temperature or core temperature increase, ISO 7933 [83].

A publication in 1997 by M.D. Morgan and J.M Moran "Weather and People" shows a chart of heat stress risk categories, quoting four levels of apparent temperature versus physiology: http://www.physics.isu.edu/weather/kmdbbd/weather-people15.pdf [55]. This chart is also reproduced in Jefferson Lab, ES&H Manual 6670 –T2 Heat Stress Index & Climate http://www.jlab.org/ehs/manual/PDF/6670T2HeatIndex.pdf [56]. The original source of this table of four categories of heat stress based on apparent temperature is believed to be the National Weather Service in the 1980's (unconfirmed by NWS) and the scientific basis used to develop the chart is unknown.

Later, in 2000, ACGIH developed the TLV for Heat Stress and Strain [66]. This departed from previous work since rational models for heat stress have evolved to consider not only excessive body temperature, but also dehydration and overall measures of burden (heat strain). The ACGIH pulls all these together, and considers metabolic rate (work level) factors. The report covers clothing, WBGT, analysis, heat strain, and heat stress management and controls, and provides TLV charts. (Note that the ACGIH report is for exposures of 8 hr days, 5 days/week, and for extended days they recommend applying the sweat rate analysis in ISO 7933.) The report highlights that an individual's response to heat stress/strain also depends on a range of personal factors including: age, obesity, hydration, medications and recreational drug use, gender, fitness level, and acclimatization to hot environments. In the ACGIH report, a chart of work/rest ratio versus work load for acclimatized and unacclimatized workers indicates TLV WBGT values in degrees C (Table 2, P.2). Also shown is the REL and RAL charts from earlier NIOSH 1986 work mentioned above, (Figures 2 and 3, pp. 13, 14).

In 2002, a report by the Health and Safety Executive (HSE), U.K., "The development of a practical heat stress methodology for use in UK industry" [60] found that "Deep body temperature has been found to be more closely related to metabolic rate, than to the rate at which body heat had to be eliminated." Also, the heart rate increases during heat stress compared to the same work rate in neutral conditions.

In 2002, a paper by R. Brake, and G. Bates, Curtin University, Aust. "A Valid Method for Comparing Rational and Empirical Heat Stress Indices" [58] was produced, which observed that there were many indices for heat stress, both empirical (environmental parameters) and rational (physiological parameters). Some have shortcomings and none are broadly accepted. Added to this is the issue of clothing effects, and acclimatization. Brake and Bates developed a method to compare most heat stress indices by relating them all to a maximum metabolic rate at which *continuous* work under given conditions, is safe (i.e. core temperature must plateau at a safe level). At the limiting condition, metabolic rate generated = heat lost by the body. Metabolic rate is expressed in $W/m^2$. The indices compared were:

- ISO 7933, 1989.

- ACGIH TLV, 1998-2000.

- U.S. Army Research Institute for Environmental Medicine (USARIEM), 1986.

- Air Cooling Power (ACP) –McPherson, 1992.

- Corrected Effective Temperature (CET) – Yagloglou & Houghton (1923), Bedford, 1946.

- Thermal Work Limit (TWL) –Brake and Bates, 2002.

This Brake and Bates 2002 report includes a table of max. wet bulb temp. for various indices and conditions at a fixed metabolic rate of $140W/m^2$ (moderate work), (Table 1, P. 171). A 2000 book by C.V. Gisolfi, and F. Mora, "The Hot Brain," MIT Press [59], details the body's

reactions to heat stress, and states that body core temp is naturally 37C, but a rise of only 4C will produce heatstroke. A report by Epstein and Moran, 2006 Israel [57] presents a list of 46 proposed systems for rating heat stress and strain (heat stress indices).

**Apparent Temperature as an Index of Heat Tolerance**

Heat and humidity will have a direct effect on occupants of an enclosed refuge area. Human tolerance to heat and humidity levels varies by individuals, depending on personal factors including age, body size, hydration, medications, gender, fitness level and acclimatization to hot environments [49]. As described above, there are a number of indices that have been developed to assign a numerical scale to combine the effects of factors including heat, humidity, air velocity, and radiant heat. Three examples are:

- Effective temperature (using temperature, RH, and wind).

- WBGT (wet bulb globe temperature, using temperature, RH, wind, and radiant heat).

- Apparent Temperature (using 20 different variables).

Apparent temperature was developed by R.G. Steadman in 1979, and was originally presented as a numerical chart, the results of extensive biometeorological studies of 20 different parameters [50] [51]. In order to evaluate the relative effects of dry bulb temperature and humidity, all of the other variables can be assigned "standard values" (e.g., male, 5'7" tall, 147 lb, dressed in summer clothing, walking slowly in a very light breeze, in the shade). By using these standard conditions, Steadman was able to produce a table that shows "apparent temperature" as a function of only (dry bulb) temperature and relative humidity, shown in Figure 2.

Because tables are inconvenient to use in algorithms, computer programs, etc., regression analysis was used to "convert" the tables to a formula:

AT= Ta + 0.33 x e – 0.70 x ws – 4.00

Definitions:

AT       is Apparent Temperature (°F)
Ta    =   dry bulb temperature (°F)
e     =   water vapor pressure (hPa) [defined below]
ws    =   wind speed (m/s) at an elevation of 10 meters
e     =   rh/100 x 6.105 x exp(17.27 x Ta/(237.7 + Ta)) where rh = relative humidity % [53]

The same formula is quoted as the definition of "apparent temperature" in the West Virginia MSTTF report, May 2006 [40]. Steadman also quotes two similar formulas derived from regression analysis in a 1984 paper [52]. These formulas are expressed in degrees Centigrade, resulting in different coefficients.

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 57.2°F (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 57.2°F, 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 80°F are generally associated with some discomfort. Values approaching or exceeding 105°F 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 2.  *Apparent temperature chart, (dry bulb temperature versus relative humidity) [38]***

The United States National Weather Service has also adopted the "apparent temperature" concept.  The NWS did their own regression analysis to develop a different formula [50].  The NWS refers to the resulting value as the "Heat Index."  This formula allows accurate representation of the Steadman chart for the range of conditions expected in a refuge station [54].

We recommend using the apparent temperature values by referring to the Steadman table of values from 1979 (see Figure 2) rather than a formula fit, since this is the most accurate reference source, is commonly accepted, and is easy to use without any calculation necessary.

**Survivable Apparent Temperature Limit**

As shown in Figure 2, apparent temperatures above 80°F are uncomfortable, and above 105 are life-threatening.  Other sources use different temperature indices in their recommendations for heat tolerance limits as shown in Table 33.

The heat tolerance chart in Table 33, indicates that 95°F apparent temperature is reasonable for survivability. A brief discussion of the chart follows:

- The University of Virginia Climatology office brackets the apparent temperatures from discomfort to possible fatality levels.

- NASA MSIS standards do not specify an index limit for heat tolerance, but the maximum temperature and humidity levels given for extended emergency conditions convert to a 95 F apparent temperature using the Steadman chart in Figure 2.

- Hyperthemia develops when body core temp rises above 39°C (102°F) and is then classified as either heat exhaustion or heat stroke, where the body has lost thermal self control [55].  The Navy document cited shows a risk of hyperthermia in conditions above 90°F air temperature.

The work by Morgan and Moran in 1996 [55] shows four apparent temperature brackets and the resulting physiological effects. The 95°F apparent temperature limit selected in this Foster-Miller report falls in the lower end of category III (90 to 105°F apparent temperature), where physical problems could occur but are not likely.  These 4 categories have also been cited for occupational hazards by the Jefferson Lab [56] assumed to be over an 8 hr day, 5 days a week. Thus the lower end of category III for continuous multi-day exposure in a refuge station seems reasonable for a survival limit. Wet bulb limits and effective temperature limits cited in the South African Mine Health and Safety Inspectorate work by R. Brake et al. [27] and the MASHA guidelines manual [29] do not directly convert to apparent temperature values, but are shown as a general rough agreement to support a 95°F apparent temperature limit.

Based upon this information, we recommend a maximum apparent temperature of 95°F for underground coal mine refuge stations (based on the apparent temperature definition of the Steadman table [51] shown in Figure 2.)

## Table 33.  Recommended maximum heat tolerance levels

| | Heat Tolerance Levels | Sources |
|---|---|---|
| 1 | Apparent temp. of 95°F maximum | West Virginia Mine Safety Technology Task Force report" Mine Safety Recommendations", 2006 [40] |
| 2 | Apparent temp. greater than 80°F: Some discomfort, at or above 105°F can be life threatening. | University of Virginia, Climatology Office, web site: http://climate.virginia.edu/apparent.htm [38] |
| 3 | Workers in temps. at or above 81.5°F Wet Bulb, or 98.6°F 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 Minimum Standards of Fitness to Perform Work at a Mine" 2001 [41] |
| 4 | Max. temp. 85°F, max humidity 75%, for 28 day emergency (*This is equivalent to 95°F apparent temp.*) | NASA Man-Systems Integration Standards, Vol. I, Standards, Section 5.8.3.1, Temperature, Humidity, and Ventilation Requirements, Figure 5.8.3.1.1 [42] |
| 5 | Effective temp.* range for persons at rest: 78 to 82°F most people will tolerate<br>Effective temp. 82 to 90°F physiological stresses can be tolerated by most people for several hours and some hardy individuals for 24 hrs<br>Effective temp. 90°F 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 [29] |
| 6 | Hyperthermia is a potential risk any time air temperature exceeds 90°F | NAVSEA TS500-AU-SPN-010, NAVY spec. for diving and hyperbaric equipment. [22] |
| 7 | 95°F Wet Bulb limit for emergency refuge stations.<br>Body core temp. maximum 102.2°F | Brake, R.,  et al., "Criteria for the Design of Emergency Refuge Stations for an Underground Metal Mine" AusIMM Journal, 1999 [27] |
| 8 | 82.4°F to 90°F effective temp. tolerable for 24 hrs by hardy people.<br>90°F effective temp. 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) [25] |
| 9 | Four categories of occupational heat stress hazard posed by ranges of apparent temperature :<br>Category I : 130°F or above<br>Category II : 105 to 130°F<br>Category III : 90 to 105°F<br>Category IV : 80 to 90°F | M.D. Morgan, J.M. Moran, "Weather and People", 1996, Prentice Hall publishers. [55]<br>Heat stroke *imminent*<br>Heat stroke, heat cramps, or heat exhaustion *likely*<br>Heat stroke, heat cramps or heat exhaustion *possible* with prolonged exposure and physical activity<br>Fatigue *possible* with prolonged exposure and physical activity |
| 10 | Max. safe body core temp. 100.4°F (38°C) | World Health Organization (WHO) recommended limit on body core temp. for sustained exposures to heat stress, 1969 |
| \*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. Development of this index predates apparent temperature, no direct relationship between them was found. | | |

### 7.3 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 Section 7.3.1.

More sophisticated self-contained shelters will be pre-fabricated and contain atmosphere control systems for life support, as discussed in Section 7.3.2.

### 7.3.1 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 7.1.1. PIB 07-03 calculations show that a single miner in an 1800 cubic foot volume would reach 3 percent $CO_2$ concentration (not good, but survivable in an emergency) in 49.5 hr. These numbers scale with number of miners and size of volume: 10 miners would reach 3 percent 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" [29], the U.S. Navy uses a formula:

Time (hours) to reach 3 percent $CO_2$=0.04 x shelter volume($ft^3$)/number of occupants

This formula assumes a significantly slower breathing rate (see Section 7.1), and thus will show longer times to reach 3 percent $CO_2$.

### 7.3.2 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. It is important that the flow rate predicted is a steady flow since a wide variation in flow rate will skew the predicted duration capacity. High quality valves, plumbing and regulators should be used to ensure steady flow at the set point.

*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 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 maximum 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 hr. Bulk forms may have service life in the realm of 6 to 12 hr.

*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 12 hr.

## 7.4   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 in. 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 34 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 cfm (53.8 l/min) per miner will be required to maintain a carbon dioxide concentration of 1 percent; 3.8 cfm (107.6 l/min) would be required for 0.5 percent.

Note that the total airflow requirement may also be influenced by the desire to maintain a small overpressure inside the shelter.

## 7.5   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

## Table 34.  Required airflow for CO₂ dilution

| | Flow Rates | Conditions and Notes | Reference Source |
|---|---|---|---|
| 1 | 3 cfm/person (85 l/min/person) | Compressed air flow to keep $CO_2$ 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 [27] |
| 2 | 12.5 cfm/person (354 l/min/person) | Compressed air line flow or borehole flow from surface compressor. $CO_2$ % unspecified | MSHA PIB 07-03 "Methods for Providing Breathable Air" [12] |
| 3 | Approximately 3 cfm/person (85 l/min/person) | 150 cfm (4247.5 l/min) at 1.3 in. wg, Forced air feed, 6 in. borehole, 4100 ft^3 refuge station, 30 person (136ft^3/person). $CO_2$ % 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 [43] |
| 4 | Approximately 2.5 cfm/person (70.8 l/min/person) | 1-10 person   25 cfm (708 l/min) 10-20 person   50 cfm (1416 l/min) 20-30 person   75 cfm (2124 l/min) 30-50 person   100 cfm (2832 l/min) Compressed air flow for 0.5% $CO_2$ level. | Rimer Alco North America, Manitoba, Canada. "Respirable Air Handbook" [30] |
| 5 | 1.87 cfm/person (52.95 l/min/person) | Airflow to dilute $CO_2$ to 1% level, (and apply some overpressure) | Foster-Miller report to USBM, "Development of guidelines for Rescue Chambers, Vol. I", 1983 [14] |

### 7.5.1   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 [44][ 45][ 46]

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) [47] found that when a full complement of miners entered a shelter from a contaminated area, 6 percent of the contaminant concentration reached the shelter.  In other words, if the adjacent area had 1500 ppm of CO, the shelter would reach 90 ppm.  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 be 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 its 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.

- Metal-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. [48]

### 7.5.2   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 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 (e.g., $CO_2$ scrubbing).  Some of this information is proprietary and unavailable.  The most interesting test to date was performed

by an independent operator and a volunteer crew at the R10 Group Coalburg No. 2 coal mine, West Virginia in September 2007.  The test utilized a concrete block stopping to form a bulkhead-based refuge station.  The oxygen supply was bottled oxygen and the $CO_2$ scrubber was lithium curtains.  A crew rotated through the shelter over a 96 hr 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 72°F.

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.

### 7.6    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 hr 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 percent) of the total refuge cost which is in excess of $100,000 per installation (see Section 9.1).  Although many rescues were performed in less than 48 hr 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 hr 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.

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# 8.   *Potential Blast Loadings for Refuge Station Bulkhead Design*

## 8.1    *Literature Review*

The Table 35 lists literature reviewed and key findings used in the preparation of this section.

## 8.2    *Characterization of Blast Events*

A fundamental driver for the design of any in-mine refuge station is the need to survive the blast loadings that can occur in the locations planned for deployment.  Much valuable research and testing has been conducted, particularly by MSHA/NIOSH at the Lake Lynn Experimental Mine  (LLEM), in which many blast conditions have been replicated, measured, and data published. For the purposes of developing rational and reasonable design criteria for the design of bulkhead-type refuge stations, much of this work along with that of other researchers has been carefully reviewed.  This has resulted in development of a basic two-level approach:

- A transient "design" pressure pulse can be developed that would envelop nearly all of those conditions which are most likely to occur, given an understanding of conservative assumptions for the many parameters that affect the magnitude and duration of such a design pulse.  The bulkhead system would need to survive this with no significant damage or compromise of operation post-blast.

- Understanding of the rare but more severe conditions that could conceivably occur with ideal combinations of circumstances, and use those conditions as an ultimate loading criterion in which damage might occur but short of the destructive level. This would provide some measure of reserve without penalizing designs for very unlikely conditions. This is explained more fully in Section 10 covering the design and performance of the proposed bulkhead-type refuge stations.

To accomplish this, a good characterization of blast events is needed, including understanding of how the important blast variables affect the blast loadings on such stations.  In this report, we base this on methane-only explosions, since in modern mines proper rockdusting control and other measures are designed to eliminate coal dust explosions.  This not only is needed for development of appropriate refuge station loadings, but also can serve to guide the management and placement of these stations to provide the maximum level of safety with economy of operations.

These variables can be grouped into the following categories:

- The exploding body of gas itself, including methane concentration, combustible gas volume, and ignition point relative to any closed or working faces. This determines the initial blast energy and nature of the blast and flame fronts that quickly move outward into the mine (see Section 8.3).

**Table 35.  Literature and key findings related to blast loading for refuge stations**

| Reference | Key Findings |
|---|---|
| Information Circular 9500, *"Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines,"* Zipf et al. [68] | • Illustration of parameters contributing to the worst case severity of methane explosions.<br>• Analytical and practical comparisons for methane only explosions in open crosscut tunnels.<br>• Provides pressure-time results including a methane explosion with peak pressures of 15 psi.<br>• Ignition points at the face.<br>• Pulse duration data. |
| *"Experimental Coal-Dust and Gas Explosions,"* Nagy and Mitchell [69] | • Point of origin studies.<br>• Provides experimental data.<br>• Description of decrease in explosion maximum pressure with distance from face.<br>• Data shows flame length = 5 x explosion length.<br>• Pulse duration data. |
| Foster-Miller, Inc., Report Excerpt, *"Appendix A – Explosive Environment Definition,"* Maser et al. [70] | • Describes physical characteristics of a methane-air explosion.<br>• Describes attenuation of pressure induced by blast wave passing open crosscuts.<br>• Pressure reduced by a factor of .8 for each open crosscut passed. |
| Report of Investigations 7581, *"Explosion-Proof Bulkheads – Present Practices,"* D.W. Mitchell [71] | Peak pressure versus distance:<br>General statement (p. 2): Seldom do explosion pressures 200 ft and more from the origin exceed 20 psig unless coal dust is excessive.<br><br>Bulkhead or Seal Strengths:<br>8 in. thick mortared concrete block wall (recessed around perim) stands 5 psig "at best."<br>German thick gypsum bulkheads stand 215 psig; fail at 260 psig.<br>Dynamic strength > static strength: Wall designed for 27 psig static survived explosions as large as 50 psig peak.<br>Description of German air-tightness measurement/monitoring practices.<br><br>Leakage into Sealed Areas<br>Cracks and fissures can cause leakage even if seals are airtight.<br>Flows not predictable, may be many hours after change in pressures (baro, etc.) |
| *"Explosion Evaluation of Mine Ventilation Stoppings,"* E.S. Weiss et al. [72] | • Charts for survival and failure pressures for various stopping materials and constructions.<br>• Provides pressure-time data from experiments.<br>• Pulse duration data. |
| *"Experimental Mine and Laboratory Dust Explosion Research at NIOSH,"* M.J. Sapko et al. [73] | • Experimental data of explosion pressure decrease effects with distance in drift with first four crosscuts sealed.<br>• Example of blast signature and decay.<br>• Pulse duration data. |
| *"Explosion Hazard in Mining,"* J. Nagy [74] | This re-summarizes much data obtained by Mitchell and Nagy in 1963, plus some new information. We include only areas regarding methane-only explosions. |

***Table 35. Literature and key findings related to blast loading for refuge stations (continued)***

| Reference | Key Findings |
|---|---|
| *"Explosion Hazard in Mining,"* J. Nagy [74] (continued) | Location of Ignition point within gas zone (p. 52): 40 ft long ideal gas ignited.<br>At face: 39 psig.<br>At center (20 ft outby): 27 psig<br>At outby end (40 ft): 1 psi<br>    *Similar conclusions to Mitchell [*69*], 1963, co authored by Nagy.*<br><br>Maximum Explosion Pressure versus % Methane (Graph, p.53):<br>Performed in a closed vessel; therefore pressures much higher than in mine. However, same <u>relative</u> drop-off when moving away from ideal 10% methane mixture as in Mitchell 1963 [69]:<br>    8% methane:       80 psig<br>    10% methane:     92 (max)<br>    12% methane:     80<br>    *Reflects 1963 Mitchell report only w/containment vessel.*<br><br>Decrease of Peak Pressure with Outby Distance: Note: as in Mitchell 1963 [69], could not find a description of the drift/passage configuration, so No. of crosscuts, sealed versus open, etc. not specifically known. For 40 ft long ideal gas ignited.<br>Outby distance zero (at face):    39 psig<br> "       200 ft:         23 psig<br> "       500 ft:         13 psig<br>    *Similar to 1963 Mitchell report data.*<br><br>pp. 52-55 – graphs. Methane percentage. Tests with a 40 foot long gas zone. Explosion pressures at 0, 200, 500 ft. 39, 23, 13 psi. Where was testing? What was mine configuration? Mitchell report 1963 [69]. p. 20 – ignition points. P. 24 – graphs. P. 25 – knockdown double check methane only.<br><br>Pulse duration data. |
| Summary of MSHA Test Data Sent to Foster-Miller on November 16, 2007 by K.L. Cashdollar. [75] | Data from NIOSH not previously published showing (including raw data) graphs, images, and raw data of explosion tests at Lake Lynn. In this test double open crosscuts had a bigger knockdown than the Foster-Miller model predictions. Pulse duration data. |
| *"Experimental Study of the Effect of LLEM Explosions on Various Seals and Other Structures and Objects,"* K.L. Cashdollar et al. [76] | Explosion tests at NIOSH Lake Lynn performed for MSHA and W. Virginia Office of Miner's Health Safety and Training in support of their investigations into the Sago Mine explosion.<br>Information on sensor type and placement at Lake Lynn.<br>Definition of static from dynamic behavior.<br>Impact of reflected pressures seen due to a contained explosion with main drift and crosscut entries blocked. This was a 71 ft gas zone (ignition zone).<br>Shows flame lengths.<br>Typical seal construction time illustrated for a Mitchell-Barrett seal.<br>Pulse duration data. |
| *"Assessment of Refuge Bay Designs in Collieries,"* J.W. Oberholzer [77] | Suction loads on walls:<br>Determined to be on order of 1 psig.<br>Cites Nagy 1981 [74] saying that "provision should be made for 5 psi." |

- The configuration of the mine encompassing the areas containing the blast location, number and nature of all intervening passages including any convergences, presence of seals, stoppings or equipment. This determines the progress and attenuation of the blast energy and pressures as they move towards potential refuge station locations (see Section 8.4).

- The location of the refuge station, including its placement in passageways such as crosscuts; distance and exposure to the incoming potential blasts.  This determines how the attenuated blast energy and pressure waves that reach the area of the refuge location might actually be applied to the station components or walls.

When examining mine explosion test data, there should be careful distinction between the direct impact pressure ("total," including gage and aerodynamic) and the 50 percent or more lower gage pressure which acts in all directions. All blast pressures are "dynamic" in the sense they are time-varying, but that is a different usage than its meaning of aerodynamic.  There is a clear explanation of this made in [73], their Section 5.

Since the terminology used in different test reports over the past 30 to 40 years varies, this is the semantic equivalence found for blast-induced transient pressures:

*Gage = "static" = "vertical" (LLEM instrumentation on vertical surfaces aimed perpendicular to incoming or passing blast fronts)*

*Total  = "dynamic" (early reports) = "wind" = "horizontal" (LLEM instrumentation on vertical surfaces aimed directly at horizontal incoming or passing blast fronts)*

### *8.3   Explosive Mixture Variation*

Methane Percentage

LLEM tests have experimented with the effect of methane percentage in the explosive mixture. It is accepted that the "ideal" gas concentration is 9.5 to 10 percent methane, which results in the most efficient blast and highest energy.  It was shown [69] that when the methane percentage fell below 8 percent, or rose above about 11 percent, measured gage pressures at the outby end of the gas zone fell off about 20 percent from their maximums for the largest (50 ft) gas volume, and quickly dropped with even lower percentages until no ignition occurred. Above 13.5 to 14 percent, a rapid burning rather than explosion occurred with much lower pressures but with the potential for a propagating flame front.

*Since this percentage in an actual scenario is impossible to predict, we plan to use cases in which the methane percentage is in the maximum pressure range.*

Gas Volume

Many different LLEM tests have been reported in which the explosive gas volume was varied. The tests most applicable to our characterizations here used a simulated "working end" of a drift passage (roughly 7 ft H x 20 ft W = 140 sq ft), in which that end of the gas volume was stopped by the end face. The tests most useful for this work had the other end of the explosion directed

down an open drift passage or the like (i.e., not completely contained, analogous to the "open end of the gun barrel"). However, the distance of the other end of the gas volume was usually varied from a small number like 10 ft (1400 cu ft) to a relatively large amount such as 50 to 60 ft in a uniform passage (7000 to 8500 cu ft). These were separated by a membrane before ignition [68] [69] (single-tunnel LLEM tests No. 468, 469 and 470). It was found that the maximum pressures varied fairly directly with volume, as expected, with the maximum pressures at the largest volume. Examples of the resulting transient gage pressures for the largest such volume were most often in the 20 psi gage range near the blast (at ideal gas percentage), dropping off with distance and passage of open crosscuts (discussed in a following subsection). In other tests, much larger volumes such as a 71 ft long section, which also added sealed end areas of crosscuts, were ignited (still with an open ended main drift), and pressures at corresponding locations were somewhat higher.

*Since mine working face gas explosions are worst case scenarios in active sections (not near gob seals), we plan to use these cases in which the methane gas volume is that from a 50 to 60 ft long filled end section and open drift, representing a fairly large volume in the 8000 cu ft range of ideal mixture.*

Ignition Point

The location of the ignition point relative to the closed end face of the gas volume dramatically affects the blast pressure in these open-ended configurations (again, considered the most representative for refuge station design). Maximum gage pressures were reached only when the ignition source is close (0 ft was 25 psig; 8 ft was 17.5 psig) to the closed "working" or end face of a 50 ft long test volume using the 9.5 percent maximum pressure methane percentage [69].

*Since a likely source of ignition is near the face in a working mine, in which new material is being exposed by mining heads, we will assume that ignition is in the inby end causing maximum pressures.*

**8.4   Mine Configuration**

Distance from Ignition

The distance from explosion origin generally attenuates the pressure peaks, but this must be considered in conjunction with the presence and number of intervening crosscut passages. In a typical mine layout, there will be intervening crosscuts, either off one side or off both sides of the drift. However, LLEM test No. 347 [73] was conducted in their C-drift with at least the first four crosscuts sealed off out to 350 ft outby the face. Crosscuts were located on one side only (at approximately 100 ft intervals on center, starting about 50 ft outby the face, but the seals were set into the crosscuts providing a slight expansion volume at their locations. The gage pressure traces at many distances progressing down from the blast origin are shown in Figure 3 (again,
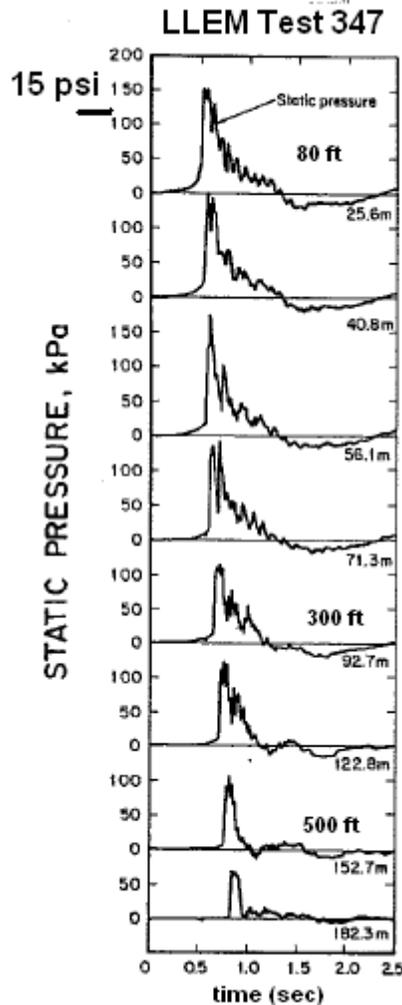
**LLEM Test 347**

15 psi

STATIC PRESSURE, kPa

time (sec)

*Figure 3.  LLEM Test  No. 347 with sealed crosscuts out beyond 350 ft*

gage pressures do not include the dynamic component, but are more suitable for the likely shelter or station locations off drifts in crosscuts).

This shows that the initial pressure peak in the 20+ psi range decreased with distance, and at the 300 ft mark, pressures were about 15 psig. Also the characteristic decaying transient pressure signature is typical, with the peak averaging 0.2 to 0.25 sec, then decaying towards low values.

For another estimate of the effect of distance with a smooth sided passage having no crosscuts at all (not even sealed recesses), we can refer to [68] in which LLEM tests  No. 468, 469 and 470 used the single-tunnel D-drift with gas volumes of 12 ft, 25 ft and 40 ft, respectively. This is not a typical or even likely actual mine configuration (smooth "gun barrel"). In No. 468 and 469, in which explosive gas volumes were lower, there was a 25 percent reduction at the 500 ft mark, likely due to passage wall/roof/floor friction and heat loss/condensation. For No. 470, there was little pressure diminution until the 500 ft distance was reached. This implies that there is usually a diminution effect with distance only in smooth tunnels, but for large gas volumes (larger

106

energy), one may not be able to always count on this reduction to be significant, at least outby to 500 ft with large volume explosions.

Effect of Crosscuts

The reductions of blast pressure resulting from passage of open crosscuts or similar crossing passages can be assessed, and are significant. From [68], LLEM tests No. 484 and 485 used the B-drift which had *two-sided* intervening crosscuts. We see that peak gage pressures at the 500 ft mark are approximately 1/3 those inby at the face area, with the passage of five crosscuts. Also, in much earlier tests [69], there was a similar factor of 3 reduction at the same distance in a similar configuration of both mine and explosive gas percentage and volume. It seems reasonable to estimate the effect in this form:

$$P_{distance} = P_{origin} \times (f_{cc})^n \text{ , where}$$

$P_{distance}$ = Peak pressure at the reference distance

$P_{origin}$ = Peak pressure at the blast origin

$f_{cc}$ = Passage reduction factor for that type of crosscut

The No. 484 and No. 485 tests used the end wall (face) vented into the open B-drift with ignited gas volumes of 25 ft and 40 ft passage length respectively, filled with ideal 10 percent methane, and ignited near the face. The [69] tests also included these conditions. This represents as mentioned, a typical situation but with the maximum effects of ideal mixture, reasonably large gas volume, and ignition at or near the working face.

In these cases, passage of five crosscuts and a total reduction in peak pressure to 1/3 of the inby value yields an average reduction factor per crosscut of about 0.80 using the above formula. These are subject to variations, but give a good order of magnitude, and clearly show that passage of more than a few open crosscuts of any type leads to significant peak pressure reductions. These tests embodied mostly two-sided crosscuts although in the early tests [69] there may have been some one-sided cuts if C-drift were used. In other reported data [75], there is reference to other two-sided crosscut passings resulting in a slightly greater reduction per passage (smaller factor than the 0.8 above).

These factors would be a little larger (i.e., cause less reduction) if crosscuts were partially blocked by equipment or partial stoppings. In that case, since a totally sealed passage with the seal very close to the drift (blast route outby the origin) shows small reduction, it would be conservative to estimate raising these factors to approximately 0.9 for major blockage. This is admittedly a great simplification of complex phenomena, but it conveys the general facts. If there is a combination of partially blocked/1-side or 2-sided cuts, these can just be multiplied out in sequence for an estimate.

As an example, if a bulkhead station were located in a crosscut 500 ft outby the explosion (and in sufficiently to avoid direct shock impact), with passage of four mostly blocked crosscuts, using an initial peak gage pressure of 20 psi 50 ft from the face, that would lead to a bulkhead pressure value of about

$$20 \text{ psig} \times (0.9)^4 = 13 \text{ psig}$$

This corresponds reasonably well with the results for LLEM 347, in which crosscuts were sealed but with some expansion volume outside the main drift ahead of the seals.

*Summary: the likely distance from a blast origin, if at a working face, would be no closer than 500 ft based on mining logistics. Therefore, the principal effect of this distance would be the presence of intervening open or partially open passages (crosscuts or other intersecting drifts). Based on peak gage pressures at a blast originating at a closed face, with the blast vented outby through a single drift with intervening passages, the likely range of origin pressures based on tests would be in the 25 to 30 psig range or lower. With the presence of at least 3 to 4 open crosscuts in that 500 ft, gage pressures at the nearest station location would be in the 15 psig peak range (transient peak in the 0.25 sec range) as a working design value. Unusual situations with no open crosscuts or even sealed drifts (only test situations or explosions behind gob seals) could lead to higher pressures, justifying use of a reserve strength capability in bulkhead station design.*

### 8.5   Location and Placement of Refuge Station

The selection of general location areas for bulkhead-based refuge stations is discussed in Section 6.4, in which the logistics and mix of fixed and portable stations for rapid personnel access and repositioning with mining progress is addressed. Here, with the distance issue covered previously, the local positioning of the stations based on minimizing blast pressures is discussed.  In most mine layouts, the favored position for any station would be in a stub-ended crosscut, possibly one created specifically for such a station.

The primary objective in station location is to minimize blast pressures by preventing the aerodynamic (wind) pressure component from striking the bulkhead wall, thereby avoiding direct shock impact. The relative magnitudes of the direct ("total") pressure versus the gage (ambient, or "static") pressure value can be seen in LLEM test data and MHSA evaluations such as in test No. 506 [76] and 498 [75].  In test No. 506 values are high due to the test configuration comprising a totally sealed chamber (crosscuts and main drift sealed by walls). This test setup (annotated) is shown in Figure 4.

Both tests used very large volumes of explosive gas in the 12,000 to 14,000 cu ft range[1], also. However, these later tests did use rapid-response pressure instrumentation which could capture total and gage pressure traces versus time. (Total pressure was measured with gages aimed at the

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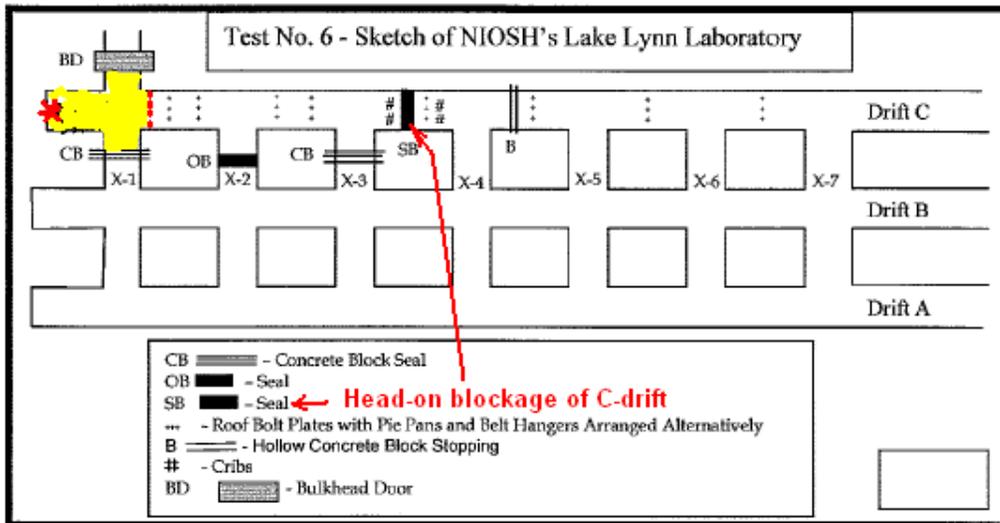[1] 71-ft section outby the face plus portions of crossing passages.

Figure 58 – Test set-up for Test No. 6 (LLEM #506).

Appx location of gas containment membrane @ 71 ft from ignition @ face

Ignition location @ face, end of C-drift

Gas-filled zone (appx 10% CH4)

**Figure 4. LLEM Test No. 506 test setup with sealed gas volume**

blast direction, called "horizontal," while gage pressures at ribs either in the main drift or in crosscuts at seal walls are aimed away from the blast direction, called "vertical").

The test No. 506 showed a short total pressure peak of 42 psi (gage + aerodynamic) fairly close to the blast at 256 ft outby the blast face (at sealed X-C 3), and a nearby gage pressure sensor at 234 ft read about 30 psig at the same time. The total pressure peak was shorter than 0.1 sec, and the gage pressure peak about 0.12 sec. These test results (annotated) are shown in Figure 5. This gives the approximate proportion of the total represented by the aero pressure (1/3) in this case. (This test also had a sealed cavity with a walled-off drift, which failed quickly as pressure passed the 5 psi range.) In another well-instrumented test No. 498, results were similar and also showed diminution with distance.

Therefore, siting the station within a crosscut, which would not likely be in the direct path of the blast wave, is desired. From considerations of shock diffraction and "turning the corner" at the start of such a crosscut or intersecting passage, others have suggested that the sealing wall (in our case, the bulkhead station wall) be away (in) from the main drift rib, to avoid the undesirable effect of a high pressure reflection on the far side of the cut then impacting the wall. Reflected shocks in mines have been observed [76], and these can show total pressure levels much higher than that of the original incoming wave, due to mutual reinforcement of peaks. Thus, a brief study of the shock front behavior at a corner moving in the 1600 ft/sec range (higher speeds for higher pressures), would indicate that the wall should be set back at least 1 to 1.5 passage widths from the main drift in which an explosion is more likely to occur. A flush location is less desirable since this would expose the wall to potential debris, and also offer no protection
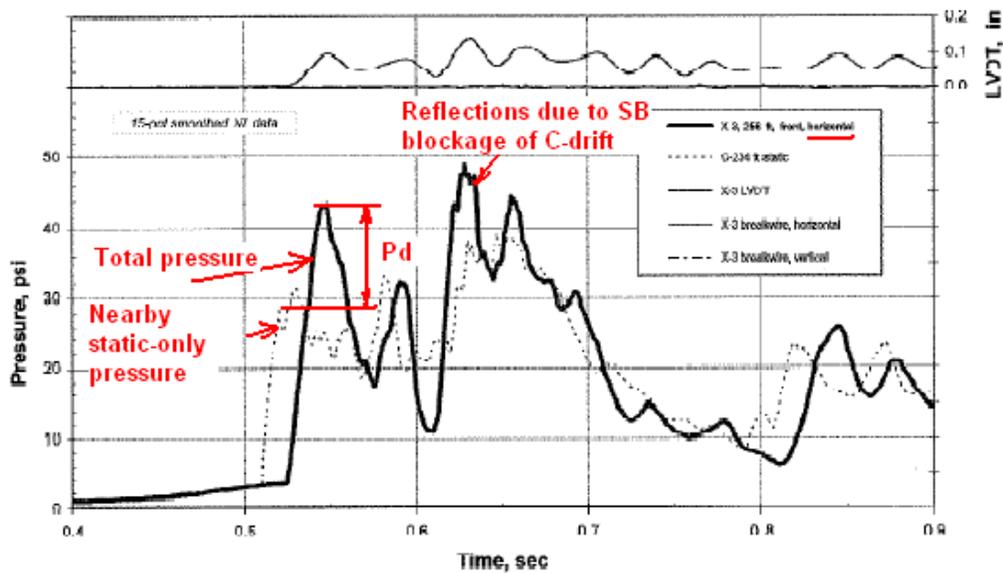
Figure 60 – Pressures and LVDT displacement at the X-3 seal during Test 6.

Pd=Appx dynamic component of pressure @ X-3 = appx 15 psi

Static pressure peak = 28-30 psi

*Figure 5.  LLEM Test  No. 506 showing relation of gage and total pressure
and reflection pressure at 250 ft distance from face*

for personnel in the main drift for explosions of any level. Further, the junction would have to be truly flush so as not to cause a local shock reflection.

Where possible, the wall should be at least 1 to 1.5 crosscut widths inset away from a main drift in which an explosion is more likely to occur.

### 8.6    Effects of Flame Fronts on Refuge Stations

The blast characterization analysis in Sections 8.4 and 8.5 shows that the flame front and resultant pressure wave last for a small fraction of a second.  We believe that MSHA's existing flame-resistance requirement (30 CFR 7.24) will govern the design of the exterior components of the refuge station.

### 8.7    Type of Pressure Appropriate For Bulkhead Refuge Station Wall Design

If the blast wave is incoming down a main or drift, and the refuge is placed in a crosscut 1 to 1.5 passage widths in, the pressure applied to the wall itself would be much closer to the gage pressure (pressure in all directions at that point, sometimes termed "static") rather than the "total" pressure which would include the additional aerodynamic loads on objects directly facing the blast wave. Also, if the blast somehow occurred in a drift or other passage not at the mine working end, unless it happened to occur directly in view of the crosscut or passage containing the station, likewise would the aerodynamic component not be a major factor. (In that latter case,

110

there would also be even less "containment" effect from an absent end face, so all pressures would be lower.)

### 8.8    Potential Blast Loadings to Use for Bulkhead-Type Refuge Station Design

As discussed above, transient blast pressure loadings have been shown to vary widely with the blast parameters. After a thorough review of these and other tests and evaluations of in-mine behavior of methane-only explosions, the transient gage pressure applied to a bulkhead face would be at or below the 15 psig transient trace shown in Figure 6, except for rare cases in which many of the parameters cited all have coincided in their optimum fashion. Thus, this 15 psig/ 0.3 sec load transient was developed to represent actual "working" load conditions for a bulkhead refuge station considering its placement in the mine. This peak average "top" equals or exceeds the great majority of blast situations, so as to represent a reasonable design basis for the survival and functioning of the refuge. This is a common approach in safe design of many structures and vehicles. While magnitudes exceed this in rare circumstances, the many tests at LLEM have shown that the maximum pressure peak time durations from methane explosions are no longer than ¼ or 1/3 sec, so that this transient nature of the load for methane-only explosions is well accepted.
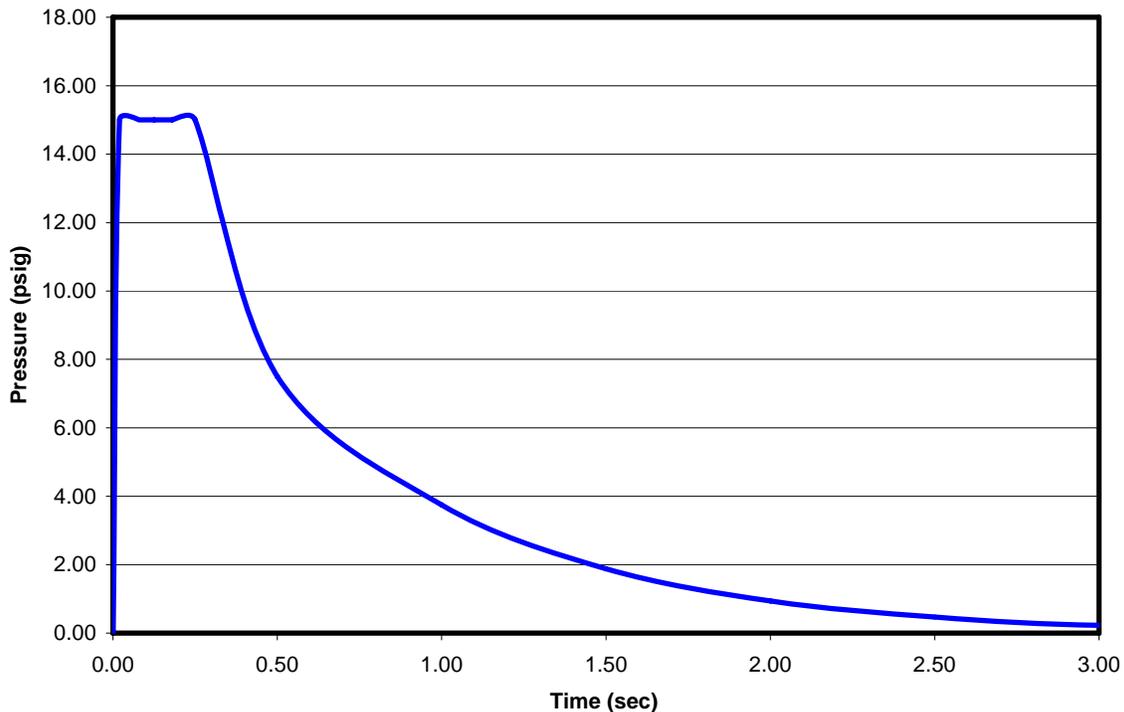
**Design Basis Pressure Pulse--Mine Blast**



*Figure 6.  Mine blast pressure-time "design pulse" at potential refuge station bulkhead locations*

111

### 8.9 Summary of Blast Characterizations

This section characterizes the major elements affecting transient blast peak pressures. Many of the unpredictable factors such as gas concentration and ignition location relative to the gas were taken conservatively to be their maximum. The others have a rational basis for estimating their contribution, and in the development of the design criteria, these were taken to be consistent with the range of locations, distances, mine configurations, and likelihood of multiple coincidences judged to be representative of the great majority of blast scenarios. A working load condition of 15 psig for 0.3 seconds has been concluded for coal mine refuge station bulkheads, as explained in Section 8.8 and Figure 6 design pulse.

# 9. Cost Estimates/Comparisons for Refuge Types

## 9.1 Introduction

Table 36 contains cost estimate comparisons for the various types of portable refuge chambers and bulkhead refuge stations studied in this project. Two types of commercially available portable chambers are included in the table:

- Rigid shell type chambers that are fully equipped with all needed supplies and ready for immediate access in the event of an emergency.

- Inflatable type chambers that are also fully equipped with all needed supplies but which would need to be deployed (inflated) by personnel before use in the event of an emergency.

*Table 36. Refuge station cost comparisons*

| | Item | Portable Chamber<br><br><br><br><br><br>Rigid Shell | Portable Chamber<br><br><br><br><br><br>Inflatable | Bulkhead Station<br><br>Energy Absorbing Chute System | Bulkhead Station<br>Panelized Blast Reduction Media System |
|---|---|---|---|---|---|
| 1 | BASIC STATION STRUCTURE | | | | |
| 1.1 | Commercial portable, relocatable refuge chamber | $80,000 to 100,000 | $80,000 to 100,000 | | |
| 1.1.1 | Anchoring system for portable chamber | $1,000 | $1,000 | | |
| 1.2 | Mine-constructed, 2-part bulkhead refuge station (partially relocatable); all materials and labor for *initial installation* | | | | |
| 1.2.1 | Energy-absorbing chute system | | | $20,000 to 21,000 | |
| 1.2.2 | Panelized blast reduction media system | | | | $10,400 to 10,900 |
| 1.2.3 | Inner fiber-reinforced concrete block wall and manway system | | | $17,600 to 18,500 | $17,600 to 18,500 |
| 1.2.4 | Stocking refuge station with all supplies (air cylinders, $CO_2$ scrubbing, food, water, sanitation supplies) - LABOR ONLY assumes 8 manhours for a laborer | | | $200 | $200 |
| 1.2.5 | Engineering services for oversight (16 hr) (bulkhead only) | | | $800 | $800 |

*Table 36. Refuge station cost comparisons (continued)*

| | Item | Portable Chamber — Rigid Shell | Portable Chamber — Inflatable | Bulkhead Station — Energy Absorbing Chute System | Bulkhead Station — Panelized Blast Reduction Media System |
|---|---|---|---|---|---|
| 2 | SERVICES | | | | |
| 2.1 | Lot price for basic living services per "Mine Lifeline" outby refuge system; includes: Breathable air cylinders, Carbon dioxide scrubbing (LiOH curtains), Living supplies (food, water, blankets, medical, tools, reading materials), Chemical toilet and related equipment | Included | Included | $45,000 | $45,000 |
| | TOTAL for Initial Installation (see Note 1) | $81,000 to 101,000 | $81,000 to 101,000 | $83,600 to 85,500 | $74,000 to 75,400 |
| 3 | REFUGE STATION REDEPLOYMENT (each movement to new location) | | | | |
| 3.1 | Commercial portable, relocatable refuge chamber (assumes one 8-hr shift for two workmen) | $500 to 700 | $500 to 700 | | |
| 3.1.1 | Anchoring system removal and redeployment | $1,000 | $1,000 | | |
| 3.2 | Mine-constructed, 2-part bulkhead refuge station (partially relocatable); all materials and labor for *each redeployment* | | | | |
| 3.2.1 | Energy-absorbing chute system | | | $4,500 to 4800 | |
| 3.2.2 | Panelized blast reduction media system | | | | $3,000 to 3,200 |
| 3.2.3 | Backup fiber-reinforced concrete block wall and manway system | | | $11,900 to 12,500 | $11,900 to 12,500 |
| 3.2.4 | Removal, movement and restocking of all station supplies and equipment - LABOR ONLY assumes 12 manhours for a laborer | | | $300 | $300 |
| 3.2.5 | Engineering services for oversight (16 hrs) (bulkhead only) | $600 | $600 | | |
| 3.2.6 | Inspection and certification, after relocation (portables only) | | | $800 | $800 |
| | SUBTOTAL for each redeployment | $2,200 | $2,200 | $17,500 to 18,400 | $16,000 to 16,800 |
| | SUBTOTAL (for example of 5 redeployments) | $11,000 | $11,000 | $87,500 to 92,000 | $80,000 to 84,000 |
| | TOTAL (Installation and 5 Redeployments) | $92,000 to 112,000 | $92,000 to 112,000 | $171,100 to 177,500 | $154,000 to 159,400 |
| 4 | BOREHOLE PLACEMENT (assumes 700 ft depth; 6 in. diameter) (*Bulkhead Station receives cost credit from elimination of stand-alone atmosphere control system) | $42,000 | $42,000 | $2,000* | $2,000* |
| Note 1 | Bulkhead-based station estimates show a range based on lower costs for smaller bulkheads in lower coal seams. | | | | |

Two types of bulkhead refuge stations are also included in the table:

- An energy-absorbing "chute" system with reinforced block wall.
- A panelized blast energy reduction media system with reinforced block wall.

Both of these bulkhead type refuge stations are two-part systems, each with an outer blast protection system and an inner fiber reinforced, sealed concrete block wall and manway system. A bulkhead-based refuge station can also be outfitted with a borehole that would eliminate the need for many of the life-support services that would be required; however, in many applications boreholes may not be viable due to cost as well as installation difficulties due to surface terrain and location. We have provided a cost estimate for boreholes as an optional add-on.

Detailed descriptions of the portable chambers and bulkhead type systems contemplated for this project, including discussions of their design and construction features as well as their supplies of equipment and living provisions, are provided in Appendix D and Section 10. Summary descriptions of the systems as presented in Table 36 are provided in Sections 9.2 and 9.3 below.

The following are notes and assumptions regarding the cost estimates in the table:

1. Table 36 contains summarized cost estimates for each type of portable chamber and bulkhead refuge station. Detailed tables showing the basis of the cost estimates for the two-part bulkhead stations are provided in Tables 37, 38, and 39.

2. The two portable chamber types assume a nominal capacity of 16 miners. The bulkhead stations also assume a capacity of 16 miners from the standpoint of stores of supplies and atmosphere-supporting equipment, though the size of the contained mine entry behind the bulkheads may be able to support considerably more people.

3. The cost estimates for the bulkhead stations are provided as ranges based on varying seam heights and entry widths.

4. The cost estimates for the portable chambers are provided as ranges because a variety of manufacturers supply them and their prices vary significantly. For completeness, we have shown both rigid and inflatable chambers in the table; however, the price ranges for these two chamber types were found to be similar and so appear the same for each type in the table.

5. Estimates are provided for the labor required to locate and install each type of refuge station including inspection and final sign-off. Estimates are also included for the labor to inspect portable chambers after relocation and to verify that they remain fit for use.

6. In addition to *initial installation* cost estimates associated with each refuge station type, costs are also estimated for *relocation and redeployment* (at approximate 1,000 ft intervals) as mining progresses. The relocation and redeployment estimates are

*Table 37.  Construction cost estimate for energy-absorbing chute system*

| Item | Category | RU or NR | Unit Cost | Quantity | Total Cost |
|---|---|---|---|---|---|
| Fabricated Chute | Material | (RU) | $  5,000 | 1 | $  5,000 |
| Energy-absorbing Shrouds | Material | (RU) | $  60 | 64 | $  3,840 |
| Mechanical Chute Hardware | Material | (RU) | $  20 | 64 | $  1,280 |
| Chute Support Frame | Material | (RU) | $  500 | 1 | $  500 |
| Steel Perimeter Reaction Frame | Material | (RU) | $  7,200 | 1 | $  7,200 |
| Frame to Mine rock bolts | Mat+Labor | (NR) | $  65 | 36 | $  2,340 |
| Assembly and Checkout | Labor | (MH-NR) | | | |
| Skilled | | | $  30 | 16 | $  480 |
| Unskilled | | | $  20 | 16 | $  320 |
| **Total For Installed System** | | | | | **$ 20,960** |
| Disassembly | Labor | (MH-NR) | | | |
| Skilled | | | $  30 | 8 | $  240 |
| Unskilled | | | $  20 | 8 | $  160 |
| Transport to new location | Service | (MH-NR) | | | $  1,200 |
| Reassembly | Labor | (MH-NR) | | | |
| Skilled | | | $  30 | 16 | $  480 |
| Unskilled | | | $  20 | 16 | $  320 |
| New NR components | Mat+Labor | (NR) | | | $  2,340 |
| **Total For Redeployed System (after initial)** | | | | | **$  4,740** |
| Notes:<br>  (RU) = Re-Usable<br>  (NR) = Non Recoverable<br>  (MH) = Man Hours | | | | | |

significantly less than initial installation because all of the reusable and non-consumed materials (such as all of the living supplies, etc.) are one-time costs only.

7. Non-perishable supplies are estimated as one-time costs only.  For comparison it is assumed that non-perishable supplies are not utilized and do not require replacement. Also, the replacement cost of perishable supplies that would require occasional replacement is ignored because all systems would incur identical costs.

8. In addition to cost estimates for initial installation as well as single relocation and redeployment, we have also provided estimates of the *total* costs associated with five cycles of relocation and redeployment to show how estimated costs will accrue as mining progresses.

9. The cost estimates *do not* include initial receipt, unpacking, inspection or movement of chambers or construction materials into the mine for initial installation.

**Table 38. Construction cost estimate for panelized blast reduction media system**

| Item | Category | RU or NR | Unit Cost | Quantity | Total Cost |
|---|---|---|---|---|---|
| Fabricated Blast Media Panels | | | | | |
| (Costed on per sq ft basis, 130 sq ft req/d for 20 ft x 7 ft less door opg) | | | | | |
| Energy-absorbing Material Packs | Material | (RU) | $ 36 | 150 | $ 5,400 |
| Fabricated expanded metal panels | Material | (RU) | $ 200 | 16 | $ 3,200 |
| Assemble 1 set of panels | Assy Labor | (RU) | $ 30 | 24 | $ 720 |
| Assembly hardware (onto block wall) | Material | (NR) | | | $ 750 |
| Assembly and Checkout | Labor | (MH-NR) | | | |
| Skilled | | | $ 30 | 16 | $ 480 |
| Unskilled | | | $ 20 | 16 | $ 320 |
| **Total For Installed System** | | | | | **$ 10,870** |
| | | | | | |
| Disassembly | Labor | (MH-NR) | | | |
| Skilled | | | $ 30 | 8 | $ 240 |
| Unskilled | | | $ 20 | 8 | $ 160 |
| Transport to new location | Service | (MH-NR) | | | $ 1,200 |
| Reassembly | Labor | (MH-NR) | | | |
| Skilled | | | $ 30 | 16 | $ 480 |
| Unskilled | | | $ 20 | 16 | $ 320 |
| New NR components | Mat+Labor | (NR) | | | $ 750 |
| **Total For Redeployed System (after initial)** | | | | | **$ 3,150** |
| Notes: (RU) = Re-Usable (NR) = Non Recoverable (MH) = Man Hours | | | | | |

10. Cost estimates to supply boreholes to the portable chambers or bulkhead stations are not included in the base cost comparison because portable chambers are provided with self-contained atmosphere systems and we have assumed the same basis for bulkhead stations. Providing boreholes is considered a separate option for the purposes of cost comparison. The rough cost of installing a 6 in. borehole is approximately $50 to $60 per foot of drilled hole depth (including equipment mobilization costs) depending on strata to be drilled, including hole casing and connections to pumps above and to the chamber or station below. The cost of surface site access is not included and would vary widely based on surface conditions and terrain. For bulkhead-based stations the added cost of a borehole is offset by the elimination of modularized atmosphere control and support systems. In portable chambers, atmosphere systems are permanent and integrated fixtures, hence, the costs of boreholes are provided without offset. In addition, a refuge chamber would need a flexible coupling to the borehole which is not estimated.

**Table 39. Construction cost estimate for backup fiber-reinforced concrete block wall and manway system**

| Item | Category | RU or NR | Unit Cost | Quantity | Total Cost |
|---|---|---|---|---|---|
| Mine passage surface preparation | | | | | |
|   Skilled | Labor | (MH-NR) | $ 30 | 2 | $ 60 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Foundation Construction | Material | (NR) | $ 40 | 12 | $ 480 |
|   Skilled | Labor | (MH-NR) | $ 30 | 2 | $ 60 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Block wall construction | Material | (NR) | $ 4 | 140 | $ 560 |
|   Skilled | Labor | (MH-NR) | $ 30 | 8 | $ 240 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 8 | $ 160 |
| Compliant sealing to roof and ribs | Material | (NR) | $ 15 | 34 | $ 510 |
|   Skilled | Labor | (MH-NR) | $ 30 | 4 | $ 120 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Rear surface fiber/composite reinforcement | Material | (NR) | $ 10 | 130 | $ 1,300 |
|   Skilled | Labor | (MH-NR) | $ 30 | 4 | $ 120 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Front surface sealing layer | Material | (NR) | $ 8 | 130 | $ 1,040 |
|   Skilled | Labor | (MH-NR) | $ 30 | 4 | $ 120 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Wall angle supports (front and rear) | Material | (RU) | $ 36 | 68 | $ 2,448 |
|   Skilled | Labor | (MH-NR) | $ 30 | 6 | $ 180 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 6 | $ 120 |
|   Attachments (rock bolts) | Inst Cost | (NR) | $ 65 | 44 | $ 2,860 |
| Manway blast door and support structure (front and rear) | Prefabr Assys | | | | |
| | Front | (RU) | $ 1,800 | 1 | $ 1,800 |
| | Rear | (RU) | $ 900 | 1 | $ 900 |
|   Skilled | Labor | (MH-NR) | $ 30 | 4 | $ 120 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
|   Attachments (rock bolts) | Inst Cost | (NR) | $ 65 | 24 | $ 1,560 |
| Furnish & Installation of Air Lock/Knife System (34" w x 42" h) | Purch Assy | (RU) | $ 3,000 | 1 | $ 3,000 |
|   Skilled | Labor | (MH-NR) | $ 30 | 4 | $ 120 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 4 | $ 80 |
| Final Assembly and Checkout | | | | | |
|   Skilled | Labor | (MH-NR) | $ 30 | 2 | $ 60 |
|   Unskilled | Labor | (MH-NR) | $ 20 | 2 | $ 40 |
| **Total For Installed System** | | | | | **$18,538** |
| | | | | | |
| Disassembly | | (MH-NR) | | | |
|   Skilled | Labor | (MH-NR) | $ 30 | | $ 210 |
|   Unskilled | Labor | (MH-NR) | $ 20 | | $ 140 |
|   Rock bolt (nut) removal, unit cost | | (MH-NR) | $ 8 | 68 | $ 544 |
| Transport to new location | Service | (MH-NR) | | | $ 1,200 |
| Re-Installation | Matl +Labor | | | | $10,390 |
| **Total For Redeployed System (after initial)** | | | | | **$12,484** |
| Notes:<br>  (RU) = Re-Usable<br>  (NR) = Non Recoverable<br>  (MH) = Man Hours | | | | | |

11. The cost estimates *do not* include installation and extension of lifelines to and from refuge stations and do not include SCSRs (it is assumed that mines will purchase all required SCSRs as part of compliance with existing MSHA and state regulations).

12. The cost estimates in Table 36 are rough order of magnitude estimates (ROMs) and are represented in 2007 U.S. dollars.

## 9.2    Description of Cost Estimates for Portable Chambers

In Table 36, the cost estimates for initial installation of portable refuge chambers are all inclusive with the exception of an anchoring system.  Hence the estimates include all living services such as breathable air or oxygen, $CO_2$ scrubbing, food, water, sanitation facilities and privacy barrier, blankets, chairs, basic tools, medical and first aid supplies, gas monitoring meters, entertainment items, etc.

Separate cost estimates are provided for anchoring portable chambers in place.  This is necessary to prevent damage due to lateral movement or rotation of the chambers from the forces of a severe explosion.

Section 3 of Table 36 provides the cost estimates for relocation and redeployment of the portable chambers for each mining advance (or retreat) of approximately 1,000 ft.  For portable chambers, we estimate one 8 hr shift for two miners to make any necessary disconnections and move the chamber to its new location.  An additional cost factor is provided for disassembly of the rock-bolted anchoring system and its reinstallation at the new location.

In the bottom portion of Table 36, the total cost estimates for a single relocation and redeployment are provided, along with a cost estimate for five relocations and redeployments.  Finally, at the bottom of the table, the total cost estimates for the initial installation and five example relocations are provided.

## 9.3    Description of Cost Estimates for Bulkhead Refuge Stations

As noted earlier, cost estimates are provided in Table T9-14 for two types of bulkhead refuge stations: the energy absorbing chute system and the panelized blast reduction media system.  Each type of station is a two-part system that in both cases also includes a fiber-reinforced concrete block wall, with integral manway, which is secured to the mine floor, roof and ribs.  In both systems, the fiber-reinforced concrete block wall provides the actual inner barricade behind which the miners would retreat during use.  The energy absorbing chute or panelized blast reduction media provides a dynamically-acting, shock absorbing outer barrier that takes the brunt of the force from an explosion and protects the inner block wall.  More detailed descriptions of these systems are provided in Section 10.

The cost estimate for the energy absorbing chute system includes separate line items for the chute component, the inner fiber-reinforced concrete block wall, a lot estimate for all of the required living services plus a minor component for stocking the bulkhead with the living

services and supplies.  In the case of the bulkhead designs, the living supplies must be removed and restocked with each relocation as mining progresses.

The lot cost estimate for the living services and supplies for the bulkhead designs are based on the materials supplied with the pre-built refuge system provided by Mine Lifeline LLC and includes all living services such as breathable air or oxygen, $CO_2$ scrubbing, food, water, sanitation facilities and privacy barrier, blankets, chairs, basic tools, medical and first aid supplies, gas monitoring meters, entertainment items, etc. similar to the portable chambers.

The cost estimate for the panelized blast reduction media system also includes separate line items for the panelized blast media component plus the same inner concrete block wall as utilized with the energy absorbing chute system.  It also includes the same lot estimate for all of the required living services along with the same estimate for stocking the bulkhead.

The cost estimates for both of the bulkhead systems assume that the stations are built within a dead-ended cut and not a through crosscut.  Estimates are provided for only a single set of inner concrete block and outer blast protection walls.  If the station were to be built within a through crosscut, another barrier would need to be provided at the other end of the station.

In the case of each bulkhead system, separate cost estimates are provided for relocation and redeployment.  In both cases, these costs are significantly less than the costs of the initial installation because many of the components of the outer blast protection wall are reusable at the new location.

Separate cost estimates are also provided for relocation and construction of a new inner concrete block wall at the new location.  The costs to prepare the new inner wall are not substantially lower than the initial installation because only certain wall angle supports and the manway system within the wall are reusable at the new location.  The old walls remain in place. They can be reused later for bulkhead refuge stations during retreat mining, significantly reducing costs at that time.

In the bottom portion of Table 36, the total cost estimates for a single relocation and redeployment are provided, along with a cost estimate for five relocations and redeployments. Finally, at the bottom of the table, the total cost estimates for the initial installation and five example relocations are provided.

As discussed in Section 6, we recommend establishing an initial bulkhead-based station within a dead-ended working section as soon as possible after the section has advanced deeply enough to accommodate it.  This will provide refuge to miners who could become trapped within the dead-ended section by fires or explosions that might occur either inby or outby in the adjoining main entries.  In this case, the provision for a borehole-fed station is advantageous if depth and surface conditions permit.  Unlike other refuge stations, this refuge would remain as a permanent installation.  The incremental cost for adding a borehole (assumed at 700 ft length) would bring the cost estimate for a bulkhead-based station to approximately $76,000 to $88,000

including the cost reduction from eliminating the stand-alone atmosphere control system which would not be needed.

Cumulative costs as mining advances will be greater for bulkhead stations when compared to portable refuge chambers. However, bulkhead systems offer advantages of greater strength and permanence in certain situations and may be the more viable option under some mining conditions, such as low coal, where use of portable chambers may not be as feasible.

### 9.4 Details of Refuge Station Cost Estimates

Tables 37, 38 and 39 provide supporting detail for the cost estimates for bulkhead-based refuge systems presented in Section 10.

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# 10.  _Bulkhead Based Station_

## 10.1  _Primary Design Drivers_

The bulkhead-type refuge station will comprise a barrier across an appropriately-selected mine passage, such as a mined-out crosscut (stub), behind which a relatively large "safe" area is thereby created.  The main advantage of this large area is that it provides for storage of ample survival materiel, such as air reserves; food, water, and medical supplies; and facilities for rest and communication.

The bulkhead refuge station must survive a potential mine blast and the location of this refuge station relative to possible blasts is discussed in Section 6.   This location bears directly on the potential range of blast loadings driving the design.

This bulkhead system must survive undamaged to the degree that it is fully capable of providing a safe refuge area behind, including sealing off any contaminating gases from the blast side. It also must provide for inclusion of a suitable entry/exit way to be used by mine personnel making use of the refuge station.  This entry should also allow for transfer of survival equipment. In the proposed barrier systems, it is assumed that this entry way subsystem could accommodate installation of a premanufactured airlock or appropriate transfer apparatus capable of personnel transfer while preventing entry of noxious gases into the refuge area.  This would be protected from direct blast damage by a covering door system and support structure capable of resisting the range of potential blast loads; however, this entry system would also be designed such that it could be easily installed after the refuge is prepared and stocked, so that all such materiel could be passed through a relatively large doorway-size opening in the bulkhead system beforehand.

The bulkhead design should also consider costs of installation, and take advantage of the fact that the locations of these refuge stations could be changed depending on progress of mining operations.  This means that the design configuration should have as many elements as possible capable of being removed and reused at the new location to reduce repetitive costs.  Any permanent elements therefore should be designed in a cost-effective manner, and use materials and techniques already familiar to mine operators and workers wherever possible.  The reusable bulkhead system components would likewise consider low cost in their design, plus ease of assembly, transport and general ruggedness in the in-mine environment.

The summary of the principal design drivers for the refuge station is as follows:

- Survival of potential mine blast loads and temperatures, remaining fully functional and operational after such an event.

- Sealing off any contaminating gases.

- Provision for inclusion of a suitable manway, with potential installation after stocking of the station.
- Use materials and techniques already familiar and acceptable to miners whenever possible.

- Include removable and re-usable elements for new refuge locations to minimize repetitive costs.

### 10.2  Potential Blast Loadings for Refuge Station Bulkhead Design

As discussed above, a "design pulse" shown previously in Section 8, Figure 6 (a 15 psig/ 0.3 sec maximum load, then decaying over 2 sec) was developed to represent actual "working" load conditions for a bulkhead refuge station considering its placement in the mine. This is intended to envelop, or consider, the great majority of blast situations, so as to represent a reasonable safe design basis for the certain survival and functioning of the refuge. If rare or very infrequent explosion scenarios arise, there will be provision made in the bulkhead design for reserve strength using the ultimate load capabilities of the structures involved.

**Principal Design Approach for Refuge Station Bulkhead Design**

Working-Level and Ultimate Strength Reserve Loading Approach

The 15 psi 0.3 sec decaying transient pressure design pulse, shown in Section 8, Figure 6 was used as a "working level" loading. This means that the bulkhead system must utilize "working level" stresses and deflections so as to survive this loading in all respects for safe operation and use after such an event occurs.  The possibility of higher pressures occurring in extreme conditions led the inclusion of a significantly larger "ultimate strength" capability for the bulkhead system configurations as a defense against these very unlikely situations, without unnecessarily leading to overly massive designs.  This combination of "working level stress" and "ultimate strength" design is the usual and accepted approach for infrastructure elements such as buildings, bridges, tunnels, etc., which typically utilize a factor of safety of 50 percent in extreme failure/overload.  For very short dynamic loading, relative to the mass/frequency response of the structure, the effective factor of safety may be somewhat higher.

Analytical Basis

Following this approach, therefore, led to the use of both static load calculations using "working stresses" for all components, and employment of advanced dynamic finite-element (FE) structural simulations of the candidate bulkhead structures to evaluate their reserve capabilities which could approach their ultimate strength or failure. These evaluations can now be made using advanced finite-element (FE) computer simulations well proven in automotive crash design, aerospace structures, and blast impacts on vehicles.

Such FE analysis modeling can contain all the key behavior of the structures and their materials beyond their working stress levels up to and including ultimate behavior. This includes the effects of large deflections, material plasticity and fracture, and has been extensively used and refined over the last 30 years for vehicle crashworthiness, building and bridge behavior in extreme earthquake and wind scenarios, aircraft and the like. The method used in this report utilized the LS-DYNA finite-element dynamic computer code as used worldwide, provided by the LS-DYNA Corporation. This entails constructing detailed FE models of all the major bulkhead system component concepts, including their material and geometric properties out to the extreme high end of their capability.

By their nature, these "ultimate strengths" are more difficult to predict and subject to more variation, since material properties, details of construction, the assumptions of the loadings, and the limitations of these analytical simulations themselves all make the results statistically subject to wide variation. Therefore, such strength capability should be relied upon primarily to capture correspondingly extreme or very rare events.

## 10.3  General Configuration of Proposed Blast Wall Systems

The blast protection system concepts embody this two-level "working level" and "ultimate" or reserve level strength approach. This is achieved by envisioning a two-stage system installed across a mine passage crosscut to create a refuge station behind:

- The first stage, or primary layer, would initially be encountered by a potential blast front. This layer reduces blast pressure and absorbs energy, while surviving the nominal or "working level" 15 psi, 0.3 sec transient pressure design pulse load as shown in Section 8, Figure 6. Two design configurations are described for this first layer. It would not be relied upon to withstand more than the working level load, but would reduce higher loads on the second stage in the short transient load peak time duration.

- The second stage, or secondary layer, would comprise a sealed wall using familiar construction materials, augmented in some cases by additional materials to make the wall much more effective in pressure resisting strength. A range of such wall types was considered, but each would be required to withstand the "working load" pressure in the unlikely event that the first stage of protection above is overpowered in an overload situation. Such a wall would still have some reserve capacity in ultimate strength. This secondary wall system would also provide the necessary "hard seal" and entry/exit capability to form the actual refuge station itself.

## 10.4  Proposed Bulkhead Concepts

Two concepts were studied, which are assumed to be constructed across a 20 ft wide x 80 in. high mine cross-cut passage, to protect the area behind as a refuge for in-mine personnel after a blast. The area behind the bulkhead is assumed to be protected or stub ended; otherwise another bulkhead would have to be erected on the other end, which would not be cost-effective.

Both concepts follow the approach of having a 1) dynamically-acting, shock absorbing system element in front, with 2) a fiber reinforced and sealed hollow concrete block wall with manway (entry) system behind, secured to floor, ribs and roof. The block wall system (2) is shared by both concepts; only the first layer or stage (which initially resists the blast front) is different for the two concepts:

The first stage, or primary layer, would comprise:

- Item A:  An Energy-Absorbing Chute System.
- Item B:  A Panelized Blast Reduction Media System.

The second stage, or secondary layer, would comprise:

- Item C:  A sealed concrete block wall and manway system.

Each of these systems comprises both permanently installed and removable/redeployable components. Thus it is important to reduce costs when refuge stations are demobilized, moved forward, and re-established at a new location. Some of the elements are left behind permanently, such as the basic concrete block walls.

Therefore we define one concept as a combination of Item A and Item C above; and the second concept comprising a combination of Item B and Item C.

A.  Energy-Absorbing Chute System (EACS) As First Layer

This concept utilizes a large, lightweight parachute-like "chute" which would cover most of the mine crosscut opening (cross section).  It would be positioned such that an incoming pressure wave would quickly "inflate" it to fill nearly all (but not necessarily tightly) the crosscut opening and thereby protect the solid refuge wall behind it at least up to the level of the working level design pulse (Section 8, Figure 6).  Using a new-technology strong fabric comprising a coated version of ordinary automotive airbag material, it would withstand and dissipate the 15 psi/ 0.3 sec blast wave via 72 energy-absorbing shrouds, each capable of 3 ft of travel attached to a steel perimeter frame secured to the crosscut floor, roof and ribs.  All components of this system would be reusable when they are redeployed to a more inby location as mining progresses.

A schematic of this EACS is shown in Figure 7.

*Perimeter Frame*

The steel EACS perimeter frame uses a standard 8 in. x 3 in. steel channel (such as an MC 8 x 20 (lb/ft) channel, anchored flat flange side out to the roof, rib and floor by standard ¾ in. D roof bolts.  There would be no need for excavation except for rudimentary surface preparation to provide a reasonably flat surface.  This allows the energy-absorbing shrouds, evenly spaced at 1 ft intervals, to react their loads into the crosscut, and redistribute loads in the event of any shroud or rock bolt malfunction. The bolts used to fasten the channel are installed approximately at 18 in. intervals, and would have removable nut ends, to permit removal and re-use of the frame. The flanges on the outby side would be drilled to receive simple mechanical hardware for attachment of the energy-absorbing shroud ends.
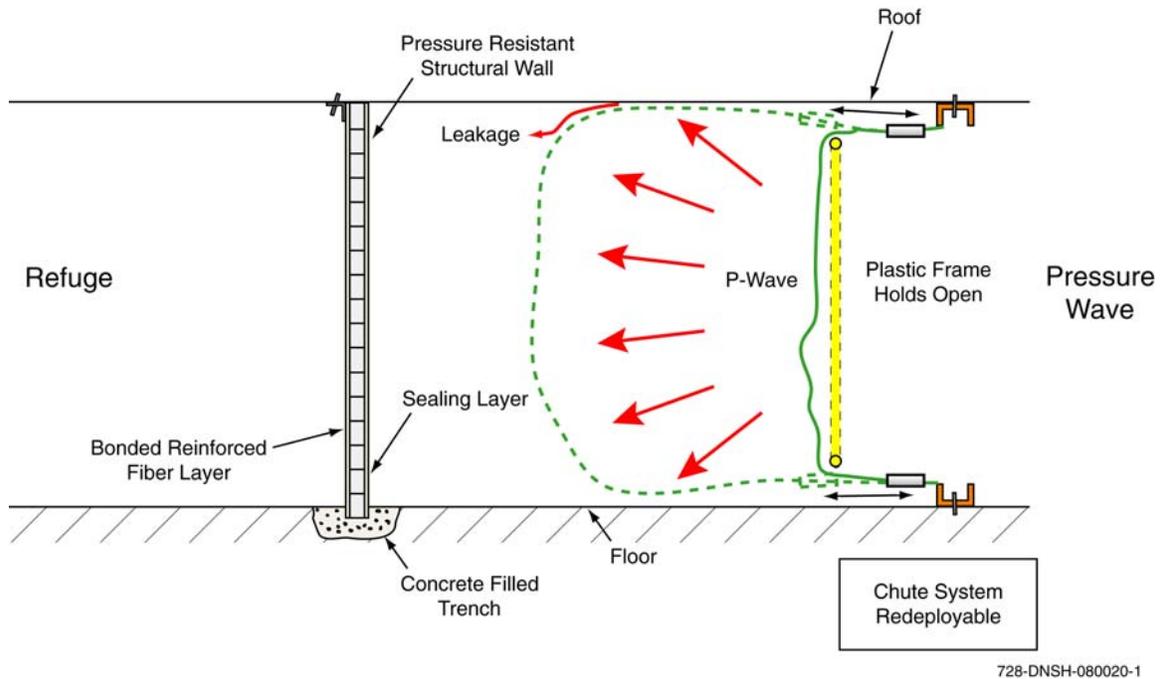
*Figure 7. Schematic of Energy-Absorbing Chute System (EACS)*

*Energy-Absorbing Shrouds*

This key element of the system provides for energy absorption of the blast force in the chute by providing a relatively constant restraining force in the 2500 to 3500 lb range over a travel of 3 ft before it becomes taut. An economical and proven configuration for such a component could comprise one or two heavy fabric strips, folded several times over, and stitched together with strong synthetic thread. The unloaded length would be approximately 9 to 12 in. (plus metal attachment hardware at the ends). This type of device has been used in military air drop hardware and personnel fall protection accessories, which can be tailored to provide a low-impact, continuous force resistance over long travel. After the initial design force is reached, the stitches progressively fail until the end of travel. In this application, the shroud is designed not to reach the end of travel, the various locations on the chute having moved out within that range. The yield load in the straps can be tailored. For instance, the initial yield load can be X, then quickly ramping up to 2X or 3X, thereby minimizing initial shock loads.

"Snapshots" of a dynamic computer simulation of the proposed EACS incorporating these energy-absorbing shrouds are seen in Figure 8, both in initial state and fully loaded with the design transient.

*Lightweight Chute Canopy*

The EACS canopy partially blocks the entry, supported "limp" on an inexpensive plastic pipe frame, so it will naturally inflate and deploy fully upon onset of the blast wave. The material

127
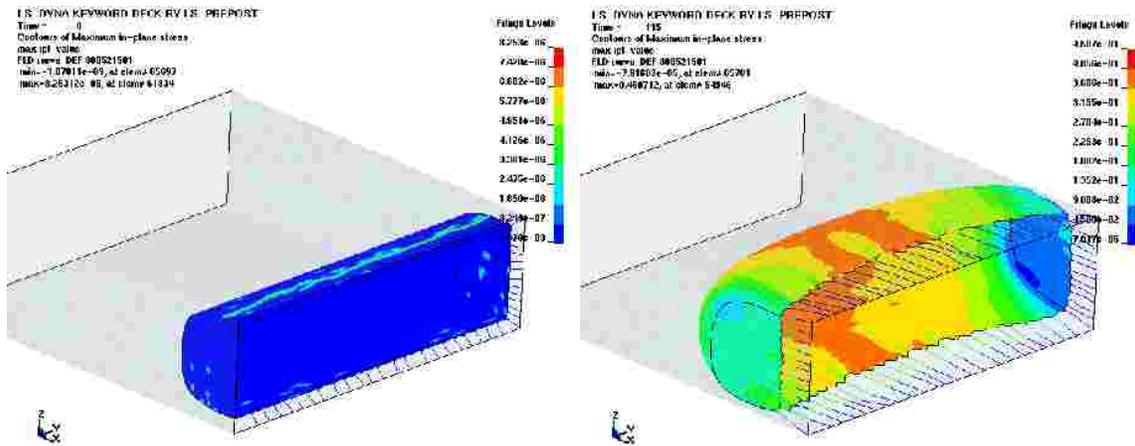
***Figure 8. (a) EACS in initial state; (b) EACS inflating showing energy-absorbing shrouds extending and chute stress distribution***

comprises a self-extinguishing coated version of ordinary automotive airbag material, which in auto deployment reaches high instantaneous temperatures. It would be reinforced at shroud attachments, and the coating would also ruggedize the canopy for the mine environment. When not used, it could be stored in a large duffel-type bag or container, along with the attached shrouds. A key element of the design is that the chute does not fully block the crosscut opening. The gap around the inflated chute is on the order of 8 in. to 1 ft, which lowers chute loads and reduces abrasion on the floor, ribs and roof. The intentional leakage around the chute will allow some loading of the secondary wall behind. If a dynamic overpressure in the 30 to 50 percent range occurs in an extreme situation, the chute could fail but during the course of that time it stays viable (including the 3 ft of travel in the energy-absorbing shrouds) and will significantly reduce the pressure peaks on the secondary wall by a corresponding amount.

Passage of personnel around or through the EACS canopy would be provided. Prior to any blast event, this is needed for miners to access, service or re-supply the refuge chamber while leaving the canopy deployed properly on its lightweight support frame after activity is completed. The size of this portal would be approximately 2 ft w x 4 ft h, or a similar size after review by government and mining staff. This access through the canopy could be provided either by (1) incorporating a strong, zippered- or double-Velcro-closure portal, using the lower-stressed end regions of the canopy (see Figure 8(b) above); or by providing quick-connect link fittings on the end of the energy-absorbing shrouds adjacent to either mine rib extending over a sufficient width in roof and floor. The chute would be disengaged here for entry, and be easily re-attached after use.

If a blast event does occur, the chute system will have been forcibly deployed and protected the main refuge wall behind. It is then considered to have completed its usefulness, and either cut through, disengaged or entered through its portal if needed for miners to reach the main refuge manway entry.

When relocating the system further inby as mining progresses, all components of the chute system would be removed from the crosscut, and reused upon relocation.

128

B. Panelized Blast Reduction Media System as First Layer

A second concept developed for the "first stage" of protection utilizes the secondary block wall as a mounting support (described in a following section, and common to both bulkhead configurations). This utilizes a material recently developed for blast protection of "common areas" used by the public, such as buildings, transit stations, and the like. It has been used in packet form, such as shown in Figure 9, lining large containers or packaged into wall-like barriers. Basically, the active ingredient comprises a mixture of expanding mineral particles like vermiculite to reduce blast energy, and fusible salts which absorb thermal energy. The vermiculite type component absorbs blast energy by both expanding chemically-entrapped water molecules, and then crushing the expanded beads. For this in-mine blast application, the blast energy on a unit basis is smaller than that for munitions (except when far away), but its cushioning effect is valuable for reducing rapid pressure peaks. Note that in-mine methane blast fronts can move at high speeds in the 1200 to 1800 ft/sec range when there is a large volume of gas mixture such as a 50+ ft-long mine section, and it is contained at a working face. (Lower speeds and pressures can occur with smaller quantities, and also with methane mixture ratios outside the "ideal" 8 to 11 percent range).
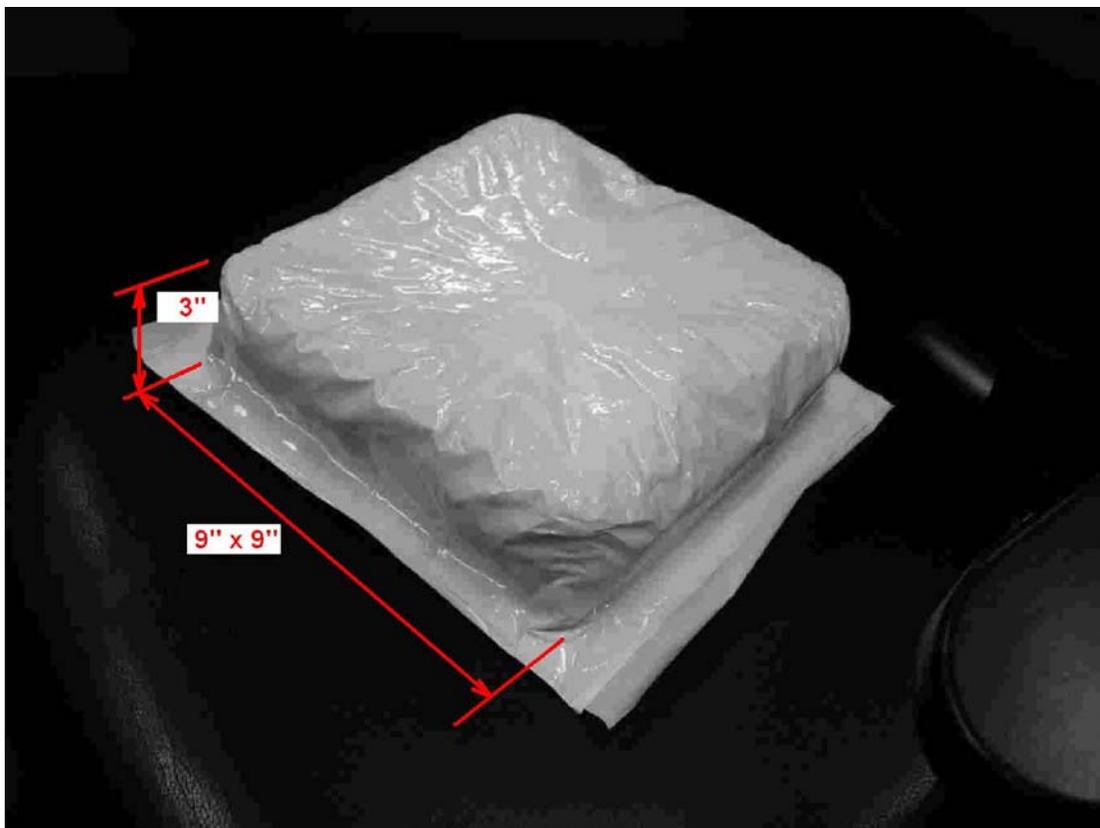


*Figure 9. BlastWrap*$^{TM}$ *packaged material in 9 in./9.5 in. square packet form*

This blast resistant material, called BlastWrap<sup>TM</sup> was developed by BlastGard® International, Inc. in Clearwater, FL.  For this in-mine application which is characterized by a fairly low-temperature flame front with a relatively low pressure (compared to munitions), it would favor use of a particle mixture mostly comprising the blast pressure reducing component with less of the fusible salt temperature-reducing component; however, the fusible salts can reduce or eliminate the progression of a flame front.

The major design issues which were addressed in the use of this concept for blast pressure reduction in the bulkhead refuge station include:

1.  Design of a rugged container system for the BlastWrap<sup>TM</sup> packets such that they could be reliably protected, transported and installed; not disperse when subjected to the blast; and, at the same time allow ample access of the blast front to the material so it can function as designed.  This resulted in design of a "panelized" version in which standard expanded metal sheet would be fabricated into hollow panels containing the blast material packets tightly nested together.

2.  Selection of an appropriate thickness of the BlastWrap<sup>TM</sup> packets, trading off better performance of thicker layers versus increased cost.  A 3 in. thick layer was selected, but in larger plan form size (9.5 in. square) since the depth is needed to act dynamically over the relatively long 0.3 sec pulse assumed for the design requirement.  It should be noted that multiple pressure peaks often occur over much shorter times, but could be clustered around the pressure top shown previously in Figure 6, leading to the simplified longer "top" of 0.25 to 0.30 sec.

    The packaging of the material in panelized form using these basic dimensions is shown schematically in Figure 10.

3.  Coordination with the design of the main secondary block wall system is required, since in this concept the panelized blast reduction panels would be mounted directly to the sealed block wall/manway system. For the same transient pressure load, the pressures on the wall behind the blast reduction panels would be somewhat higher than those behind the EACS (chute) system described in (A); however, the blast panel approach is simpler and cheaper. Due to the progressive crushing nature of the panelized blast media material, the blast protection panel layer provides a greater reduction of pressure on the secondary wall as the incoming pressure spikes increase beyond the "working" design pulse level. Thus, the blast panels provide a significant measure of protection in possible overpressure scenarios.

Installation of a 30 in. x 40 in. Panelized Blast Reduction Media System on the secondary wall is shown below in Figure 11.

These panels would not need to tightly fill the space of the exposed secondary wall, but would likely also have a section or two designed to be compatible with the manway and blast door needed for the wall system.
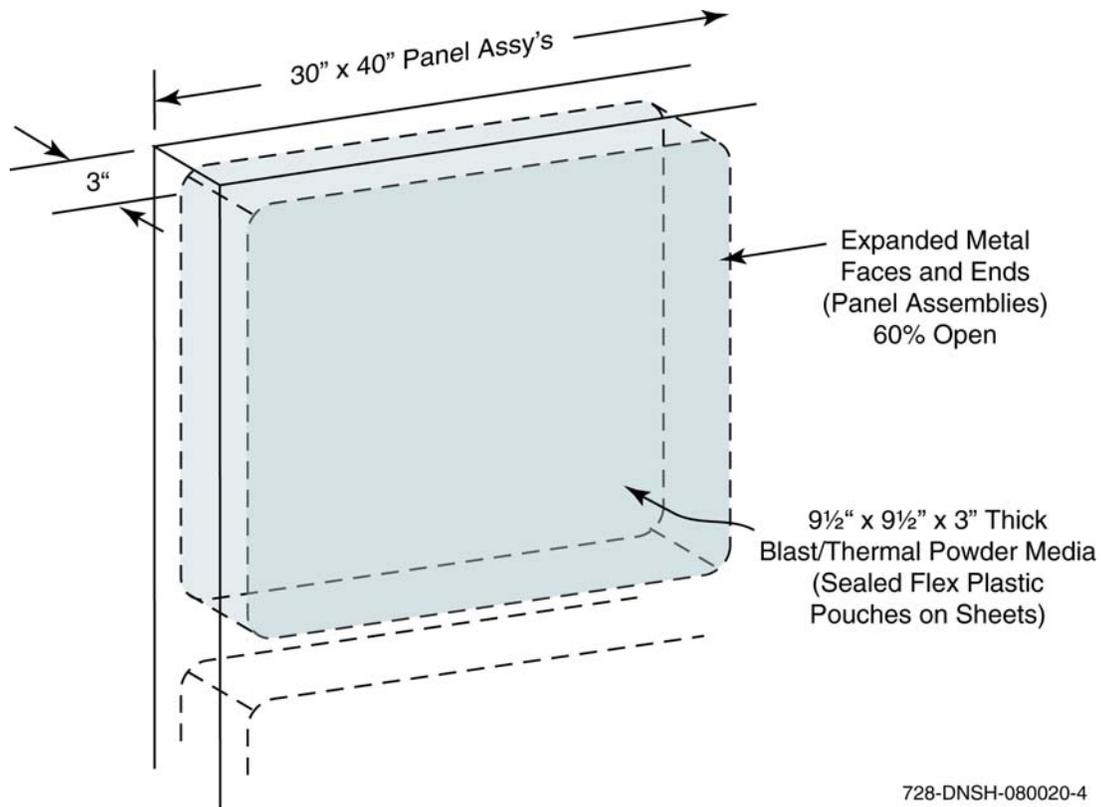
*Figure 10.  Panelized containment of 9.5 in. x 9.5 in. x 3 in. BlastWrap$^{TM}$ Packets*
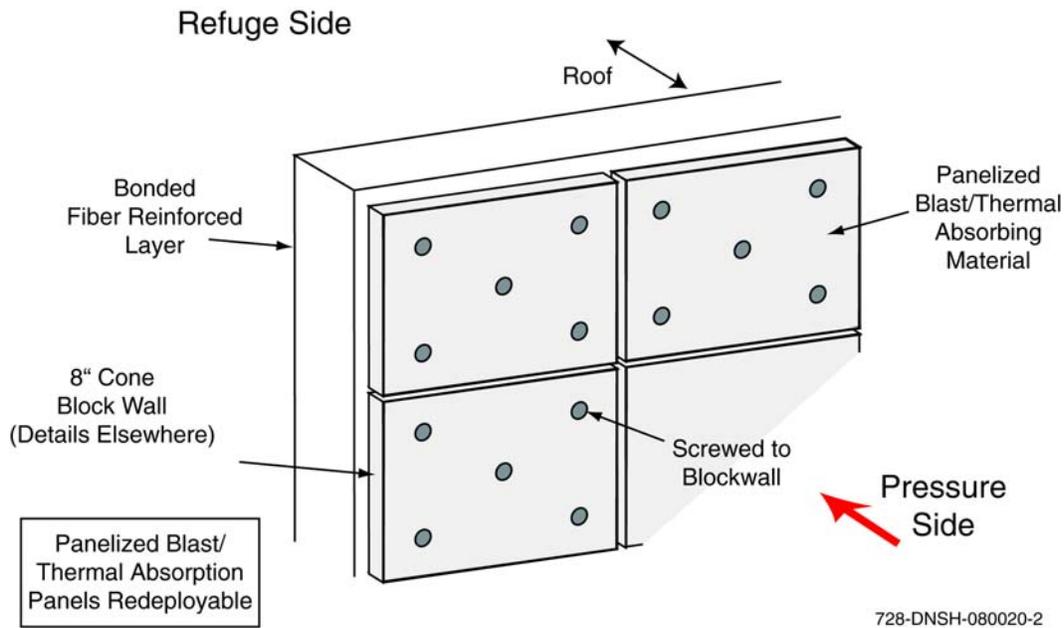


*Figure 11.  Panelized blast reduction media system installed on secondary wall*

131

The blast reduction panel components of this system could be removed from the secondary wall and re-used in the event of redeployment of the bulkhead refuge station.  Only the masonry screw fasteners would need replacement.

Of the two options, we selected the blast reduction media system for the Universal Refuge Bulkhead.  The blast reduction media system is integral with the block wall and provides more flexibility in installation and sizing of refuges.  In addition, the energy absorbing chute may be difficult to maintain in a ready condition for an extended duration within a mining environment due to its use of lightweight materials in a rugged mining environment.

C.  Secondary Reinforced and Sealed Concrete Block Wall/Manway System.

Both bulkhead concepts rely upon having a sealed structural wall with manway (entry) system behind the dynamically-acting, shock absorbing system elements in front.  This wall must survive the "working loads" without any damage or compromise in operation, in the event that an overpressure event causes pressures behind the primary layer to reach that design level.  Such a wall would still have some additional reserve capacity in ultimate strength to survive even more unusual scenarios such as a methane explosion occurring nearby the bulkhead station.

This "secondary" wall system would also provide the necessary "hard seal" and entry/exit capability to form the actual refuge station itself.  It would use familiar construction materials, and also contain a manway.  A range of wall construction styles was considered for this second "layer," but the basic configuration practical for in-mine use would favor some type of built-up block wall, which would be capable of safely reacting the transient design pressures.

*Strength of Block Walls Used as Mine Stoppings*

Many types and configurations of built-up block walls have been used for closing off a typical mine crosscut or drift opening.  These block walls are relatively weak and used primarily for ventilation control. When some degree of integrity for in-mine blasts is sought, stronger forms of these walls are used, however, even with mortared joints and relatively strong block material (such as solid concrete blocks, 6 or 8 in. thick), without significant steel reinforcement such walls have been shown to fail in mine blast tests in the range of 5 to 6 psi [69].  This is primarily due to the very low tensile strength of concrete and cement mortars (sometimes under 100 psi) which prevents flexural (bending) strength from being mobilized.  This fact has driven the design of steel "rebar" reinforced concrete construction, in which the tension portion of the concrete cross section in bending is assumed to fail, with the tension reacted entirely by embedded steel reinforcement. The presence of the steel mobilizes the strong compressive strength of concrete on the compression side of the section which results in significant flexural strength.

Some of these forms of reinforcement are inconvenient and expensive to use in mine passages, which typically are low in height (4 to 7 ft range being typical). The needed vertical reinforcement in particular can be difficult to install.  In many applications, dry-laid (un-mortared) concrete block walls have been used and tested, in which the dry laid wall is wedged in at the roof and ribs to provide some limited coupling. These walls in 8 in. thickness were seen

132

to have adequate strength (in the 5 ft high by 20 ft wide configuration) to resist a load of about 3.6 psi [78].

*Typical Concrete Blocks*

Concrete blocks used in normal construction have evolved in several ways which should be noted as they apply to in-mine construction.  The concrete material is not completely solid, so its failure strength is in the 1700-1800 psi range rather than 3000-4000 psi as in structural concrete.  The material is also about 2/3 as dense as structural concrete.  Also, so-called hollow concrete block (in many configurations) has cells to further reduce the weight of the block, but it has proportionally less bearing and shear strength.  Figure 12 shows a typical two-cell block, while a stronger version likely used in structural mine application would have three cells and more wall thickness (area).  Note the nominal face dimensions are 8 in. high x 16 in. long, including 3/8 in. for mortar joints.  The "stretcher" unit in an alternating pattern is normally used for running wall areas. An 8 in. deep block is shown, which would weigh about 50 lb with a 3-cell configuration.
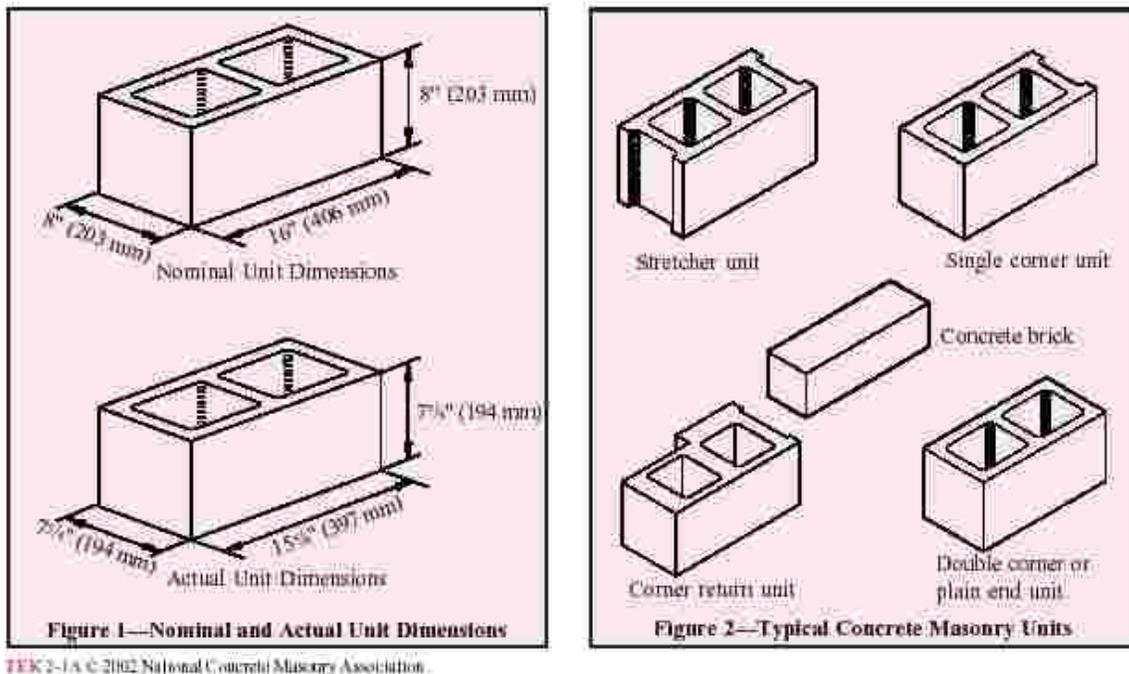


**Figure 12.  Basic concrete block configuration**

*Other Block Materials and Sizes*

A large but lightweight proprietary block material called Omega 384 Block® was developed many years ago by Burrell Mining Products International, Inc. in New Kensington, PA. Its use as a seal material is described in detail in [79].  Omega-384 blocks are lightweight, noncombustible, glass-fiber reinforced blocks with a nominal size of 8 in. by 16 in. by 24 in., weighing about 46 lb.  Omega blocks typically have compressive strength in the range of 70 psi to 110 psi.  These are laid in various interlocking patterns to construct walls to 40 in. thick, with larger

133

"pilasters" (embedded solid columns required for strength under pressure load). The Omega block seals are constructed using Quikrete BlocBond® mortar, which is manufactured by the Quikrete Company in Atlanta, GA.

The intent with this type of block construction is to provide a very thick wall which could take some advantage of its geometric depth to resist bending loads without tensile reinforcement (so-called "arching action"). In some LLEM tests, the 40 in. thick Omega block walls, plus thicker pilasters and with tightly wedged wall-to-roof joints, survived a 20 psi blast pressure [79]; therefore, these blocks could be considered for use for the secondary wall if other factors could be addressed, particularly the inclusion of a manway system.

To be effective, the Omega blocks must be tightly fitted into the mine opening. The limitation of relying on this type of behavior is described in a later section as it applies to walls installed across mine passages to resist potential blast pressures.

*Structural Behavior of Unreinforced Walls in Mine Passages*

A typical unreinforced 4 to7 ft high by 20 ft wide wall (in elevation view) needs both some form of moment-bearing strength and reasonably good attachment to floor, ribs and roof to successfully react significant pressure loads.  For this face-on aspect ratio (passage width being 3 to 5 times the height), the primary span in bending would be in the shorter direction (vertical), since a slab simply supported at its edges has significant horizontal bending moments only near the ribs.  Internal bending moment due to evenly distributed loading increases with the square of the span, so designing such a wall to "beam out" the loads vertically is much more efficient than in the horizontal direction; however, appropriate strength horizontally near the ends and at any openings is also required.

Figure 13 (a) shows how a typical wall slab would react to pressure loads to the roof and floor of a passage, if sufficient horizontal reaction were available at the floor and roof, but without counting on moment restraint there (so-called "pin-ended" or "simply-supported" beam action). To withstand bending moments, the slab or wall needs some sort of internal bending moment capacity.  If this capacity is at least $M=ph^2/8$ at the mid height[2] (where M is peak moment/unit wall width,  p is pressure, and, h is wall height), no further vertical or wedging forces at roof or floor need be provided. The wall will also require adequate shear strength near the attachment to the roof and floor.

If the slab or wall material has little tensile strength; however, the wall will have no significant bending strength, and the tension side will crack as shown in Figure 13 (b). The wall center displaces, and the wall fails if moment resistance cannot be created.  Figure 14 (a) shows that the internal bending moment is maximum at mid-height in this configuration.  Figure 14 (b) shows that *if* the crushing stiffness and strength of *both* the wall material and the supporting roof and floor material is high enough to provide large bearing reactions (shown as triangular stress distributions across the compression side of the wall thickness), such a moment resistance can be

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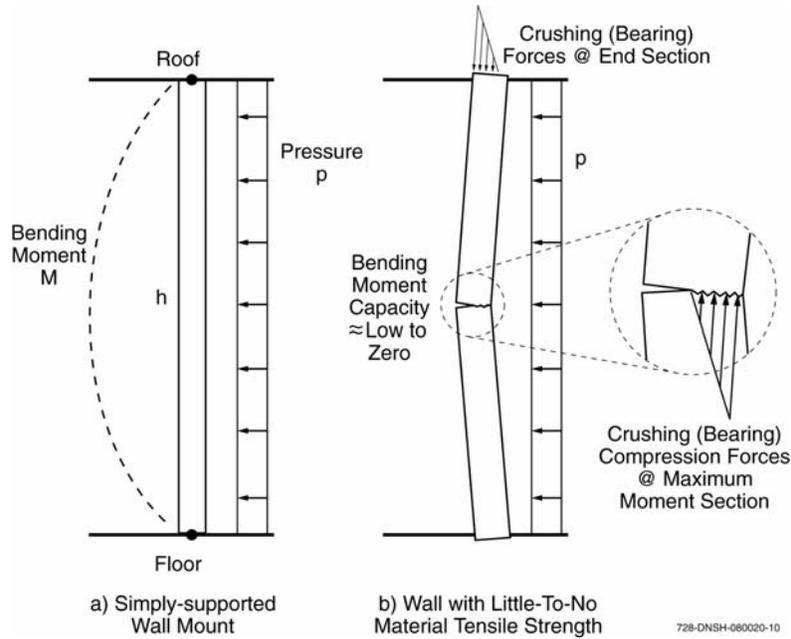[2] Moment is per unit length of wall

*Figure 13.  (a) Bending moments in pressure-loaded vertical wall simply supported top and bottom; (b) Bending failure in walls with low tensile strength*
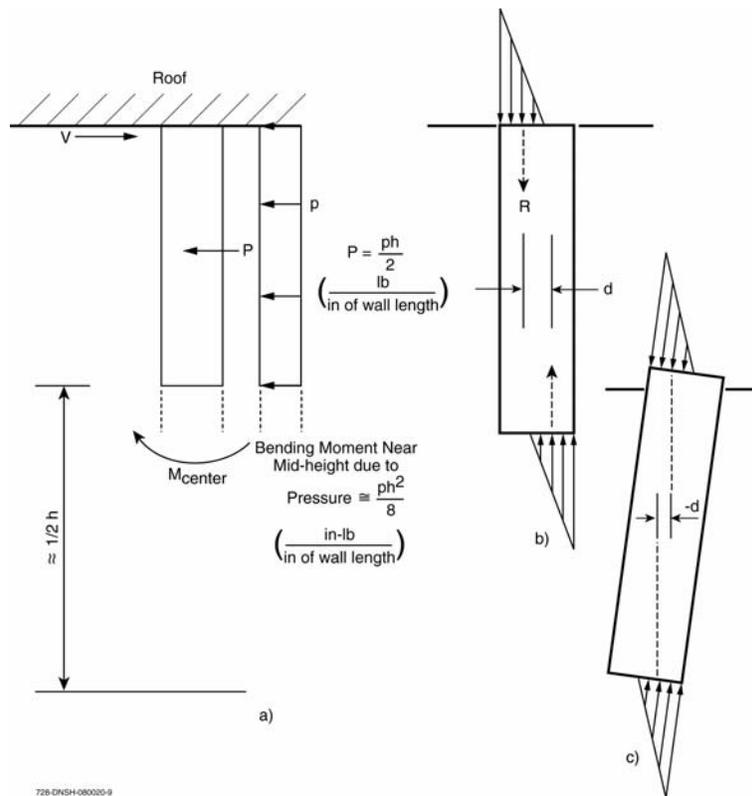


*Figure 14.  (a) Bending moments in vertical walls reacting pressure loads;*
*(b) Bending in masonry wall with low tensile strength mobilizing compression;*
*(c) Instability failure of masonry wall with insufficient bending strength*

135

mobilized but it is dependent on the horizontal displacement to develop these "wedging" or "arching" reactions.

If these forces are sufficiently strong to allow such reaction moment to develop while the small horizontal lever arm (shown as "d" in the Figure) is still a positive number (Figure 14 (b)), then some moment can be reacted; however, a large horizontal displacement will crumble the wall. In the case where wedging action of the wall top-to-roof is employed (e.g., timber or block wedges being tightly driven into the joint), this can slightly raise the bending capability by adding an overall compressive stress into the wall; however, material creep in the wedge or roof material will reduce the wedging effect. Roof convergence will create very high local bearing (compression) stresses and make the wall unstable, as in Figure 14(c).

The above discussion shows why only very thick walls would have a significant potential moment-carrying capability even with a material which fails early in tension, more able to mobilize the so-called "arching action" via restraining the rotation at cracked sections in mid-height and at top and bottom. This approach can be considered for mine seals, and was demonstrated in work documented by MSHA [79]; however, another efficient way of providing moment strength that is not so dependent on high local bearing strength (especially in the roof and floor material) is to restore the bending strength of a block wall with another form of tension side reinforcement, not necessarily embedded steel which is unwieldy and difficult to implement in the in-mine environment.

*Unreinforced Concrete Block Wall Strength*

As mentioned above, in-mine tests at the LLEM showed that dry-laid, unreinforced concrete block walls failed in the 3.6 psi (static pressure) range. This was with 6 in. thick block. In view of the preceding discussion on unreinforced block wall behavior, use of 8 in. thick block would be expected to be slightly better, and observations by others mention the 5 psi range as a typical limit strength [71]. Strengths of solid block versus hollow block walls could be slightly higher, in part due to the higher dead weight of the blocks providing more vertical compression in much of the wall, and also possibly the higher mass providing more inertial resistance during the short-term blast pressure pulse.

*Strength Improvement Using Tension-Side Reinforcement of Block Walls with Fiber-Reinforced Composite Facing*

The development of a much stronger bulkhead wall construction is possible by increasing its bending resistance. For an 8 in. mortared concrete block construction this is accomplished by adding tension carrying material. A primary requirement would be to use inexpensive and common construction practices, plus materials suitable for in-mine use. Such a stronger wall configuration would be capable of vertically[3] "beaming out" the pressure loads via bending strength as if it were a simple edge-supported slab, not much dependent on the displacement-dependent "arching action" or roof wedging discussed previously. This approach would require two key features:

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[3] Also laterally at the ribs (sides of wall)

1. Addition of tension-resisting material on the rear (tension-side) block wall face, which would then provide high bending strength of the wall under pressure loads. This is depicted in Figure 15, but without using the normal embedded vertical steel rebar which is difficult to install in mine passages; and

2. Horizontal, simple support of the wall at floor, roof and ribs by design features of the wall system (no bending resistance at slab edges required).
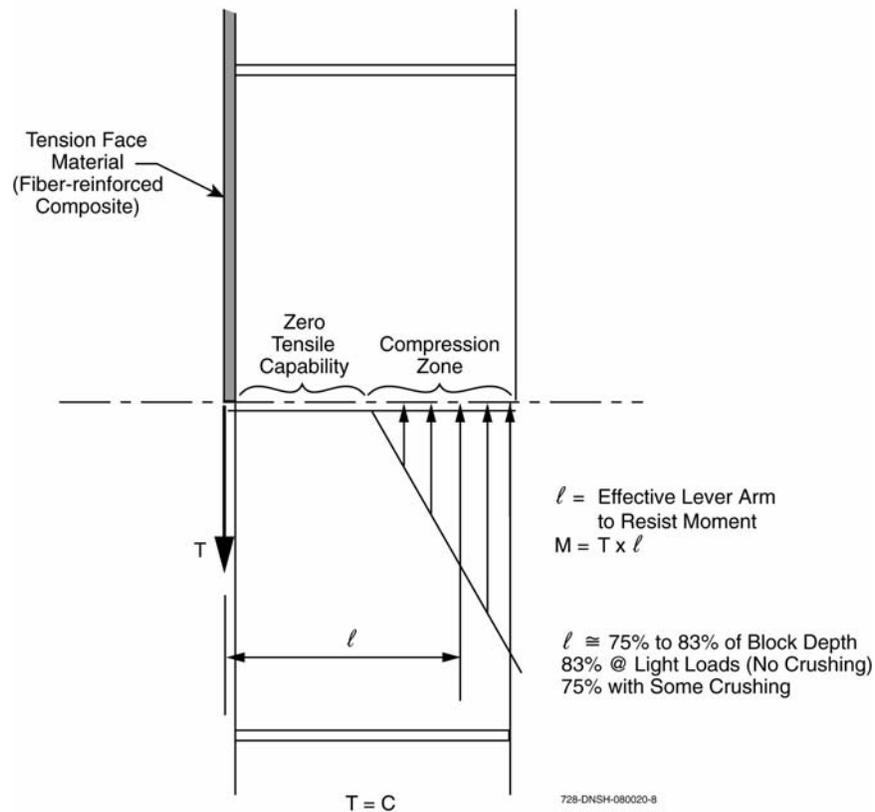


*Figure 15.  Creation of bending resistant block wall using*
*tension-side composite fiber-reinforced layer*

Table 40 shows the estimated working load and estimated failure load for the three types of concrete block walls.

### 10.5  Selection of Fiber Reinforced Hollow Concrete Block Wall for Bulkhead System

Based on the previous discussions, an 8 in. thick mortared concrete block wall with the rear (tension side) face reinforced with a standard fiberglass/composite layer was selected as the secondary wall configuration for the bulkhead refuge station. This wall would be supported at

***Table 40.  Concrete Block wall strength with lateral pressure loading in mine passages***
***(load in psi applied to wall)***

| Construction Type | Hitching to Roof and Floor | Estimated Working Loading | Estimated Failure Loading |
|---|---|---|---|
| Dry Laid | Tight to floor and roof but no hitching | 2.2 to 2.5 psi[4] | 3.6 psi [78] for solid CB, slightly lower for hollow CB |
| Mortar Laid, Running Bond | Tight to floor and roof but no hitching | 3.5 to 4 psi[5] | 5 to 6 psi [78] for solid CB, slightly lower for hollow CB |
| Mortared Wall Reinforced with Fiber-Composite[5] On Rear Face–Foster-Miller Backup Wall Design | Supported by 6 in. x 6 in. x 5/8 in. std steel angles bolted to  roof and ribs; concrete trench floor foundation | 15 psi[6] | 22 to 24 psi[7] |
| Assumptions:<br>8 in. x 16 in. x *8 in. thick* single wythe (layer) concrete block wall<br>No conventional steel reinforcement<br>Static loading assumed | | | |

the roof and ribs of the crosscut passage by steel angles anchored with standard roof bolts (having nut-type ends to allow later removal). The wall would be set into the floor via a concrete-filled trench familiar to the mining industry.

The wall system must incorporate a manway (door) and support structure to resist blast loading and to protect the airlock or air-knife type entry/exit manway installed through the wall itself. Also, the wall must be sealed on the front face (potential blast side) to prevent entry of contaminating post-blast gases.

The 8 in. fiber-reinforced concrete block wall was preferred over the Omega block type thick wall described previously, although both are capable of resisting the design transient pressure load. The principal reasons for this decision include:

- Reliable support at roof and ribs via positive horizontal load-carrying capability of bolted steel angles, which can also be re-used at new locations.

- No wedging at roof and ribs required, which cannot easily be monitored or assured over the life of the wall.

- Allowance in roof-to-wall space for compliant sealing to accommodate limited roof convergence.

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[4] Estimated as 65% that of failure load

[5] 1/8" thick std fiberglass, 50% woven roving, 50% polyester resin

[6] Established by Foster-Miller finite element analyses

[7] 30 psi confirmed failure by Foster-Miller dynamic finite element analyses; 24 psi estimated from FE results.

- Less volume of construction material (by factor of five for wall itself – 8 in. versus 40 in. thick plus pilasters).

- Relatively thin wall can accommodate a variety of manway access systems.

- Likely to provide higher reserve ultimate strength although this is difficult to predict for the Omega block construction.

Both wall construction configurations use materials that are familiar and relatively inexpensive in the mining industry. The only "new" component would be the tensile fiber composite reinforcement applied to the block wall rear face. This would be a common fiberglass industrial material as used in many marine, automotive and construction products. As will be seen in the cost estimates, the steel and manway components used in any system can be designed for easy removal and redeployment to new locations.

The overall configuration as designed for the bulkhead refuge station is shown schematically in Figure 16. (Small angle iron sections on the front/pressure side to react small suction loads are omitted for clarity.)
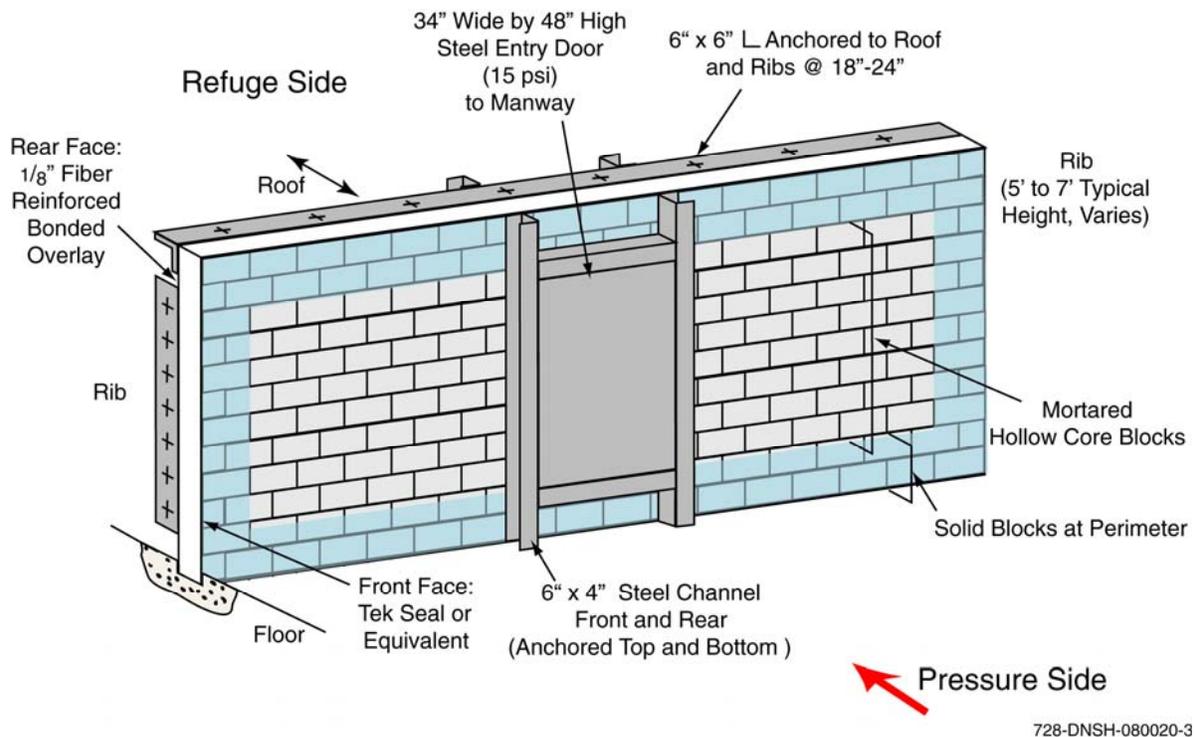


*Figure 16.  Overall configuration for secondary wall system in bulkhead refuge station*

*Design Features*

- The 1/10 in. to 1/8 in. fiberglass tension-resisting back facing is comprised of standard woven FG E-glass or S-glass roving (loose cloth) in a 50 percent proportion with standard polyester resin. This can be made easy to install on a vertical face by incorporating some resin in the cloth ahead of time (pre-impregnated cloth, or "prepreg"). This is self-supporting so that a layer of resin is rolled onto the block, the prepreg set in, and another rolling of resin completes the job with a cure time of a few hours. The material is also self-extinguishing with suitable chemistry. The addition of this tension-resisting layer increases the moment (bending) strength of the wall by a factor of three to four over that of an unreinforced concrete block wall.

- The horizontal support comprises a 6 in. x 6 in. x 5/8 in. standard steel angle iron hitched to roof and ribs with roof bolts having nut-type ends to allow removal. The design permits the 6 in. flange to engage the block wall top with 3 in. of overlap to allow for installation of a compliant seal material which permits limited roof convergence and/or roof irregularity. 4 in. is preferred. This is shown in detail in Figure 17. These bolts are acting primarily in shear, so they may be shorter than the long roof bolts required for bolting of weak mine roofs.
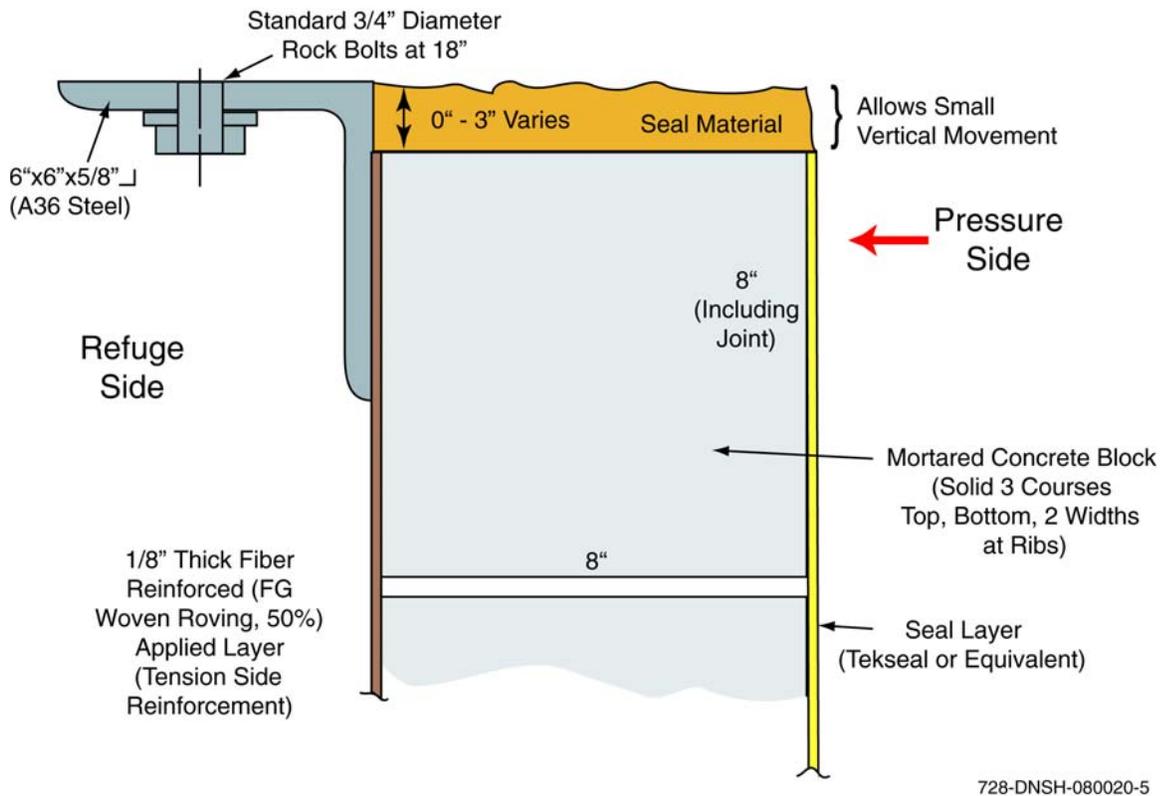


*Figure 17. Detail at steel roof support angles*

- The concrete blocks around the wall perimeter are recommended to be solid concrete blocks of the same nominal 8 in. x 8 in. x 16 in. size, since their higher shear capacity is required adjacent to support at roof, floor and ribs.

- A front face coating of sealing material, such as TekSeal is troweled on in a ¼ in. or thicker layer to seal the wall system from gas intrusion. TekSeal is manufactured by Minova of Georgetown, KY and is a cementitious powder, water, mixed in a higher range of recommended density and strength.

- An air-knife or airlock type manway system is installed in the block wall, such as the one shown in Figure 18.  The one shown in the figure is somewhat lower in height than what we feel is needed to facilitate entry for multiple personnel in emergency situations.  Internally, a multiple curtain system insures only minimal exchange of gases on each side of the bulkhead; however, the air lock entry door is not designed to resist the design blast pressures, so a protective structure and door on the potential pressure side is required. The doorway size allowed for in the Foster-Miller design is 34 in. wide x 42 in. high, set up off the floor at a convenient height.



*Figure 18.  Representative air seal manway subsystem for wall installation*

- This protective structure is constructed from standard steel 6 in. channel, and comprises two uprights from floor to roof on each side of the manway, with two cross members connecting them above and below the manway. The vertical members have adjustable overlapping sections to accommodate some variation in roof height. The end fittings are terminated in

square steel plates, with bolt holes permitting standard ¾ in. D roof bolts or rock anchors to hitch the door frame to roof and floor. The components form a bolted assembly which can be carried in pieces and also removed for redeployment at future bulkhead station locations. One such assembly without a door is used bearing on the rear side of the wall, to react the loads around the discontinuity from the manway opening. An identical assembly with a blast protective door, comprising steel sheet and welded ribs plus two dog-type latches, is used on the front of the wall to protect the manway from pressure loads.

- The block wall is set into a simple foundation comprising a 24 in. wide floor trench, with a 9 in. wide x 3 in. deep recess formed in to accommodate the mortared blocks.

Views of the bulkhead secondary wall construction are shown in the following figures. In Figure 19, the essential component assemblies are shown. This shows angle irons restraining the front also to react possible suction loads, but these can be much smaller in size and have only partial application on the perimeter, since suction loads are only in the 1 to 3 psi range. Figure 20 shows the installed secondary wall system, and Figure 21 shows a vertical cross-section through the door area. These show a stub-ended refuge station.  Also, the maximum door size is shown.

Analytical Validation

The structural integrity of the complete bulkhead system was evaluated dynamically using several LS-DYNA finite-element simulations of the secondary wall, the chute, and the panelized blast media subsystems. This included all the key behavior of the structures and their materials beyond their working stress levels up to and including ultimate behavior. This analysis included the effects of large deflections, material non-linearity and fracture. The behavior under the 15 psi/0.3 sec design pressure pulse shows that all sections remain undamaged.
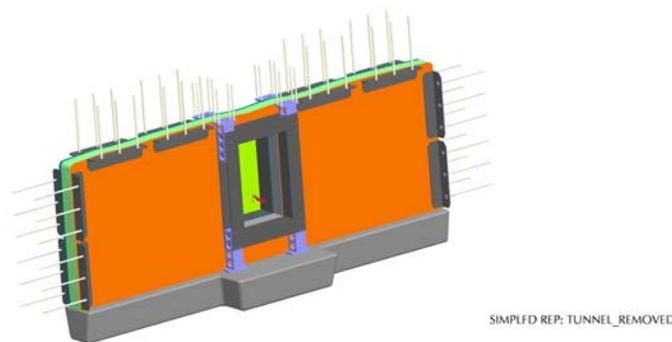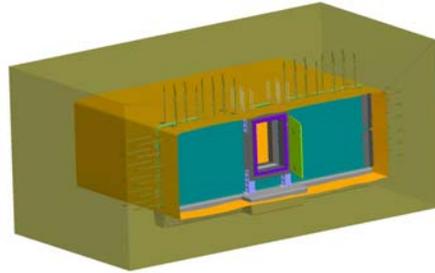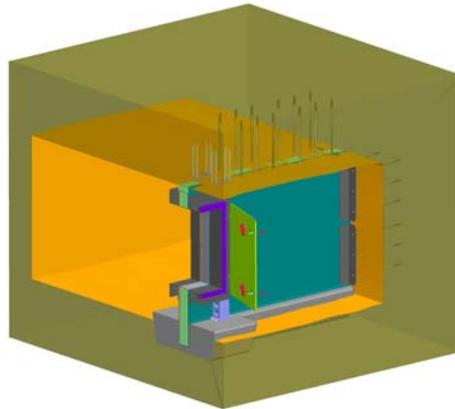


SIMPLFD REP: TUNNEL_REMOVED

*Figure 19.  Front face of secondary block wall system*
*showing hitching and door structure*

SIMPLFD REP: DOOR_TWO

*Figure 20.  Installed secondary block wall system
showing entry door*



SIMPLFD REP: DOOR_TWO

*Figure 21.  Vertical cross section of secondary
bulkhead wall through door area.*

A limited number of higher loads were also evaluated for each of the two approaches (chute in front of block wall or blast panel in front of block wall).

Under 50 percent overload (1.5 x the design pulse) the protective layer in both cases (chute and blast panels) would sustain damage yet the block wall and its structures would likely be reduced to approximately 20 to 30 percent overload (1.2 to 1.3 x design pulse) and be operable and intact sufficiently for performing their bulkhead function since their ultimate strengths in critical areas were not exceeded, by design.

Under a 100 percent overload (2.0 x the design pulse) either the chute or the blast panels in front of the block wall would fail, and the pressures on the block wall are estimated to be reduced to the 40 to 65 percent overload range (1.4 to 1.65 x design pulse). In both cases, this range of 40 to 65 percent overload is marginal for survival of the wall, supports, and manway structure. Its function or refuge capability could be compromised, so it could not be assured.

Under a 100 percent overload (2.0 x the design pulse), the wall system standing alone with no protective barrier in front, would fail primarily in the block portions and peripheral attachments.

## 10.6 Summary

The two-layer bulkhead systems as proposed are designed to withstand the "working level" 15 psi/0.3 sec transient design pulse (Section 8, Figure 6) with no significant damage and would be functional post-blast in all required aspects. The first stage, or primary layer would comprise either an Energy-Absorbing Chute System, or a Panelized Blast Reduction Media System. The second stage, or secondary layer would comprise a Fiber-Reinforced and sealed Concrete Block Wall and Manway System, hitched to roof and ribs and set into a floor foundation. Under 50 percent overload, there would be damage of the first layer, with survival of the secondary wall with some damage using its reserve strength. This is based on limited trial evaluations of the structural behavior under extreme loadings, but could be further investigated through more extensive simulations, and testing of a selected configuration.

Each of these systems comprises both permanently installed and removable/redeployable components, which reduces costs when refuge stations are re-established at a new location.

Based on a review of the two energy absorbing layer concepts, we down selected to the panelized blast reduction media system. The blast reduction media system is integral to the block wall and provides more flexibility in installation and sizing of refuges. Volume III of this report presents the design and construction of the universal bulkhead in detail.

## 11. _Development of Guidance Document_

Based on all of the preceding research performed on this program, Foster-Miller developed a comprehensive guidance document for the coal mining industry for the selection, installation, and provisioning of refuge stations in underground coal mines.

The guidance document provides an introduction to the basic types of refuge alternatives. It provides guidance on selecting the locations, sizes, and types of refuges as well as on providing life support equipment and general equipment and supplies. The guidance document concludes with detailed instructions for the design and construction of the Universal Fixed Bulkhead Refuge Station. The final guidance document was delivered to NIOSH in November, 2008.

### 11.1  Introduction

The goal of the guidance document is to help mine operators select, install, and provision refuge stations in underground coal mines. It provides practical tools for determining where to locate refuges, calculating how many people the station must support, and selecting the type(s) of refuge station most suited to a specific mine configuration. It also contains easy-to-use tables for determining the types and amounts of life support equipment and general supplies required for the variety of refuge station sizes and configurations available. A final section includes detailed design and construction instructions for the universal refuge bulkhead which can be used to construct a refuge station that is applicable to almost all mine configurations.

### 11.2  How to Use the Guidance Document

To use the guidance document, mine operators should first read the provided information describing various refuge alternatives currently available and general requirements for locating, sizing, and provisioning these stations.

The next step is to use the tools in Section 2 of the guidance document to decide on the location(s), size(s), and type(s) of refuge station(s) to use. The tools ask the user for information about their mine and operations. Users fill in this information on worksheets. Users should read the instructions for each question on the worksheet before attempting to answer the questions. They should also review the example. When the worksheets are completed, the user will have selected the appropriate locations, sizes, and types of refuge stations for their mine. Note that once the worksheets are completed, the user may still have options. Each tool concludes with further considerations to help decide among these alternatives. While cost is always a consideration when evaluating alternatives in a mining operation, the tools do not address this factor. Costs can vary widely among equipment options and vendors. Mine operators should perform their own cost evaluations when more than one option is available.

Once the mine operator has completed Section 2 and determined the type(s), location(s), and size(s) for the refuge station(s) for their mine, they proceed to Section 3 of the guidance document. This section contains tables to determine the required life support equipment and supplies and general equipment and supplies. By following the instructions for each table a mine

operator can develop an equipment and supply list for each refuge station. Examples are provided.

If the mine operator plans to purchase refuge station(s) from a vendor, they can use the information in Sections 2 and 3 of the guidance document to help them select and provision appropriate models. If they plan to install refuge stations using the universal refuge bulkhead, instructions for designing and constructing universal refuge bulkhead in almost all mine conditions are provided in Section 4 of the guidance document. This section also includes a guide for inspection, testing, and maintenance of the bulkhead components. The mine operator should first read the summary description of the bulkhead system. A mining engineer should review the specifications, construction guides, and supporting information and then create plans for the bulkhead. These plans can use the schematic drawings provided as a baseline for the actual bulkhead in the selected location.

When complete, the bulkhead system will need to be inspected and approved per the inspection guide provided which includes a detailed checklist, plus a filled-out example. This same checklist can also be used for subsequent inspections to maintain station readiness.

### 11.3  Refuge Station Location, Size, and Type

Section 2 of the guidance document provides worksheets to assist mine operators in determining the location, size, and type of refuge station for their mine. Worksheets were selected as the appropriate tool since it was determined that the questions required to determine location, size, and type all had a numerical impact on the final answers. The format of the worksheets is to ask questions and fill in numbers in the worksheet based on the answers. The responses to each question are then added to provide a final answer. See Section 2.2 of the guidance document for an example. The worksheets should be completed in order since the location of a refuge station is required to determine its size and size can help determine station type.

For each worksheet, the guidance document provides general instructions on the use of the worksheet as well as considerations that the mine operator should be aware of when completing the worksheet. Specific instructions for each question or line item in the worksheet are provided. An example of a completed worksheet, based on a specific mine configuration, is also provided.

When determining refuge station type, the user answers a series of questions about their mine and the characteristics of the candidate refuge stations. Answering these questions may indicate that one or more candidate stations is not usable in their mine. These stations are eliminated from consideration. Once all questions have been answered, any remaining candidate stations can be used in the mine. The user should also review the guidance document section "Special Considerations when Selecting Refuge Station Type" prior to making final selections of a refuge station.

The types of refuge stations considered in the guidance document include:

**Fixed Position Refuge Stations**

1. *Borehole fed bulkhead based type, constructed in a cross cut or stub entry.* This type of station is fed with surface air via forced fan above ground or a compressed air line through a borehole from the surface directly into the refuge station. This method can supply unlimited air quantity, and a desirable overpressure to keep out contaminant gases. The station is typically constructed by enclosing a section of a cross cut with two sealed bulkheads, or a stub entry with one bulkhead, such that the bare coal surface ribs, roof and floor form the rest of the enclosure.

2. *Self-contained bulkhead based type, constructed in a cross cut or stub entry.* This is a bulkhead refuge station as above, but sealed airtight, with no outside source of breathable air. The bulkheads will have man-entry airlock or airknife systems to purge or prevent gas contamination. An atmosphere management system will be included to scrub out carbon dioxide, and provide make-up oxygen in order to maintain breathable air.

**Portable Refuge Chambers**

1. *Portable, self-contained hard-sided (rigid) type.* This type is a fully assembled, ready for use sealed rigid room station, which can be transported directly to the mine location. Miners arriving at the station after an event enter the station through the airlock, and start the atmosphere management system to maintain breathable air.

2. *Portable, self-contained soft-sided or inflatable type.* This is a deployable type of station, wherein a central boxed unit is transported into the mine, containing all supplies needed, plus an airlock, and a soft-sided chamber which is stowed until needed. The station stands ready for deployment after an event. Deployment may be accomplished by automatic inflation of an airbeam supported tent or the tent section may be manually pulled out from the box in accordion fashion while cylinder air is filling the tent. Miners can then enter the breathable atmosphere tent through a supplied airlock.

3. *Portable, unenclosed, umbilical respirator mask breathable air system type.* This is a mask based system, where miners are out in the open, wearing respirator masks connected via umbilical manifold lines to a central container of compressed breathing air cylinders. The miners will wear the masks for the duration of their refuge, and liquid food and water can be ingested through a valved tube in the masks. Valves allow inhaled air to be drawn from a cascaded bank of cylinders, and exhaled air is expelled into the mine.

4. *Future systems may include pre-positioned materials in a protected enclosure. These would be used for post-disaster fast-erectable stoppings such as inflatable bulkheads or curtains.* Though not yet available, this type may include a rapidly inflatable bulkhead which will accommodate a range of opening sizes. Air management (toxic air scrubbers and oxygen source) would be provided from equipment on a skid for mobility. These mobile, barricade type materials will be easily transportable for frequent moves as the face progresses, and will have provision for man entry and exit through soft seals.

Any of these refuge station types can be used in mines, provided they meet the criteria for MSHA approval in the final rule CFR 30, Parts 7 and 75 "Refuge Alternatives for Underground Coal Mines," and are suited to a specific mine.

### 11.4  Life Support and General Equipment Supplies

Section 3 of the guidance document provides worksheets to assist mine operators in providing life support systems and supplies and general equipment and supplies for refuge stations. Life support systems and supplies including breathable air and water are addressed first followed by general supplies not related to life support.  The information is provided in a series of tables or matrices describing the type of system or supply category, what the system or supply is required to provide per refuge station occupant, how the system or supply can be provided, and adjustments to quantities based on the planned number of refuge station occupants.  These tables provide detailed, specific information on what must be provided to ensure the survival and comfort of the occupants during refuge station use.  All tables are based on occupancy of the station during an emergency for a maximum of 96 hr.  The tables describe how to calculate supplies and equipment for the anticipated maximum number of occupants for the station.

Section 3 also presents important considerations when selecting life support equipment and supplies.  This information should be read prior to completing the worksheets.

Worksheets are provided for use by mine operators in developing equipment and supply lists. Instructions are  provided for each worksheet.  Some items require the user to multiply the number of occupants by a per occupant adjustment factor.  For these items, quick reference tables are provided after the worksheet.  The user can look up the number of occupants on the quick reference sheet and determine the required amount by selecting the number in the correct column in the quick reference.

Examples of completed worksheets, based on a specific refuge station type and capacity, are included.

The general supplies (not connected with life support) listed are a guideline of what is needed to be stocked in the station, based on surveys of information on mine accidents, existing refuge stations, submarine, spacecraft, military and civilian close quarters environments for survival. Many types of off the shelf (OTS) items can be substituted in the general supply list as long as they provide the basic requirement and meet existing mine regulations. Recent testing of refuge stations by both government agencies and private industry has provided good insight into what is desirable, useful and necessary inside a refuge station. The matrices provided are based on size, occupant load, and anticipated duration.

### 11.5  Design and Construction of a Universal Refuge Bulkhead

Section 4 of the guidance document provides instructions for the design and construction of a Universal Refuge Bulkhead which is used to form a refuge station.  The bulkhead is constructed using a composite-reinforced concrete block wall system and manway installed across a mine

passage or stub end. The guidance document describes all the components and construction procedures required for the bulkhead, including a guide for inspection, testing and maintenance in service. Mine operators should first review the initial summary description of the bulkhead system, which is broken down into eight major subsystems labeled (a) to (h). The specification and design/construction guidelines for each of the eight subsystems should then be reviewed.

The structural design of the bulkhead wall system is documented in Section 10 of this report and is based on the "design pulse" developed in Section 8. The flash fire heat criterion of 300°F for 3 sec was used by the State Of West Virginia Office Of Miners' Health, Safety And Training which incorporated this criterion in their Emergency Shelters/Chambers §56-4-8.6(2). This criterion was in turn based on the National Fire Protection Association flash fire criterion in NFPA-2113.

The bulkhead system has been structurally designed to fit any mine passage up to 20 ft wide and between 3 ft and 6 ft high without further detail design of components. Users should carefully measure the actual site location, and then use the design/construction guide to determine the quantities of materials required. Tables to aid in this process are provided. An engineering assessment of the suitability of the passage conditions should be made before proceeding. Steel members should be cut to the proper length to fit the passage before construction. Transportation and storage of these materials to the selected location in the mine should be planned to allow efficient construction to then proceed.

Although the system uses standard construction components such as mortared concrete block, standard steel angles and channels, mechanical rock bolts and anchors, mine sealant, etc., there are three areas in which specialized components need to be provided. 1) The composite fiberglass-resin reinforcing layer as called for references a manufacturer who also approves installations. An engineer should review this source or an alternative and arrange for proper installation meeting the manufacturer's standards. 2) The front-mounted blast panels can be fabricated from expanded steel sheet and light angle, but their contents are obtained from the manufacturer. Engineering approval for any alternative should be sought, if desired. Alternatively, a vendor could provide the units complete and ready for installation. 3) The entry manway system shown is used for illustration only. It is supported on a structure provided in the guidance document, but users may select an alternative in accordance with the construction guide and supplemental information provided.

A steel angle and channel perimeter support layout must be bolted to the roof, ribs and floor. A suitable rock drilling and bolting machine, or hand-operated version, will need to be available. An engineer must draw plans showing the members cut and placed, the arrangement of solid and hollow concrete blocks, the arrangement of the blast reduction panels, and the bolt pattern, all using the construction guide and supporting information provided. These plans can use the schematic drawings provided as a baseline for the actual bulkhead in the selected location.

When complete, the bulkhead system will need to be inspected and approved by mine engineers or designees per the inspection guide. A detailed checklist, plus a filled-out example is provided. This same checklist can be used for subsequent inspections required as described in the Inspection, Testing and Maintenance Guide.

A station built using the universal refuge bulkhead requires atmosphere and life support supplies and general supplies as described in Section 3 of the guidance document.

## 12. _Summary, Conclusions, and Recommendations_

The observations and conclusions from the program effort are provided below, divided into the seven major work areas performed:

- Evaluation of Mine Disasters.
- Development of Refuge Station Design Parameters.
- Refuge Location Analysis.
- Atmosphere Management.
- Blast Loading Characterization.
- Universal Refuge Bulkhead Design for Bulkhead-based Stations.
- Cost Estimates/Comparisons for Refuge Station Types.

This is followed by a brief set of recommendations for further study in support of the objectives of this program. These recommendations are submitted for NIOSH's consideration.

### 12.1 Observations and Conclusions from the Mine Disaster Review

The results of the event tree analysis indicate that refuge stations would have had a positive impact on the outcomes in about one-third of the disasters studied. A total of 74 (75%) of the 99 fatalities who were not killed immediately would have been positively impacted and potentially would have survived the accident. We caution that these numbers must be viewed in light of the assumptions that were made during our analysis of the mine disaster reports. This analysis was designed to provide insight into the design and use of refuge stations and is not intended to make any statement about the actions and events described in these reports.

By far the greatest single outcome that would have been positively impacted is the case of miners who perished during their escape attempts. Our assessment indicates that 57 (85%) of the 67 miners might have been positively impacted.

A second major conclusion of the study is the positive benefit on those miners who barricaded. While barricades were used in only two relevant incidents, these incidents combined involved 17 (and possibly 19) fatalities. All of these miners would likely have been positively impacted by stations.

The primary benefit of refuge stations is providing a breathable atmosphere to miners since in most of these outcomes miners died from lack of breathable air.

Refuge stations would not be useful to miners who are too injured to move following an accident. They cannot be useful when miners are killed instantly or if they perish shortly after an incident from noxious atmosphere when there is no time to react to the situation.

Refuge stations could also create a positive impact on miners who escaped successfully. These individuals might have used refuges as way stations on the way out of the mine to safely change SCSRs, try to communicate with the surface, rest, and obtain first aid.

It does not appear that refuge chambers would be a viable refuge for miners subject to water inundation.  Unless stations were built to resist signification hydraulic pressure head, they would not be able to counteract the forces from flooding.

Based on the review of specific reports and findings from the mine disasters it appears likely that mine rescue methods and procedures will need to account for recovery of trapped miners from shelters. With rescue teams readily able to determine the type, location, and capacity of the refuge stations within the mine, their rescue plans and approaches would be significantly impacted.  To ensure readiness this would likely include preparation and practice that has to be integrated into mine rescue procedures and protocols.

## 12.2  Observations and Conclusions from the Design Parameter Assessment

A thorough review of all design parameters was completed for both portable and fixed refuge stations.  From our analysis we present the following observations and conclusions:

- Development of design loads and specifications:
  - Locate "out of the line" of potential projectiles.

- General atmosphere management:
  - Boreholes are the gold-standard for  refuge station atmosphere control.
  - In closed systems, $CO_2$ must be absorbed and oxygen supplied.
  - Dangerous $CO_2$ buildup occurs before oxygen depletion.
  - Effects of initial spike loading (when miners first enter) must be mitigated.
  - Effects of overloading (more miners than specified capacity) on systems must be mitigated.
  - High $O_2$ environment and permissibility of electrical devices may require further evaluation.

- Portable chamber-specific issues:
  - Portable systems are more likely to be used near working faces which are constantly being advanced.
  - It is likely that portable units will have closed-system atmosphere management.
  - In-mine transport details must be established to minimize handling damage; post-transport inspection is essential.

- Fixed Bulkhead-specific issues:
  - Bulkhead-style stations are more likely to be installed in locations that are permanent or semi-permanent.
  - Refuge stations constructed using bulkheads are ideal candidates for borehole-supplied fresh air to seal off a safe area.
  - Site preparation and construction should be performed under supervision with appropriate sign-offs.
  - Sealing and anchoring of bulkhead must be adaptable to a variety of conditions (seam height, uneven perimeter gaps, slope, stratification).

- We provided input to the atmospheric testing protocol under development by NIOSH. Ideas and debate regarding atmosphere control testing (both simulated and man-tested) and structural (explosion) testing will likely continue.

## 12.3 Refuge Location Analysis

The summary of our work and resulting conclusions and recommendations for the placement of refuge stations within underground coal mines is as follows:

- In some of the cases studied, refuge stations would have been most effectively located within 1,000 ft from the faces of mining sections while in other cases stations would have been more effective at the 2,000 ft locations. This creates two options: place stations at both locations or provide one about 1500 ft. In addition, station(s) should be located at nominal locations that prescribe a location within a range such as 1000 to 2000 ft, to account for continuous face advancement.

- At least one station must be active for a working section at all times. A portable chamber cannot be considered "in-service" when it is being moved. If only a one-station system is being used it would require being moved during non-working shifts. If a mine is maintaining a two-station system, one can be dismantled and moved while the other station remains in service.

- Note that special consideration has not been given to very low coal seams in this recommendation. Mines may need to consider placement of refuge stations within ranges closer to the faces depending on the height of their coal seams or on other mitigating factors that would make travel to a station particularly difficult.

- In sections such as longwall sections where miners are spread widely throughout the face area and alternate escape routes are provided (as in headgate and tailgate escapeways), stations should be provided within each of the main escapeway routes where feasible. This may be difficult in tailgate entries due to obstructions.

- Stations should be located within crosscuts (preferably stubs) off standard designated intake escapeways. If necessary in some instances, they may be located off designated return escapeways.

- We strongly recommend establishing an initial station within a dead-ended working section as soon as possible after the section has advanced deeply enough to accommodate it. This will provide refuge to miners who could become trapped within the dead-ended section by

fires or explosions that might occur either inby or outby in the adjoining main entries. This is in agreement with research by others [9].

- The timeframe required to rescue miners from the assumed refuge station locations varied widely. The range was from a few hours to a maximum of 96 hr with most within 48 hr. We recommend that stations be equipped to handle stays of up to 96 hr to accommodate the maximum range of the rescue timeline and to account for the potential for stations to be overloaded (occupied beyond their designed capacity).

- Our study has shown that additional outby stations would only rarely be helpful and we do not recommend maintaining additional outby stations. If boreholes are constructed at regular intervals; however, one might consider maintaining some of the stations.

- Stations should not be located within escapeway crosscuts that are close to belt drives or other potential fire hot spots. Stations near overcasts should also be avoided.

- Stations should not be positioned within or off track entries when other options are available.

### 12.4 Atmosphere Management

The summary of findings, conclusions, and recommendations for atmospheric requirements is as follows:

- We recommend that for design purposes, breathing supplies should be sized to provide 0.022 cfm (0.623 l/min) of oxygen delivery capacity per occupant and 0.019 cfm (0.538 l/min) of carbon dioxide removal capacity per occupant.

We recommend the following criteria related to atmosphere management:

- *Oxygen levels of 19 to 23 percent.* Note that there is an upper limit on oxygen concentration as well as a lower limit. The upper limit is primarily due to the increased risk of fire or explosion. Electrical permissibility standards are also affected.

- *Maximum carbon dioxide concentration of 0.5 percent,* with short (less than 1 hr in 8) excursions to no greater than 1.0 percent.

- *Maximum carbon monoxide concentration of 25 ppm* over the design life of the chamber and 50 ppm maximum in any eight period. Other higher limits might be possible for shorter exposures. A significant concern is that it may not be possible to devise a test to verify that this specification is being met. To date, the technology to control carbon monoxide inside a sealed environment is not well developed. The alternative is to purge reducing the carbon monoxide concentration by dilution. A 100 percent volume purge would be required to reduce CO levels by 50 percent. While this could be readily accomplished with a borehole, it would require large quantities of stored air (compressed air bottles) for chambers without boreholes.

- Note that the limits for both $CO_2$ and CO vary depending upon the length of exposure. It might therefore be desirable to permit short exposures above a baseline threshold.

- *Apparent temperature* should not exceed 95°F.

- 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.

The following approaches are considered for atmosphere management:

- *Oxygen supply* is typically, medical-grade oxygen bottles supplied with gauges, regulators, and flow meters.

- *Carbon dioxide* scrubbing can be accomplished using state of the art commercially available systems. The two major scrubbing technologies are soda lime and lithium hydroxide.

- *Fresh air* can be supplied to a shelter via a surface borehole or suitably protected compressed air lines. Boreholes as small as 6 in. 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 supplied air can also simplify temperature and humidity control. No separate O2 supply and no $CO_2$ scrubbing system are necessary. We conclude that an airflow of 1.9 cfm (53.8 l/min) per miner will be required to maintain a carbon dioxide concentration of 1 percent; 3.8 cfm (107.6 l/min) would be required for 0.5 percent.

- *Carbon monoxide control* is critical but no commercial systems exist. 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.
  - Metal-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.

- *Testing of atmosphere life support systems in refuge chambers* 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. Four commercially available chambers were tested. The NIOSH report is due out at the end of December 2007.
  - *Human subjects testing* has to date only been conducted somewhat informally by equipment manufacturers, either on a complete system or a single design feature (e.g., $CO_2$ scrubbing). The most interesting test to date was performed in West Virginia in September 2007. The oxygen supply was bottled oxygen and the $CO_2$ scrubber was lithium curtains. A crew rotated through the shelter over a 96 hr period, keeping 10 miners inside at a time. Oxygen and carbon dioxide remained within norms at all times and the temperature did not rise above 72°F.

- *Recommended design life* for refuge stations is 96 hr.

## 12.5  Blast Loading Characterization

Literature was reviewed and key findings used to develop blast loading characterization. Eleven significant reports were examined that covered work and experimental testing conducted during the past 40 years. Valuable research and testing has been conducted at the Lake Lynn Experimental Mine (LLEM), in which many blast conditions have been replicated, measured, and data published. For the purposes of developing rational and reasonable design criteria for the design of bulkhead-type refuge stations, much of this work along with that of other researchers has been carefully reviewed.

We conclude that the transient gage pressure applied to a bulkhead in most cases will be at or below the 15 psig transient trace shown in Figure 22. This 15 psig/0.3 sec load transient which decays over 2 sec was developed to represent actual "working" load conditions for a bulkhead refuge station considering its placement in the mine. This pressure transient equals or exceeds the great majority of blast situations at potential refuge locations, and therefore represents a reasonable design basis for the refuge bulkhead. While magnitudes exceed this in rare circumstances, the many tests at LLEM have shown that the maximum pressure peak time durations from methane explosions are no longer than ¼ or 1/3 sec, so that this transient nature of the load for methane-only explosions is well accepted.

The effects of flame fronts on refuge stations is based on the blast characterization analysis which showed that the flame front and resultant pressure wave last for a small fraction of a second. We believe that MSHA's existing flame-resistance requirement (30 CFR 7.24) will govern the design of the exterior components of the refuge station.

## 12.6  Summary of the Bulkhead Design for Bulkhead-Based Stations

Two concepts are proposed. Both concepts follow the approach of having a 1) dynamically-acting, shock absorbing system element in front, with 2) a fiber reinforced and sealed hollow

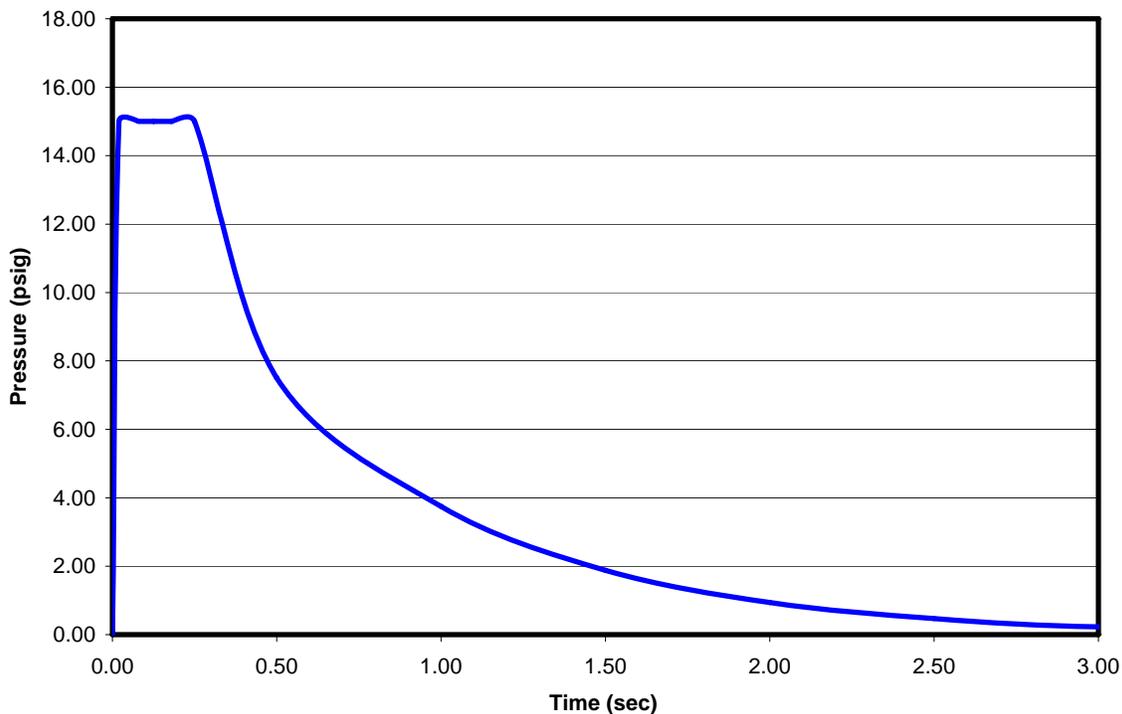**Design Basis Pressure Pulse--Mine Blast**



*Figure 22. Mine blast pressure-time "design pulse"*
*at potential refuge station bulkhead locations*

concrete block wall with manway (entry) system behind, secured to floor, ribs and roof. The area behind the block wall is stub ended or otherwise protected.

- The first stage, or primary layer, would initially be encountered by a potential blast front. This layer reduces blast pressure and absorbs energy, while surviving the nominal or "working level" design pulse. This layer would not be relied upon to withstand more than the working level load, but would reduce higher loads on the second stage in the short transient load peak time duration.

- The second stage, or secondary layer, would withstand the "working load" pressure in the unlikely event that the first stage of protection above is overpowered. This secondary wall system would also provide the necessary "hard seal" and entry/exit capability to form the actual refuge station itself.

The two options for the primary layer are an Energy-Absorbing Chute System or a Panelized Blast Reduction Media System.

The Energy-Absorbing Chute System (EACS) utilizes a large, lightweight parachute-like "chute" that is positioned such that an incoming pressure wave would quickly "inflate" it thereby protecting the solid refuge wall behind it at least up to the level of the working level design

pulse.  Using a strong fabric similar to automotive airbag material but coated with a protective layer, it would withstand and dissipate the blast wave via energy-absorbing shrouds.

The Panelized Blast Reduction Media System uses BlastWrap$^{TM}$ packets that absorb energy from the blast. The blast panel approach is simpler and less expensive than the chute option but for the same transient pressure load, the pressures on the wall behind the blast reduction panels would be somewhat higher.  However, in an overpressure situation, due to the progressive crushing nature of the panelized blast media material, the blast protection panel layer provides a reduction of pressure on the secondary wall.

Both bulkhead concepts rely upon having a sealed structural wall with manway (entry) system behind the dynamically-acting, shock absorbing system elements in front.  This wall must survive the "working loads" without any damage or compromise in operation.

This "secondary" wall system would also provide the necessary "hard seal" and entry/exit capability to form the actual refuge station itself.  It would use familiar construction materials. The basic configuration practical for in-mine use would favor some type of built-up block wall.

We selected the panelized blast reduction media system for the universal refuge bulkhead because it is integral to the block wall and provides more flexibility in installation and sizing of refuges.

### 12.6.1  Selection of Fiber Reinforced Hollow Concrete Block Wall for Bulkhead System

An 8 in. thick mortared concrete block wall with the rear (tension side) face reinforced with a standard fiberglass/composite layer was selected as the secondary wall configuration for the bulkhead refuge station. This wall would be supported at the roof and ribs of the crosscut passage by steel angles anchored with standard roof bolts (having nut-type ends to allow later removal). The wall would be set into the floor via a concrete-filled trench familiar to the mining industry.  The wall system would incorporate a manway (door) and support structure.  Also, the wall must be sealed on the front face (potential blast side) to prevent entry of contaminating post-blast gases

The 8 in. fiber-reinforced concrete block wall was preferred over the Omega block type thick wall mainly due to less volume of construction material (8 in. versus 40 in. thick plus pilasters) and the thinner section can accommodate a greater variety of manway access systems.

### 12.6.2  Conclusions from the Bulkhead System Design

- The behavior under the 15 psi/0.3 sec design pressure pulse shows that all sections remain undamaged. The structural integrity of the complete bulkhead system was evaluated dynamically using several LS-DYNA finite-element simulations of the secondary wall, the chute, and the panelized blast media subsystems.

- A limited number of higher loads were also evaluated for each of the two approaches and the results demonstrated that at 150 percent of design load the two layer bulkhead wall system remained intact but with some damage.

- The two-layer bulkhead systems as proposed are designed to withstand the "working level" 15 psi/0.3 sec transient design pulse with no significant damage and would be functional post-blast in all aspects.

- Under 150 percent of design load there could be extensive damage of the first layer, but survival of the secondary wall with some limited damage using its reserve strength with basic functions likely retained.

## 12.7  Cost Estimates/Comparisons for Refuge Station Types

Cost estimates including installation for portables are $81,000 to $100,000.  Cost estimates including installation for bulkhead stations based on the design concepts presented in Section 10 are $74,000 to $85,500.  Total costs for installation and five redeployments are $92,000 to $112,000 for portables and $154,000 to $175,500 for bulkhead-based stations.

We recommend establishing an initial bulkhead-based station within a dead-ended working section as soon as possible after the section has advanced deeply enough to accommodate it.  This will provide refuge to miners who could become trapped within the dead-ended section by fires or explosions that might occur either inby or outby in the adjoining main entries.  In this case, the provision for a borehole-fed station is advantageous if depth and surface conditions permit.  Unlike other refuge stations, this refuge would remain as a permanent installation.  The incremental cost for adding a borehole (assumed at 700 ft length) would bring the cost estimate for a bulkhead-based station to approximately $76,000 to $88,000 including the cost reduction from eliminating the stand-alone atmosphere control system which would no longer be required.

In general, cumulative costs will be greater for bulkhead stations when compared to portable refuge chambers as mining advances; however, bulkhead systems offer advantages of greater strength and permanence in certain situations and may be the more viable option under some mining conditions, such as low coal, where use of portable chambers may not be as feasible.

## 12.8  Guidance Document

Based on the research performed on this program, Foster-Miller developed a comprehensive guidance document for the coal mining industry for the selection, installation, and provisioning of refuge stations in underground coal mines.

The guidance document provides an introduction to the basic types of refuge alternatives.  It provides guidance on selecting the locations, sizes, and types of refuges as well as on providing life support equipment and general equipment and supplies.  The guidance document concludes with detailed instructions for the design and construction of the Universal Refuge Bulkhead Refuge.  The final guidance document was delivered to NIOSH in November, 2008.

### 12.9  Recommendations for Further Study

In this section, we submit our recommendations for further study for NIOSH's consideration. These topics comprise:

- *Expansion of the mining disaster/accident review work to include investigation of selected non-fatal incidents.*  The intent of the additional study is to help us provide better guidance on where to locate refuge stations and to help determine when refuge station use could have a negative impact on miner survival.

- *Design response of the bulkhead system to blast loadings* - Limited trial evaluations of the structural behavior under extreme loading and testing of a selected configuration.

- *Diffusion/leakage test for non-pressurized refuge stations* - Better understanding of the potential for gas ingress if positive pressure is not available or practical.

- *CO scrubbing device development (active or passive systems).*  Three approaches:
  - Develop Metal-Organic Framework (MOF) material for CO scrubbing.
  - Coordinate efforts underway with TPMFG on active CO scrubbing.
  - Coordinate with STC Catalyst on active CO scrubbing.
  - CO removal testing on scrubbing candidate technologies.

- *Fire resistance and blast tests on BlastWrap.*

- *Tests with alternative coatings for tension, sealing, and strength, e.g., Line-X and Defend-X polyurea spray coating.*

- Support to further develop the NIOSH test protocol for shelter evaluation.

- *Development of a web-based guidance tool for the NIOSH website.*  This tool would be accessible by mine operators and would efficiently lead them through the guidance information based on their specific needs.

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