RESEARCH REPORT ON REFUGE ALTERNATIVES FOR UNDERGROUND COAL MINES

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Centers for Disease Control and Prevention
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Purpose

Section 13 of the Mine Improvement and New Emergency Response Act of 2006 ("MINER Act"), PL 109-236, required NIOSH to conduct "research, including field tests, concerning the utility, practicality, survivability, and cost of various refuge alternatives in an underground coal mine environment, including commercially available portable refuge chambers." This report summarizes the findings of such research, focusing on specific information that could inform the regulatory process on refuge alternatives. Further, gaps in knowledge and technology that should be addressed to help realize the full potential of refuge alternatives are also identified.

Scope

NIOSH's research on refuge alternatives was limited to underground coal mine applications. Historically, the use of refuge chambers has been more prevalent in underground metal/nonmetal mines, and some findings from this research may be useful for metal/nonmetal application. Notwithstanding, the underlying differences between mining sectors are significant and practices in one sector cannot be generalized to the other. Therefore, the information provided here is not intended for rote transfer to metal/nonmetal applications.

This research into refuge alternatives for underground coal mines has identified knowledge and technology gaps and the need for new training. While this report specifically addresses the elements of refuge alternatives that should be considered in the regulatory processes, the completion of the research to fully describe and address the above issues is ongoing.

All discussion in the remainder of this report applies specifically to coal mines and coal miners, unless stated otherwise.

Refuge Alternatives

Historically, miners trapped underground by a fire or explosion have built a "barricade" to take "refuge," i.e., to isolate themselves from the potentially poisonous environment and await rescue. These barricades could be concrete block walls or brattice cloth fastened to the ribs, roof, and floor, and serve to contain a breathable atmosphere for the miners while isolating them from contaminated air. Although barricading is reported to have been a useful practice in mines near the beginning of the 20th century, NIOSH has no evidence to support the practice of barricading in modern mining operations. Barricading is not considered to be a viable refuge alternative.

Two well-known refuge alternatives are chambers, which can be stationary or portable, and in-place shelters, such as safe havens, safe rooms, and bulkhead-based refuge stations. Another alternative currently under development is an escape vehicle that could also serve as a place of refuge. This report will focus on chambers and in-place shelters, and many of the findings can apply to refuge alternatives in general. When there is a need to distinguish between chambers and in-place shelters, then the specific refuge alternative will be named.

Chambers typically consist of manufactured rigid or inflatable vessels that are outfitted with supplies and equipment to sustain life for a period of time. In-place shelters are developed by taking an existing part of the mine, e.g. a crosscut, isolating it with one or more bulkheads, and then equipping the shelter similarly to a chamber. Chambers are manufactured off-site, delivered to the mine, and moved to appropriate locations underground, whereas in-place shelters are constructed within the mine. Two common ways of constructing an in-place shelter are: (1) installing a bulkhead at each end of a crosscut to create an isolated space; or (2) mining a cut into a block of coal and installing a bulkhead to isolate this dead-end heading.

Research Activities

A literature survey was performed to identify the findings from any past research on refuge alternatives and topics related to mine refuge and mine disasters, escape, and mine rescue. Visits were made to mines, nationally and internationally, and meetings were held with mining experts from labor, industry, and government in the U.S., Australia, and South Africa to collect information on refuge alternatives and to discuss contemporary issues associated with refuge alternatives. A research contract study of existing international practices, regulations, and products was conducted, and more detailed studies of practices in Australian and South African coal mines were completed under two other contracts. However, this work revealed very little information related to *coal* mining refuge applications, and several knowledge and technology gap areas were identified within the first four months of NIOSH's research into refuge alternatives. As a result, a major research contract was developed and awarded to address the gap areas, including guidance for locating and positioning refuge alternatives and establishing specifications for chambers and in-place shelters[1]. Concurrently, NIOSH researchers examined non-mining applications where survival in confined spaces is critical – notably

[1] The gap areas were identified at the end of the international survey effort, which was performed during July through October 2006. The technical part of the contract to address these areas was completed at the end of October. The actual contract award, conducted in compliance with the Federal Acquisition Rules, was made in March 2007. Work on this contract will continue through 2008. The contractor was able to provide key inputs for the preparation of this report to Congress.

civil defense shelters, submarines, and space capsules – in search of guidance for the coal mining application. Overall, NIOSH researchers studied a range of practical issues associated with refuge (such as movement of chambers from place to place), collected cost data on refuge alternatives and performed cost analyses, and conducted testing of refuge chamber performance at the Lake Lynn Experimental Mine.

Separate research projects were initiated as related gap areas were uncovered and the research remains ongoing. For example, one project focuses on the development of communications technology specifically for use in refuge alternatives, while another addresses the development of training modules for using refuge alternatives during escape and rescue. As a final example, a series of user booklets are being developed to assist mine operators in the location, installation, inspection, maintenance, and provisioning of refuge alternatives. The outputs from these projects are expected to begin late in 2008 and continue through 2009.

Report Format

The remainder of this report summarizes the findings of the research, and it is organized into the categories of utility, practicality, survivability, costs, and testing to correspond to the areas specified in the MINER Act. Training has been added to this list, as it is assessed to be critical to the successful use of refuge alternatives. Detailed supporting information and key references are included in the NIOSH docket, organized under docket #125. The docket can be accessed at: http://www.cdc.gov/niosh/docket.

UTILITY

The usefulness of refuge alternatives to help save the lives of trapped coal miners was investigated as part of the research. An analysis of historical mine disasters was performed to assess the effect that the presence of refuge chambers might have had in the outcome of these disasters. The results of this analysis are mixed. Given the overall small number of disasters and the specialized and mine-specific circumstances under which they occurred, it is difficult to make a strong case for or against a specific refuge alternative, or even for or against the efficacy of trapped coal miners taking refuge. Nevertheless, recent mine disasters have again focused attention on the utility of refuge alternatives, and it has been argued that the availability of refuge alternatives may have been useful in these disasters.

The usefulness of refuge chambers has been debated in the U.S. at least since the passage of the Coal Mine Health and Safety Act of 1969, PL 91-173. Despite significant research by the U.S. Bureau of Mines nearly 30 years ago, the use of refuge chambers had not been embraced by industry, labor, or government. The paradigm was to focus on escape.

Based on the totality of research associated with the utility of refuge alternatives, NIOSH believes the significant opportunity today is to recognize that refuge alternatives can be extremely useful to facilitate escape from the mine as well as to serve as a safe haven of last resort. Moreover, the potential of refuge alternatives to save lives will only be realized to the extent that mine operators develop comprehensive escape and rescue plans that incorporate refuge alternatives. Such an approach would be far superior to one in which refuge chambers are simply placed into the mine to comply with a regulation.

Ultimately, the utility of refuge alternatives will depend upon the suitability of the engineering specifications for the intended application, the integration of these refuge alternatives into a comprehensive escape and rescue plan, and the implementation of appropriate training for mine workers and mine managers. The engineering specifications have received considerable attention over the past 18 months, and are addressed in upcoming sections of this report. The establishment of escape and rescue strategies has received less attention, other than some debate on appropriate locations for refuge chambers; notwithstanding, this area is beyond the scope of this report. Work has been initiated under a separate research project to examine escape and rescue strategies. Training is also a critical component for success, and this report addresses the need for training in three areas: operation and maintenance of refuge chambers, expectations for the use of chambers, and escape and rescue procedures, i.e., how and when to use chambers during a mine emergency.

The utility of refuge alternatives to facilitate escape, as well as to serve effectively as refuge, will be greatly enhanced if two-way communications are provided between each refuge alternative and the surface. The technology to accomplish this does not exist generally, but is expected to become available over the next few years, and should be incorporated into most refuge alternatives as soon as practicable.

PRACTICALITY

Refuge alternatives have been successfully installed in underground coal mines abroad and to a limited extent in the U.S. Refuge alternatives are available commercially. Although no documentation is available to illustrate the successful use of a refuge chamber in an underground coal mine in an emergency circumstance, there is no evidence to suggest that refuge chambers or alternatives are impractical. It is well-understood that the installation of certain refuge alternatives and the moving and maintenance of such chambers will require an ongoing effort on the part of mine operators, and the costs of these activities are examined as part of the cost analysis that follows. There was also concern that the moving of refuge alternatives to advance or retreat with mining could be difficult and possibly impractical. After a thorough investigation of this issue including numerous site visits, it was found that the movement of refuge alternatives can be done safely and practicably. Notwithstanding, it may be impractical to implement viable refuge alternatives in the few mines that operate in very low coal, e.g. less than 36 inches.

The finding of the NIOSH research is that refuge alternatives, to facilitate escape and to serve as a refuge of last resort, are practical for use in most underground coal mines.

SURVIVABILITY

Survivability, for the purpose of this report, focuses on the required characteristics of refuge alternatives to ensure that workers who must use the alternatives will be able to survive for a specific duration. The most crucial specifications address the following issues: establishing and maintaining an atmosphere that will support life; maintaining structural integrity through an initial explosion and a possible subsequent explosion; and providing for the most basic human needs, e.g. water, food, and waste disposal. The location and positioning of a refuge alternative can affect its survivability as well.

The engineering design criteria for acceptable performance are optimally set based on experimental observations and/or simulations. A number of factors make optimal design difficult with respect to refuge chambers. The reasons for this are varied and include the following: complexities of mine explosions and the interaction of the explosion with the physical environment; conflicting data in the literature; and the limited number of observations of post-explosion environments. Generally, there are significant tradeoffs and potential "penalties" when selecting among design criteria options, i.e., optimizing one parameter will adversely affect another. The design parameters for refuge chambers and in-place shelters are selected with the understanding that the internal environment needs to support life for a limited time under emergency conditions, and not to serve as a routine workplace. Accordingly, none of the values suggested for refuge alternatives are intended to apply to workplaces.

The key design parameters that apply to portable or stationary refuge chambers and in-place shelters are summarized in Table 1. Additional comments on many of the parameters are provided in the footnotes. Except for the "strength" parameter, the values were chosen based on the literature, practices in other countries, and guidance obtained from the study of non-mining applications. The strength parameter is based on explosion experiments at Lake Lynn Laboratory in addition to the review of literature and modern practices. The values listed in the table should not be considered as absolute, but rather as reasonable starting points for specifications.

Table 1. Design and performance specifications for refuge alternatives.

PARAMETER	RECOMMENDED VALUE or PRACTICE
Minimum Rated Duration	48 hr
Strength[2]	15 psi overpressure for 0.2 sec
Anchor System[3]	Not recommended at this time

[2] Must withstand a pressure wave that rises to 15 psi in 0.10 second and then returns to 0 psi after another 0.10 second. Any damage to the housing of an inflatable chamber must not affect the deployment time, and all associated equipment must be fully functional after the overpressure. Any damage to the housing of a rigid chamber must not impair operation or sealing of the access door, i.e. there can be no leakage into the chamber from any external point, and all equipment inside of the chamber must remain in working condition after the overpressure.

[3] The pressure from the initial explosion may cause substantial movement with significant translational and rotational components. Studies of this issue are ongoing, but in some cases anchor systems could worsen damage.

PARAMETER	RECOMMENDED VALUE or PRACTICE
Fire Resistance [4]	300° F for 3 sec
Deployment Time [5]	Minimize this time when establishing the location of the refuge alternative and consider as part of the travel time
Min Concentration O_2	18.5%
Max Concentration O_2	23%
Max Concentration CO [6]	25 ppm
Gases to be Monitored Inside Chamber	O_2, CO, CO_2
External Gases to be Monitored	O_2, CO
Max Concentration CO_2 [7]	1.0%, not to exceed 2.5% for any 24-hr period
Apparent Temperature [8]	95° F
Entry and Exit	Provide a means of egress without contaminating the internal environment and/or a means to maintain a safe environment during and after ingress/egress
Potable Water per Person	2-2.25 qt per 24 hr
Durability [9]	Structurally reinforced and of sufficient physical integrity to withstand routine handling
Purge Air Volume [10]	No specific recommendation (see Entry and Exit parameter)
Food,[11] per Person	2000 cal per 24 hr
Human Waste Disposal System	Required
First Aid Kit	Required
Occupant-Activated Annunciation	Battery-powered strobe light or radio homing signal [12]
Communication with Surface[13]	Survivable post-disaster system
Minimum Distance to Working Face	1000 ft

[4] This parameter is based on NFPA-2113, but additional investigation is warranted; a fire resistance specification should be selected to protect exposed surfaces from the initial, not a subsequent explosion.

[5] This is the elapsed time beginning with the arrival of miners at the location of the chamber and ending when the environmental systems within the chamber have begun to function. Additional work is needed to establish reasonable boundaries for this time frame. In the interim, deployment time should be considered as part of the travel time needed to reach a chamber.

[6] The concern here is CO contamination during ingress and egress (see purge air volume).

[7] Scrubber materials must not become airborne or otherwise cause respiratory distress or other acute reactions.

[8] Apparent temperature is a measure of heat stress, but other indices or standards could be used, such as the wet bulb temperature. Regardless of the index selected, the numerical value must be assigned to prevent heat stroke. Thus, if wet bulb temperature were selected, then a corresponding numerical value of 84 deg F would be appropriate, based on available medical evidence.

[9] The expectation is that the structure can withstand the expected number of moves without visible evidence of structural damage and without damage to the internal contents.

[10] It is unclear whether all commercial chambers can purge contaminated air from the chamber; this will require further investigation.

[11] Food stores should be selected to minimize waste and flatulence and to meet basic nutritional needs.

[12] This would allow rescue teams to concentrate their efforts on refuge alternatives that are occupied. The use of the battery in this application is controversial and additional study is warranted.

[13] Systems are under development and should be applied as soon as they become available. These systems should be independent of the mine's communications system, to the extent practicable.

PARAMETER	RECOMMENDED VALUE or PRACTICE
Maximum Distance from Working Face	Distance that a miner could reasonably travel in 30–60 minutes, under the expected travel conditions
Security	Visual indication that a refuge alternative has been entered; inspection and maintenance actions required subsequent to discovery
Repair Materials	Materials and instructions supplied by manufacturer
Testing and Approval	Required
Unrestricted Floor Space	> 15 ft^2 per person
Unrestricted Volume	> 85 ft^3 per person
Capacity[14]	Sufficient to accommodate the maximum number of miners in the area to be served by the refuge alternative

Location and Positioning

The location of refuge alternatives is best established in the context of an escape and rescue plan for each mine. A refuge chamber or in-place shelter should be available and readily accessible from each active working section. Additionally, refuge alternatives such as in-place shelters may be desirable in more "outby" locations, e.g. between the mouth of the panel and the shaft, to facilitate escape or the handling of injured miners. However, the presence of escape shafts or other means of exiting the mine could effectively eliminate the need and desirability of outby refuge alternatives, and the benefit of these additional locations should be evaluated on a mine-by-mine basis.

The location of the refuge alternative serving each active face is important, but establishing the exact location is problematic. It would appear advantageous to place the refuge alternative as close to the face as possible to minimize the time and effort required for miners to reach it. On the other hand, locating the alternative closer to a possible explosion source will increase the chance that it is damaged by either the overpressure or flying debris from the initial explosion. It is also argued that refuge alternatives should be located farther from the face to encourage and facilitate escape rather than refuge. Furthermore, the effects of subsequent explosions, with their more varied possible locations, must be considered in addition to the initial explosion.

An analysis of past disasters as well as various probable scenarios provides conflicting evidence to support any particular location for refuge alternatives. Nonetheless, the experience of studying mine explosions at NIOSH's Lake Lynn Experimental Mine, and the resulting explosion pressure profiles, suggests that refuge chambers should normally be located a minimum of 1000 feet from the working face and in some cases as far as

[14] Consideration should be given to short term needs as well, such as at shift change.

2000 feet.[15] Distance is an appropriate measure with regard to decay of explosion overpressure, for example, but the distance parameter alone cannot account for the time it will take miners to travel to the location of the refuge alternative. Lower seam heights, difficult bottom conditions, and the presence of smoke, among other factors, will increase travel times. Thus, the maximum distance from a working section to the refuge chamber or in-place shelter should be based on projected travel time rather than actual travel distance. Unless there is a compelling reason otherwise, the refuge alternative should be located within approximately 30–60 minutes[16] from the face under the expected travel conditions, assuming smoke-filled entries and a directional lifeline.

Arguably, one reason for allowing a greater distance and travel time would be to reach an in-place shelter. Typically, an in-place shelter would have a vastly greater volume per occupant, better environmental and sanitary conditions, and might be connected to the surface by a borehole with its attendant services. However, it is impracticable to move these shelters frequently. Therefore, if the in-place shelter is constructed to offer significant advantage over a portable chamber, it may be desirable to allow greater distances that would require a travel time of 60 minutes or slightly more.

Refuge alternatives should be positioned in crosscuts rather than entries, or in dead-end cuts made specifically for the refuge alternative, and they should be positioned off of the intake or return escapeway whenever feasible. They should not be located within approximately 1000 feet of any mine seal, nor in or off of track entries whenever practicable. Locations near overcasts should be avoided; as should sources of potential fire such as belt drives.

Site preparation is particularly important for portable inflatable refuge chambers. Adequate clearances to the roof and ribs must be provided to ensure an unobstructed volume for the inflation of the chamber. The area, including the floor, should be free of materials that could puncture the chamber, and the floor should be reasonably flat and level and free of mud holes, ruts, and rock. Special consideration should be given to the condition and stability of the ribs, roof, and floor around all chambers.

COSTS

A cost analysis of refuge chambers was conducted, with the associated costs separated into three segments: (1) purchase, installation, and training; (2) maintenance and inspection; and (3) moves. The costs for these segments were quantified and the assumptions used in the analysis are summarized in Table 2. Benefits associated with the

[15] The most likely locations of an initial explosion can be predicted with some certainty, and this information can be used to guide decisions on the location and characteristics of refuge alternatives. Mine-wide ventilation is often disrupted as a result of the initial explosion, and once disrupted, methane can accumulate at any number of locations in varying quantities. If there is an ignition source, there could be subsequent explosions, although the location and strength of these is more difficult to forecast. Accordingly, the discussion here focused more on the events that can be anticipated and therefore be used to provide guidance.

[16] This guidance is based on experience with traditional self-contained self-rescuers (SCSR). The style of SCSR or the presence of SCSR caches, for example, could be used to justify a change in these times.

costs of the refuge chamber were not evaluated in this analysis. Information to quantify costs was obtained from requests for certification of emergency shelter documents submitted to the state of West Virginia by the manufacturers of portable refuge chambers, from state regulations for refuge chambers, and by contacting the manufacturers directly.

Table 2. Assumptions used for quantifying costs for refuge chambers.

Cost Assumptions for One Portable Refuge Chamber
Mine operates 24 hours/day for 365 days/year
Discount rate = 9.5%, 10-year lifespan

Chamber Purchase, Installation, and Training		
Description	**Initial Costs**	**Annual Costs**
Refuge Chamber	$80,000	
Installation (8 hours using mechanic ($30.21 hour), electrician ($30.04/hour), and laborer ($27.28/hour)	$700	
Safety Training (Initial = 2 hours. Annual after each move = 15 minutes, 60 times/year)		
Manufacturer Training ($1000/day)	$1,000	
Personnel Costs (3 continuous miner crews ($223.52/hour per crew)	$1,341	$10,058
Total	$83,041	$10,058

Chamber Maintenance and Inspection

(Daily and monthly performed by mine; all other inspections performed by manufacturer twice/year)

Description	Initial Costs	Annual Costs
Personnel Costs		
Manufacturer Inspection (2 inspections per year at $1000/day)		$2,000
Mine Personnel Inspections (Monthly 15-minute inspection by mine foreman ($47.52/hour)		$140
Supplies (All items have a 5-year life, items with * incur costs in 5th year only)		
Batteries*		$2,500
CO2 Scrubber System*		$11,500
First Aid Kit*		$1,000
Food and Water	$1,400	
Oxygen*		$2,500
Total (Annual cost)	$1,400	$2,140
Total (5th year cost)		$19,640

Chamber Moves

(60 moves/year calculated from typical mine production rates and maintaining 1000-foot distance in a 3-entry room and pillar system)

Description	Initial Costs	Annual Costs
Personnel Costs (4 hours using mechanic ($30.21/hour), electrician ($30.04/hour) and laborer ($27.28/hour)		$21,007
Supplies ($100 per move)		$6,000
Total	$0	$27,007

Net present value calculations were performed on the quantified costs, shown in Table 2, over a 10-year life span for the refuge chamber, using various discount rates. Results of these calculations are summarized in Table 3. The total costs shown in the table are more substantial than the initial purchase price of a chamber, but these present worth costs include the quantified costs for the tasks of installation, training, maintenance and inspection, and moving. These quantified costs are necessary in order to realize the potential benefits of a refuge chamber.

Table 3. Summary of costs, for varying discount rates, of a portable refuge chamber over a 10-year life span.[17]

	3% Discount Rate	7% Discount Rate	9.5% Discount Rate
Purchase cost	$80,000	$80,000	$80,000
Installation	$700	$700	$700
Training	$88,100	$73,000	$65,500
Maintenance and Inspection costs	$34,600	$28,500	$25,400
Moving costs	$230,400	$189,700	$169,600
Total	**$433,800**	**$371,900**	**$341,200**

Moving costs are a significant portion of refuge chamber expenses, and changes to the number of moves can have a significant impact on cost. A sensitivity analysis conducted on moving costs showed that, as the number of required moves was varied from 30 to 90, the total net present value of the costs ranged from $256,400 to $426,000 with a 9.5% discount rate.

An analysis of in-place shelters using movable bulkheads was also conducted, and as expected it is not feasible from a cost perspective to advance in-place shelters with mining, as the present worth costs would exceed $7,000,000 per shelter. However, the net present cost to install such a shelter in a location that would be moved or abandoned once per year is similar to the present worth cost of a portable chamber; if the shelter were moved twice per year the present worth cost would increase by approximately 75%, using similar assumptions to those for portable refuge chambers. An important function of an in-place shelter is its connection to the surface with a borehole, when practicable[18]. However, the costs of drilling this borehole and providing air and communication lines were not included in the analyses.

[17] OMB circular A-94 requests agencies use discount rates of 3% and 7%. A discount rate of 9.5% represents the December 2007 lending rate of LIBOR + 5% for a fixed rate loan.
[18] The mine would need to acquire surface rights, and the surface would have to be accessible and free of obstructions, e.g. protected structures or a body of water, before a borehole could be considered.

TESTING

The need for any specific type of testing was undefined at the beginning of NIOSH's research on refuge alternatives. Initially there were no commercially available chambers to test and none of the knowledge gaps surrounding refuge alternatives suggested a specific type of experimental investigation. Approximately 10 months into the study, the State of West Virginia mandated specific performance standards for approval of chambers for use in West Virginia coal mines. A NIOSH review of the approval criteria established by the West Virginia Office of Miners' Health, Safety, and Training found them to be appropriate, based on a review of the literature and the application of mining heuristics. The State's approval of individual chambers was conditioned upon certification by a registered professional engineer.

NIOSH had concerns that the information needed to approve a chamber could be fully obtained from manufacturer-submitted materials and calculations, and that this information would need to be supplemented with the results of experimental testing. Accordingly, NIOSH began to develop a protocol for testing chambers in the 12^{th} month of this study. Although an experiment involving human subjects in the chambers was desired, the risks were deemed sufficient that a full human subjects review board review and approval would be required. To address many of the issues within the time constraints of this study, the decision to simulate human occupancy was made, and a protocol was developed, peer reviewed, and then implemented.

The research goals of the testing were limited to the areas of greatest interest in the context of time constraints, and these were to investigate CO_2 levels, oxygen flow rates, and the heat index (i.e., apparent temperature during chamber operation), and to observe the overall deployment and operation of the chambers. The protocol defined the means of simulating human occupancy to facilitate the evaluation of the chamber. In the simplest terms, the simulation of human occupancy was accomplished as follows: the oxygen flow rate into the chamber was set based on the occupancy limit and measured as a surrogate for the chamber's ability to provide adequate oxygen levels; CO_2 was injected into the chamber based on the respiratory quotient and the CO_2 level was then monitored; the heat from light bulbs was used to mimic the metabolic heat load of the expected occupancy; humidified air was injected into the chamber to simulate moisture from human respiration and perspiration, and then the temperature and humidity were measured for the calculation of apparent temperature. The tests were conducted continuously over a 96-hour period. Four manufacturers provided chambers for testing in the 16^{th} month of this study. The testing and preliminary analyses were completed in the 18^{th} month of the study. Major findings from the experiments are summarized in Table 4, and more specific observations are given below.

The innovation of the four manufacturers is evident in their products, and their ability to create new products to fill the gap in the market for portable chambers is commendable.

Notwithstanding, the testing did reveal shortcomings in the chambers. Those shortcomings, as outlined in Table 4, are sufficiently serious in three of the chambers to require correction before deployment. In most cases, but not all, these shortcomings should be correctable, or have already been corrected, with minor technical changes, the addition of clear instructions, and/or improved engineering. Major findings of the testing are as follows:

- All four chambers had been approved for use in West Virginia based on manufacturer representations and certification by a registered professional engineer. Nevertheless, testing revealed potentially serious deficiencies, underscoring the fact that computational models and other engineering analyses alone cannot be relied upon for approval and certification of complex systems such as refuge chambers. The results of the testing indicate the need for independent evaluations and testing beyond the chamber manufacturers.

- Heat dissipation was more of a problem in the steel than the inflatable chambers, and the heat stress index[19] in both steel chambers exceeded the levels established as acceptable by the state of West Virginia. Despite these findings, steel chambers are assessed to have certain inherent benefits over inflatable ones, such as their ability to withstand subsequent explosions, and it would be desirable to correct this observed limitation so that rigid steel chambers can be approved for use. The heat created during the exothermic scrubbing process would be reduced by allowing higher CO_2 values as listed in Table 1. Further, an increase in the surface area of the steel chambers would allow more heat loss to the environment and the rated occupancy of the chamber could be decreased, which would reduce the heat generated within the chamber. It should be noted that the ambient air temperature for the tests was approximately 60 degrees F; if the steel chambers were used in mines with ambient temperatures closer to 70 degrees F, as is found in some deep mines, the problem would be exacerbated.

- The time to deploy[20] each chamber varied from a few minutes to more than 30 minutes in two cases. There is no consensus on the amount of time that is reasonable, but the time to deploy a specific chamber should be considered when establishing the maximum distance that a chamber can be located from the face.

- Three of the four chambers were unable to maintain CO_2 concentration below the level specified by West Virginia OMHST, but the levels were within the range suggested in Table 1. Two of the four chambers were unable to deliver oxygen for the duration of the test.

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[19] West Virginia specified "apparent temperature" as a measure of heat stress and established an upper limit of 95° F, which is reasonable and is conservative.

[20] This is the elapsed time from arriving at the chamber until the environmental systems inside the chamber have begun to function. This time would include the setup and inflation time for an inflatable chamber in addition to the time required to start the oxygen flow and CO_2 scrubbing inside of the chamber.

Testing revealed deficiencies with the documentation provided for each chamber, and this information has been provided to the manufacturers. Opportunities for improving the usability and performance of chambers were noted and will be investigated further. Finally, although these research experiments were not intended to be tests that would be employed in a certification process, they have provided insights that can be used to develop independent evaluations.

Table 4. Survivability evaluation of four mine refuge chambers.

		Chamber 1	Chamber 2	Chamber 3	Chamber 4
Specifications	**Chamber Type**	Inflatable	Inflatable	Steel	Steel
	Capacity (persons)	20	36	12	26
	CO_2 Scrubbing System	Passive soda lime curtains	Powered soda lime cartridges	Passive lithium curtains	Powered soda lime cartridges
	Basis to Change Scrubbing Materials	Specified time - 96 hrs	Specified time - 24 hrs	Specified time - variable	Specified time - 16 hrs
Results	**CO_2 Scrubbing Criteria (0.51 l/min/man)** *(CO_2 level <= 0.5%)*	Did not meet Exceeded maximum	Met	Did not meet Exceeded maximum	Did not meet Exceeded maximum
	Comments	Exceeded 0.5% 42 hrs into test, remained above 0.5% from 44 hrs to end	Stabilized between 0.35% and 0.40%	Maximum reading was 0.72% (Due to error in deployment instructions rather than failure of scrubbing materials)	Maximum recorded reading was 1.34%
	O_2 Supply Criteria (0.62 l/min/man) *(O_2 >= 19.5%)*	Did not meet, Insufficient	Met	Met	Did not meet, Insufficient
	Comments	O_2 flow ended at app. 71 hrs		O_2 flow and conc. starting dropping at 94.5 hrs	O_2 flow ended at app. 37 hrs
	Apparent Temperature Criteria[21] *(< 95 deg F)*	Met	Met	Did not meet Exceeded maximum	Did not meet Exceeded maximum
	Comments	Apparent temperature app. 76° F (73° F and 62% RH)	Apparent temperature app. 73° F (70° F and 69% RH)	Apparent temperature app. 102° F (87° F and 86% RH).	Apparent temperature app. 110° F (90.5° F and 92.6% RH)
	Duration Criteria *(96 hours)*	Did not meet, Less than required	Met	Met	Did not meet, Less Than Required
	Comments	Test continued for 96 hours			Test continued for 56 hours. Failed scrubber containers and loose soda lime forced early termination.

[21] Apparent temperature computed according to West Virginia Emergency Rule 56-4-4, page 51, 2006.

TRAINING

To ensure the successful implementation of refuge alternatives, mine workers need to be trained in their use, and those involved in moving and maintaining chambers would require additional training. All miners and mine managers should be trained in the use of refuge alternatives in the context of that particular mine's escape and rescue plan.

NIOSH research indicates that motor task training, i.e. *how to use* refuge alternatives, should be given quarterly, possibly in conjunction with the mandatory mine evacuation training and drills. This would also be an appropriate time to include training on decision-making skills, i.e. *when to use* refuge alternatives. Finally, expectations training would be useful to reduce the level of panic and anxiety associated with the use of refuge alternatives, and should be included with the other training components described in this paragraph.

The proper movement, maintenance, and inspection of refuge alternatives are necessary prerequisites to saving lives with refuge alternatives. Task training would be appropriate to ensure that those charged with the responsibility are equipped with the skills to successfully complete refuge chamber moves, maintenance, and inspection.

NIOSH researchers and technical staff are developing training materials to meet the needs identified here, and most of the materials are expected to be completed within the next 12 months.

SUMMARY

Refuge alternatives have the potential for saving the lives of mine workers if they are part of a comprehensive escape and rescue plan, and if appropriate training is provided. Two viable refuge alternatives have emerged over the past 18 months: in-place shelters and portable chambers that are inflatable or rigid. Portable chambers are well-suited to providing a refuge alternative to workers as the active face advances or retreats.

In-place shelters can offer a superior environment for refuge and in many cases could be connected to the surface via a borehole to provide vital services. Unfortunately, it is impracticable to move in-place shelters frequently, and as such it would be impossible to keep them within 1000-2000 feet of the face. However, their strengths compared to portable chambers are so significant that consideration should be given to allowing extended distances, if in-place shelters are used to provide refuge for face workers.

NIOSH testing found that some commercially available portable chambers have operational deficiencies that will delay their deployment in mines. We conclude that approval or certification of refuge chambers based on laboratory and/or field testing is necessary for refuge chambers. In-place shelters should also be inspected and certified to meet at least the applicable requirements in Table 1.

There are some remaining knowledge or technology gaps for the design and specification of refuge alternatives. Nonetheless, the benefits of refuge alternatives and the general specification of these alternatives are sufficiently known to merit their commercialization and deployment in underground coal mines. NIOSH research suggests that any regulations on the specification, location, and conditions of use for refuge alternatives should accommodate the rapidly changing state of knowledge and technology.