

Facilitating the Use of Built-in-place Refuge Alternatives in Mines



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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
BIP	built-in-place
BOM	Bureau of Mines
CFR	Code of Federal Regulations
chgovr	changeover
CH ₄	methane
CMU	concrete masonry unit
CO	carbon monoxide
CO ₂	carbon dioxide
Dec	decision
DLF	dynamic load factor
HBA	Hubble Breathable Air
NA	not applicable
LLEM	Lake Lynn Experimental Mine
NIOSH	National Institute for Occupational Safety and Health
OMSHR	Office of Mine Safety and Health Research
PVC	polyvinyl chloride
RA	refuge alternative
SCSR	self-contained self-rescuer
Seq	sequence
Trvl	travel
UFC	Unified Facilities Criteria

UNIT OF MEASURE ABBREVIATIONS

CI	confidence interval
diam	diameter
fpm	feet per minute
ft	feet
ft ³	cubic feet
hr	hour
in	inch
ksi	kilopounds per square inch
lb-in	pounds inch
m	meter
min	minute
ppm	parts per million
psi	pounds per square inch
SD	standard deviation
sq	square

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Executive Summary

Background

Three major coal mining disasters occurred in 2006, involving either fires or explosions, killing 19 miners. In all of these tragedies, miners survived the initial disaster but were unable either to escape or successfully isolate themselves from the poisonous gases present in the mine environment resulting from the disaster. In response, Congress passed the Mine Improvement and New Emergency Response Act (MINER Act) of 2006 (Public Law 109-236). Among its mandates, the MINER Act called for the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) to “provide for the conduct of 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.” The primary function of a refuge alternative (RA) is to provide safe refuge for miners unable to escape their work area immediately after a disaster due to toxic gases or a blocked escapeway. To be effective, the RA must survive the initiation of the disaster, whether it is an explosion or fire. Furthermore, it would additionally be beneficial if it would protect the miners inside the RA from the blast impacts of a secondary explosion.

In response to the MINER Act mandate, NIOSH OMSHR conducted research on refuge alternatives and provided its findings in the form of a report to Congress [NIOSH 2007]. In sum, this report found that refuge alternatives were practical for use in most underground coal mines to facilitate escape and to serve as a refuge of last resort, provided that mine operators develop comprehensive escape and rescue plans incorporating refuge alternatives and training on their

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use. These findings applied to both portable RAs and built-in-place (BIP) RAs, with the BIP RAs emerging as being able to provide a superior environment. They offer the potential to provide miners with an improved psychological and physiological environment, which can be greatly advantageous to their health and safety in the stress of an emergency, and they can be provided with fresh air via a borehole to the surface or a protected compressed air line.

Despite these advantages, current BIP RA designs cannot be moved frequently from a practical standpoint—with movement of the RA location required to keep up with dynamic mining production—and as such it would generally be impractical to keep them within 1,000 feet of the nearest working face, as prescribed in 30 CFR¹¹ 75.1506(c). Notwithstanding, OMSHR’s 2007 report to Congress on refuge alternatives concluded that, as compared to portable RAs, the strengths of built-in-place refuge alternatives “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 2007].

Currently, there are approximately 30 BIP RAs in U.S. underground coal mines; however, all of these are located outby the face area and none are designed to be advanced with the working face. The usage of BIP RAs that can be advanced with the working face will only be practical if three issues can be addressed: (1) locating BIP RAs further from the face; (2) providing a consistent process for the design and approval of RA stoppings; (3) delivering a reliable supply of clean, breathable air to a BIP RA. In this Report of Investigations, these three issues are explored in detail.

Summary of Approach

To investigate the first issue—the possibility of locating BIP RAs further from the face—OMSHR researchers developed three different approaches to determine how far from the face area miners could travel given the 120 minutes of breathing time afforded them by currently available self-contained self-rescuers (SCSRs). This available 120 minutes of breathing time is based on 30 CFR 75.1714-4(a)(1), which calls for the mine operator to provide “at least one additional SCSR, which provides protection for a period of one hour or longer, for each person at a fixed underground work location.” It should be noted that the Refuge Alternatives for Underground Coal Mines Final Rule [73 Fed. Reg.¹² 80656(2008)] makes it clear that the times included are based on a worst case of only one SCSR being available to each miner.

The three different approaches to determine how far from the face area miners could travel are as follows:

- Approach 1 was based on SCSR-mandated storage cache locations, and examined the MSHA-established criteria for distances between SCSR storage caches as a method of determining acceptable distances from the face area for RA locations.
- Approach 2 was based on worst-case SCSR usage times, with OMSHR performing a timeline study of an assumed worst-case scenario for miners involved in a disaster,

¹¹ Code of Federal Regulations. See CFR in references.

¹² Federal Register. See Fed. Reg. in references.

beginning with the time they first don their initial SCSR and including the times it would take to travel to the face area, assemble as a group, make decisions, and perform switchover to a new SCSR if needed.

- Approach 3 was based on established travel times and escape probabilities determined from NIOSH and U.S. Bureau of Mines research, including research from 2011 involving actual miners traveling in airways filled with dense smoke in high coal without lifelines, and research from 1990 that considered the probability of making a successful mine escape in high coal with a single SCSR.

To address the second issue—design and approval of RA stoppings—OMSHR analyzed the criteria that engineers must consider when submitting RA stopping designs for approval under the requirements of MSHA’s Refuge Alternatives for Underground Coal Mines [Federal Register 2008] and guidelines for coal mine seal design applications [MSHA 2008]. Using the MSHA application guidelines as a model, OMSHR developed extensive guidelines for RA stopping design applications as well as specifications for an RA stopping design to serve as an example. The example RA stopping design is presented to illustrate the application of the proposed design guidelines in preparing a design submittal to MSHA District Managers for approval. Significantly different RA stopping/door systems for BIP RAs have already been approved by MSHA for use, and NIOSH believes that if BIP RAs become more commonly used in U.S. coal mines then many more acceptable and economically viable stopping/door designs that meet the 15 psi static pressure criteria will be developed.

To explore the third and critical issue—delivering a reliable supply of clean, breathable air to a BIP RA—OMSHR considered the available technologies approved by MSHA for providing breathable air to an RA via a protected compressed air line. OMSHR also analyzed the practical and technical considerations for the surface compressor station and the protected compressed air line.

To obtain information relevant to the above three issues, OMSHR researchers visited a number of underground coal mines to view BIP RAs and discuss with mine officials why they employ them. Researchers gathered extensive information on the construction, location, capacity, air supply, and provisioning. Mines in Colorado, Kentucky, Montana, and New Mexico were visited, with the specific mines selected to obtain a cross section of the industry including high and low coal and eastern and western coal mines.

Summary of Findings

Locating BIP RAs at Greater Distances from the Working Face

Based on Approaches 1 and 2 as described above—using SCSR-mandated storage cache location criteria and worst-case SCSR usage times—OMSHR determined that the worst-case time required for non-escapeway travel activities to the face would be *30 minutes*. A detailed statistical analysis along with MSHA-established values of realistic travel distances to SCSCRs in emergency situations were used to establish this 30-minute figure. Mine workers will have two SCSCRs available to them, providing 120 minutes of breathing time. In OMSHR’s assumed worst-case scenario, if miners use 30 of their 120 minutes of SCSR time to travel to the face, this leaves 90 minutes for travel time from the face to the RA.

Based on Approach 3 of using established travel times and escape probabilities determined from published research, and choosing the most conservative estimates of travel times needed, OMSHR calculated 90-minute travel distances in smoke-filled escapeways based on entry height. These worst-case scenarios combined three pieces of information: the regulations in 30 CFR 75.1714-4(c)(2)(ii) for 30-minute travel distances in various entry heights; the fact that smoke-filled airways increase travel times, and the above-outlined discussion that escaping miners should have 90 minutes of SCSR breathing time available for travel from the face to an RA. The resulting evidence clearly justifies the argument that RAs can be located further from the face, and that greater maximum distances of the RA from the face can be used in parallel with greater entry heights.

Combining the results from these three approaches, conservative maximum distances from the face to the RA for various entry heights were established, grounded in the assumption that miners have 90 minutes of available travel time in the escapeway to reach the RA. Based on these findings, OMSHR believes that mines could locate built-in-place refuge alternatives at distances from the working face based on the guidance provided by the table below.

The following table presents a summary of these findings, rounding down the most conservative distances arrived at in this report as the maximum BIP RA distances from the face, with these distances varying based on entry height.

Entry height	Approach 1: Based on SCSR- mandated storage cache locations	Approach 2: Based on worst-case SCSR usage times	Approach 3: Based on NIOSH and BOM established travel times and escape probabilities	Maximum BIP RA distance from the face
<40 inches	2,200 feet	2,640 feet	NA	2,000 feet
>40–<50 inches	3,300 feet	3,960 feet	NA	3,000 feet
>50–<65 inches	4,400 feet	5,280 feet	6,000 feet	4,000 feet
>65 inches	5,700 feet	6,480 feet	6,500–7,000 feet	5,000 feet

Allowing mines to locate BIP RAs at greater distances from the working face as outlined in this table introduces a number of advantages: (1) a higher likelihood of the BIP RA avoiding damage from both primary and secondary explosions that often occur at the face area, which also increases the likelihood that the communication system to the RA survives a disaster; (2) a reduction in the number of BIP RAs required to be constructed; and (3) the introduction of a wider variety of BIP RA designs, which could potentially improve the safety as well as the psychological and physiological comfort and mental well-being of confined miners.

Locating BIP RAs further from the face requires a trade-off of the advantages of locating an RA close to the face—such as the ability to easily assist injured miners in reaching the RA location and a shorter travel distance for miners to the RA—against the significant potential advantages gained from the use of a BIP RA. This argument is consistent with OMSHR’s position in its 2007 Report to Congress on refuge alternatives [NIOSH 2007]. Therefore, consideration should be given to allowing mines to locate RAs further from the face only if they employ new RA technologies that meet the following three criteria:

1. Provide a constant supply of air to the RA either via a protected compressed air line into the RA or a borehole from the surface into the RA.
2. Provide additional RA space per occupant. The original minimal space requirement of 85 ft³ per occupant as noted in the NIOSH report to Congress on refuge alternatives [NIOSH 2007] is recommended.
3. Maintain the RA interior atmosphere under positive pressure when not in use to ensure that the RA contains breathable air immediately upon entry and to keep contaminated air from entering the RA with miner entry. It would be advantageous to have a differential pressure gauge on the RA which could be inspected regularly to ensure that the positive differential pressure is maintained with the RA door closed. In many cases it will not be feasible to maintain the RA under positive pressure when it is not occupied. This would be the case when the air supply system for the BIP RA is not permanently located at the borehole but is only transported to the borehole in the event of a mine disaster. While the air supply to the BIP RA might be established before escaping miners arrive at the RA, this cannot be assured. Further, miners entering the RA prior to the ventilation system being established could bring contaminants into the RA. In these situations, additional SCSRs must be available in the RA to sustain miners until the RA can be adequately purged of contaminated air by the air supply to the RA. Importantly, to investigate these issues, NIOSH OMSHR is currently constructing a BIP RA in its Experimental Coal Mine in Pittsburgh to research issues related to BIP RA contamination with miner entry, the advantages of airlocks, airlock purging systems, and other means of keeping contaminants out of the RA—such as a membrane entry system or a series of overlapping plastic strips through which miners would enter. Research will also be completed on pressure relief valves and ways to ventilate the BIP RA during everyday operation to ensure against the buildup of methane or other harmful gases in the RA.

It should be noted that while BIP RAs may not be practical for all underground coal mine applications, OMSHR believes that they should play an important role in the available suite of RA options. As an example, one consideration would be to locate a BIP RA with a borehole to the surface or a protected compressed air line and communication to the surface at the mouth of each section. The BIP RA would be built in a crosscut or blind cutout with stopping/door systems at the ends set back to better survive possible explosion forces. Depending on the distance to the face, the RA could be the first one that miners travel to from the face or may be an additional outby RA. Also, the BIP RA being at the mouth of the section could provide miners a good location at which to decide on a further course of action with respect to continued escape or continued refuge with continuous fresh air supply and communications with the surface and rescue teams. Additionally, a combination of BIP RAs located at distances presented in the table above along with mobile RAs much nearer to the face would give miners more options for refuge.

Lastly, it is important to emphasize that in the event of any mine disaster, if at all possible, the primary goal of miners should always be to evacuate the mine before considering taking refuge.

Designing RA Stoppings for MSHA Approval

Based on OMSHR's analysis of design and approval criteria for RA stopping design, and using the MSHA guidelines for coal mine seal design applications as a model, OMSHR believes that the guidelines set forth in this report could be used by industry when submitting stopping design applications for approval by MSHA.

OMSHR's recommended design pressure-time curve for an RA stopping has a magnitude of 15 psi, a rise time of 0.1 seconds, a fall time of 0.1 seconds, and a duration of 0.2 seconds.¹³ Because of the slow rise time, this pressure-time curve always has a dynamic load factor of 1.0 and an equivalent static design pressure of 15 psi. This design pressure-time curve is illustrative of the pressure-time history close to an explosion originating in a face area of a development entry. It is similar to reported explosion pressures in recent underground coal mine disasters, and is commensurate with the blast pressure tolerance of the human body as analyzed in this Report of Investigations. This curve is identical to that developed in OMSHR's 2007 report to Congress on refuge alternatives [NIOSH 2007]. The justification of the 15 psi design criterion for an RA stopping is based on human survivability to explosion pressures. Finally, following the extensive guidelines recommended here for RA stopping design, OMSHR provides an example RA stopping design consisting of a conventional rebar-reinforced concrete wall that can withstand the expected 15-psi explosion pressures.

Delivering Clean, Breathable Air to a BIP RA

As noted in this report, most of the advantages of a BIP RA disappear if the RA is not guaranteed a constant and highly reliable supply of clean, breathable air. A borehole from the surface directly into the BIP RA is the most advantageous and reliable approach. However, a borehole from the surface to the BIP RA is often impractical due to such factors as drilling costs and surface rights issues. Instead, using a protected compressed air line carrying clean, breathable air to a BIP RA is emerging as a practical and achievable goal. One such system already has MSHA approval¹⁴ and it is anticipated that other systems will be developed if there is an opportunity for BIP RA designs to be advanced with the working face of coal mines. OMSHR believes that a constant supply of clean, breathable air can be provided to BIP RAs either from a borehole to the surface or through a protected compressed air line system. Several efforts to develop and test such systems are already being undertaken by private companies.

Considering Economic Drivers when Designing New BIP RAs

Based on the findings gathered by OMSHR researchers during mine visits, all of the approximately 30 BIP RAs with a constant air supply (all via borehole to the surface) in the U.S. have MSHA-approved stopping and door systems, and all are located outby the face areas. Each of these BIP RAs provides more than the 85 ft³ of space per occupant recommended in the NIOSH report to Congress on refuge alternatives [NIOSH 2007]. The costs of these existing BIP RAs range from \$50,000 to \$150,000, depending mainly on stopping and door system costs and

¹³ These criteria are specified in 30 CFR 7.505 and further clarified in the April 29, 2009, section of the document, "[Questions and Answers: MSHA's Refuge Alternatives Requirements](#)."

¹⁴ The Hubble Breathable Air Units (Models HBA75, HBA 100, and HBA 250) have already been approved by MSHA (Approval No. 07-LCA110001) for use in providing breathable air to an RA via a protected compressed air line.

borehole costs. Given these costs, it does not appear to be economically viable to provide these types of RAs within 1,000 feet of the working face of mines. However, if RAs can be located at greater distances from the face, as suggested here, OMSHR believes it may become more economically viable to introduce new BIP RA designs. Some work in this area is already being undertaken by private companies.

In the context of economic drivers, design needs for new BIP RAs that can be advanced with the face are (1) designs that employ stopping and door systems inexpensive enough to build and leave in place, or systems designed to be quickly and easily disassembled, moved, and reassembled; (2) novel BIP RA concepts that provide more space and breathable air per occupant and can be easily moved with the face; and (3) designs that provide a protected compressed air line that supplies breathable air to the RA occupants and can be advanced with the face.

Introduction

Three major coal mining disasters occurred in 2006. At the Sago Mine in Upshur County, West Virginia, 12 miners died after succumbing to the smoke and toxic gas while trapped underground for two days following an explosion. One miner was rescued in critical condition and recovered. The Sago miners had hung curtains recovered from the face area to build a crude barricade for themselves, but it was not enough to keep them in fresh air. One by one they lost consciousness while they were awaiting rescue [MSHA 2007a]. At the Aracoma Alma No. 1 Mine in Logan County, West Virginia, two miners died when a conveyor belt caught fire and they became lost and disoriented while trying to escape. Due to poorly constructed stoppings, the fire spread to the intake airway, impairing the visibility in the primary escapeway. The two miners were separated from the 10 other crew members in the dense smoke and died of carbon monoxide (CO) poisoning [MSHA 2007b]. Finally, at the Darby Mine No. 1 in Harlan County, Kentucky, a methane explosion occurred, resulting in five fatalities. The forces from the explosion resulted in fatal injuries to two miners, and while attempting to escape, three miners died due to carbon monoxide poisoning along with smoke and soot inhalation [MSHA 2007c]. In all of these tragedies, miners survived the initial disaster but were unable either to escape or successfully isolate themselves from the poisonous gases present in the mine environment resulting from the disaster.

In response to the above mine disasters, Congress passed the Mine Improvement and New Emergency Response Act (MINER Act) of 2006 (Public Law 109-236). The MINER Act calls for each underground coal mine operator to develop and adopt a written accident response plan to “provide for the maintenance of individuals trapped underground in the event that miners are not able to evacuate the mine.” The MINER Act also charges the National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) to “provide for the conduct of 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.” Significant research has been conducted for decades on refuge alternatives (RAs) as potential safe havens for miners while waiting for rescue crews to reach them in the event of an emergency; however, RAs have not always been fully embraced by either labor or industry, both of which believe that the primary focus understandably and correctly should be on methods and resources to help ensure successful escape rather than refuge. Refuge should always be a “last resort” decision.

The term refuge alternative can be applied to either mobile chambers that are advanced as the mining face advances or to built-in-place (BIP) RAs that are generally permanently located in the outby areas of a mine. Although the commercial availability of mobile RAs¹⁵ was almost nonexistent at the time of passage of the MINER Act, a task force from the State of West Virginia developed the initial RA requirements [WV 2007] from which a number of manufacturers began developing, marketing, and selling mobile RAs. These RAs were initially

¹⁵ Also referred to as portable RAs.

approved by the State of West Virginia and subsequently “grandfathered in” by the Mine Safety and Health Administration (MSHA) when federal regulations were developed, adopted, and took effect on March 2, 2009 [30 CFR 7 and 30 CFR 75].

NIOSH OMSHR completed its mandated research into RAs in 2007 and provided its findings in the form of a report to Congress [NIOSH 2007]. In sum, this report found that refuge alternatives were practical for use in most underground coal mines to facilitate escape and to serve as a refuge of last resort, provided that mine operators develop comprehensive escape and rescue plans incorporating refuge alternatives and training on their use. These findings applied to both portable RAs and BIP RAs, with the built-in-place refuge alternatives emerging as being able to provide a superior environment, in particular because they could supply a constant supply of breathable air via a borehole to surface or through a protected compressed air line. BIP RAs also offer the potential to provide miners with an improved psychological and physiological environment, both because the available air makes the space more comfortable and due to the larger amount of space provided per occupant. Boreholes or protected compressed air line air supply systems also provide a much higher probability of there being communications to the RA.

Despite these advantages, current BIP RA designs cannot be moved frequently—with movement of the RA location required to keep up with dynamic mining production—and as such it would be impractical to keep them within 1,000 feet of the nearest working face, as prescribed in 30 CFR 75.1506(c). Notwithstanding, OMSHR’s 2007 report to Congress on refuge alternatives concluded that, as compared to portable RAs,¹⁶ the strengths of built-in-place refuge alternatives “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 2007]. OMSHR also envisions that future BIP RA designs will be less expensive and easier to advance with the face.

Currently, there are approximately 30 BIP RAs in U.S. underground coal mines;¹⁷ however, all of these are located outby the face area and none are designed to be advanced with the working face. The usage of built-in-place refuge alternatives that can be advanced with the working face will only be practical if three issues can be addressed:

1. Locating BIP RAs further from the face;
2. Design and approval of RA stoppings;
3. Delivering a reliable supply of clean, breathable air to a BIP RA.

In this report, these three issues will be discussed in detail after a background summary of the potential advantages and disadvantages of BIP RAs.

¹⁶ As a follow-up to OMSHR’s 2007 report to Congress, OMSHR also undertook an extensive research program to investigate improvements that could be made to portable RAs. This research on portable RAs and specific recommendations about their use is reported in two NIOSH Report of Investigations, published in 2014: “[Investigation of Purging and Airlock Contamination of Mobile Refuge Alternatives](#),” NIOSH Publication No. 2014-116, and “[Investigation of Temperature Rise in Mobile Refuge Alternatives](#),” NIOSH Publication No. 2014-117.

¹⁷ This number is based on discussions between OMSHR researchers and members of industry.

In developing considered responses to these issues, OMSHR personnel visited a number of mines currently employing BIP RAs to obtain site-specific information on characteristics including their construction, location, air supply, and provisions and inventories. Additionally, OMSHR conducted an analysis of the number of BIP RAs currently in U.S. underground coal mines, the number of coal companies and mines employing them, how they are currently used, and their role as part of a mine's comprehensive escape and rescue plan. To give full context to the OMSHR findings that follow, this detailed summary of the current status of BIP RAs is presented in Appendix A.

Potential Advantages and Disadvantages of BIP RAs

Based on numerous discussions with industry and labor and observations by OMSHR personnel, properly constructed BIP RAs provided with a constant supply of breathable air hold a number of substantial advantages over mobile RAs. These potential advantages result from how the BIP RAs are constructed, the larger space available to miners, a constant clean air supply, and greater quantities of supplies and personal comfort features. The primary potential advantages of BIP RAs over mobile RAs are as follows:

1. A BIP RA with a continuous supply of fresh breathable air will likely minimize or eliminate the need for RA purging.¹⁸ It may be possible to create a positive pressure with clean breathable air in the shelter prior to entry, which should eliminate the need for purging. However, in many cases it will not be feasible to maintain the RA under positive pressure when not occupied. This would be the case when the air supply system for the BIP RA is not permanently located at the borehole but is only transported to the borehole in the event of a mine disaster. While the air supply to the BIP RA might be established before escaping miners arrive at the RA, this cannot be assured. Further, miners entering the RA prior to the ventilation system being established could bring contaminants into the RA. In these situations, additional SCSRs must be available in the RA to sustain miners until the RA can be adequately purged of contaminated air by the air supply to the RA. Importantly, to investigate these issues, NIOSH OMSHR is currently constructing a BIP RA in its Experimental Coal Mine in Pittsburgh to research issues related to BIP RA contamination with miner entry, the advantages of airlocks, airlock purging systems, and other means of keeping contaminants out of the RA—such as a membrane entry system or a series of overlapping plastic strips through which miners would enter. Research will also be completed on pressure relief valves and ways to ventilate the BIP RA during everyday operation to ensure against the buildup of methane or other harmful gases in the RA.
2. A BIP RA with a continuous supply of fresh breathable air does not require carbon dioxide (CO₂) scrubbing, which is necessary in an occupied mobile RA because there is minimal or no air exchange capability. When continuous breathable air is supplied

¹⁸ Current regulations in 30 CFR 7.508 require mobile refuge alternatives to purge the internal atmosphere from 400 parts per million (ppm) of carbon monoxide to 25 ppm.

at or above the rate specified in 30 CFR 7.506(c) (12.5 ft³/minute per occupant), the need for CO₂ scrubbing is generally eliminated. Additionally, eliminating the need for CO₂ scrubbing makes the operation of the RA less complex and provides more room in the RA. It will be necessary to ensure that the flow of air from the air inlet is distributed in a fairly uniform fashion throughout the RA volume.

3. In BIP RAs, the thermal issues that accompany the occupation of a mobile RA can be minimized. Mobile chambers rely on compressed O₂ to be provided at the rate of 1.32 ft³/hour per occupant to maintain adequate O₂ for miners (30 CFR 7.506(d)). Due to size restraints, mobile chambers cannot provide the alternative of 12.5 ft³/min per occupant of compressed air. The much greater flow rate of 750 ft³/hr of air per occupant rather than 1.32 ft³/hr of O₂ per occupant creates a much higher rate of air changeover in the RA, resulting in a more efficient dissipation of heat and humidity.
4. The communication system in a BIP RA can be designed to have a greater chance of surviving an explosion or fire. For example, a reliable communication system could be provided from the surface through a borehole or via a protected compressed air line to the BIP RA.
5. BIP RAs can be made larger and provide more available room for refuged miners than can be made available with mobile RAs. The fact that only the BIP stopping has to be advanced with the face rather than the entire BIP RA allows for this larger size benefit. The larger size also affords the opportunity to include in the shelter more food, water, and personal comforts. Finally, this larger size could minimize many of the psychological and ergonomic issues that could be associated with taking refuge in a smaller mobile RA.
6. There is a higher likelihood of the BIP RA surviving a secondary explosion by comparison to a portable RA employing a tent-type design. This assumes that the BIP RA is farther from the face and possible explosion source, and that the stoppings are built to withstand 15 pounds per square inch (psi) overpressure for 0.2 seconds prior to deployment, as specified in 30 CFR 7.505. Portable tent-type mobile RAs are especially problematic in relation to surviving secondary explosions as have occurred in many mine disasters.
7. BIP RAs with constant breathable air supply have fewer operating requirements than portable refuge alternatives; thus miners should be able to easily learn how to operate these shelters. There would likely be no purging and CO₂ scrubbing systems to learn to operate because they are not needed as outlined in points 1 and 2 above. Further, preparation and entry time into a BIP RA should be much shorter than with a mobile RA.
8. The 96-hr survival time as mandated in 30 CFR 7.506 for breathable air sustainability is no longer a serious limitation because there is likely to be an unending supply of fresh, breathable air and access to additional food and water. Thus, the “ticking clock” for refuged miners is eliminated. The race against time for rescuers is also diminished, which should allow rescue teams more time for decision making.

9. The number and order in which miners arrive at a BIP RA are much less important by comparison to a mobile RA, because purging is generally not needed and thus the availability of purge air is not as critical as it would be for mobile RA. Also, if a need arises for some miners to leave a BIP RA and others to stay, there is less of a problem of RA contamination because there is adequate breathable air available to keep the RA livable, even if some outside contaminated air enters the RA during the process of miner departure.

In addition to the above advantages, some potential disadvantages associated with the use of BIP RAs are also important to note, as follows:

1. The cost of current BIP RA designs, if they are required to be kept within 1,000 ft of the active mining face, would be prohibitive as compared to using mobile RAs. However, if the use of BIP RAs becomes more universally accepted, it is likely that much more economical designs will evolve.
2. Economically viable BIP RA stopping/door systems will need to be developed which are either inexpensive enough to be abandoned in place or which can be disassembled, moved, and reassembled at a new BIP RA location closer to the face. Several such designs are currently being investigated by manufacturers and universities.
3. Depending on the circumstances at the mine, providing a constant supply of air either via a borehole to the surface or via a protected compressed air line will require significant planning and may be costly. It would be desirable to maintain a constant low flow of breathable air to the BIP RA to prevent a buildup of methane and to keep the BIP RA under constant positive pressure fresh air. Research is needed in this area to develop guidelines for protected compressed air lines that will survive the 15-psi over 0.2-sec pressure requirement.
4. Locating BIP RAs further from the face than the currently required 1,000 ft or less distance could make it more difficult for injured miners, either on their own or with assistance, to travel to the RA.

Locating BIP RAs Further from the Face

MSHA's 30 CFR 75.1506(c) states that refuge alternatives shall be provided "within 1,000 feet from the nearest working face and from locations where mechanized mining equipment is being installed or removed."¹⁹ To meet this 1,000-feet requirement, all underground coal mines are currently employing mobile RAs (tent-type and rigid steel-type structures). Approximately 1,700 mobile units are currently located in underground coal mines in the United States.

¹⁹ The regulation also includes an exception for anthracite coal mines with no electrical face equipment, in which case RAs are provided if the nearest working face is greater than 2,000 feet from the surface. However, this exception does not relate to the specific findings reported here.

In order to facilitate the introduction of new BIP RA concepts into U. S. underground coal mines, OMSHR has investigated practical distances from the working face for the placement of RAs.²⁰ OMSHR's goal is to provide maximum safety for miners while allowing for a wider variety of RA designs. Applying more habitable RA designs could increase the likelihood of miners using an RA when escape is impossible as well as improve their psychological and physiological comfort.

To address the issue of locating BIP RAs further from the face, OMSHR researchers developed three different approaches to determine how far from the face area miners could travel given the 120 minutes of breathing time afforded them by currently available SCSRs.²¹ Each of these approaches assumed that new RA technologies with BIP designs will be employed under the following conditions: to provide a constant supply of air to the RA either via a protected compressed air line or a borehole to the surface; to provide additional RA space per occupant;²² to maintain the RA's internal atmosphere under positive pressure when not in use to ensure that the RA contains breathable air immediately upon entry and to keep contaminated air from entering when miners enter.

Employing the 120 minutes of breathing time and the application of new technologies that meet the conditions outlined above, OMSHR considered three approaches to locating BIP RAs further from the face, as described in the following subsections.

Approach 1: Based on SCSR-mandated Storage Cache Locations

This approach examined the MSHA-established criteria for distances between SCSR storage caches as a method of establishing acceptable distances from the face area for RA locations. MSHA's 30 CFR 75.1714-4(c)(2) defines these distances as follows: "Storage locations shall be spaced along each escapeway at 30-minute travel distances no greater than the distances determined by: (i) calculating the distance an average miner walks in 30 minutes by using the time necessary for each miner in a sample of typical miners to walk a typical length of each escapeway; or (ii) using the SCSR storage location spacing specified in [Table 1], except for escapeways with grades over 5 percent."

²⁰ This investigation was designed solely for determining the allowable distances that new and innovative RA concepts, such as BIP RAs, or other novel RA concepts that offer the advantages of BIP RAs, can be located in the active working sections of underground coal mines. This analysis was not intended for and should not be used to locate currently mobile RAs currently employed in underground coal mines.

²¹ Every miner working at the face has at least two SCSCRs available—an initial SCSCR and an additional one. The requirement for an additional SCSCR that provides protection for at least one hour for each person at a fixed underground work location can be found in 30 CFR 75.1714-4(a). With at least two available SCSCRs, each miner generally has a total of 120 minutes of reliable SCSCR life. Additionally, on some faces, miners actually have access to additional SCSCRs. Some longwall mines locate SCSCRs at the longwall tailgate and midway on the longwall face. At mines where 20-minute SCSCRs are employed, miners have two additional 60-minute units available to them prior to beginning travel down the escapeway.

²² Based on the 2007 report to Congress on refuge alternatives [NIOSH 2007], it is recommended that the original NIOSH minimal space recommendation parameter of 85 ft³ per person be used.

Table 1. Travel distances to SCSR storage locations (adapted from 30 CFR 75.1714-4)

Average entry height	Maximum distance between SCSR storage locations	Travel rate*
<40 in (crawl)	2,200 ft	73 fpm
>40–<50 in (duck walk)	3,300 ft	110 fpm
>50–<65 in (walk head bent)	4,400 ft	146 fpm
>65 in (walk erect)	5,700 ft	190 fpm

*Travel rates in fpm have been added to the original table.

MSHA has established the values in Table 1 as realistic travel distances to SCSCRs in emergency situations, and OMSHR concurs that these travel distances are realistic.²³ Because these distances are acceptable for SCSR locations, OMSHR posits that they should also be acceptable travel distances to BIP RAs if those RAs are spaced based on entry heights,²⁴ and if new BIP RA designs that are under positive fresh air pressure and require minimal deployment time prior to entry are used. Very little SCSR breathing time is required for RA deployment and entry with these new BIP RA designs.

Approach 2: Based on Worst-case SCSR Usage Times

To develop this approach, OMSHR performed a timeline study of an assumed worst-case scenario for miners involved in a disaster, beginning with the time they first donned their initial SCSR. For this analysis, researchers assumed the maximum realistic times for each step; that miners would be walking in a smoke-filled travelway without lifelines; and that they would be traveling in entries with different heights. The timeline included times for donning their initial SCSR, traveling to the assembly location on the face and deciding on a course of action, switching over to their second SCSR, traveling to the BIP RA, and preparing and entering the RA where there is a safe, breathable atmosphere. Maximum times were assigned to each of these actions, with the exception of the travel time to the RA. The travel time to the BIP RA was determined by calculating the breathable air time the miners had remaining from their SCSCRs after times for all other actions were subtracted out. This time was used to estimate the distance that BIP RAs could be placed from the face as a function of entry height.

The following is a summary of the assumed worst-case timeline scenario for miners located at the face area deciding to seek refuge in a new BIP RA design during a mine disaster.

²³ It is important to note that in most situations, travel in escapeways to both SCSR caches and RAs would be done with escapeway lifelines, which have been shown to significantly facilitate travel speeds.

²⁴ Put simply, greater entry heights allow for faster travel.

1. *SCSR Donning.* When miners at the face become aware of a disaster situation either via self-recognition or through a warning notification, in the worst-case scenario, they would immediately don their SCSRs, and the time clock for their 120 minutes of available breathable air would begin. In this worst-case scenario, it is assumed that it takes miners *5 minutes* from the time they start breathing into their SCSRs to complete the donning of the device. It can also be assumed that at this point they would, either alone or with their co-workers, start to escape (towards a BIP RA) or travel to an assembly point near the start of the escapeway.
2. *Face Area Travel, Assembly, and Decisionmaking.* Once miners leave their working location, they head directly to the escapeway or meet at an assembly location near the start of the escapeway to decide on a course of action or to communicate with the surface to learn about the circumstances. There are many considerations in calculating how much of a miner's available SCSR breathable air time is used in face area travel, assembly, and decisionmaking. Depending upon the situation, miners may don their SCSRs before they begin travel to the start of the escapeway or they may travel along the face to the escapeway without starting the use of their SCSRs. Based on which occurs, significant differences can result in travel distances and these distances could result in face travel times that exceed 15 minutes. However, in many mines with long face travel times such as longwall mines, there are generally additional SCSRs at locations along the face which would provide extra breathable air time.²⁵

If miners do meet at an assembly location, they would generally make a rapid decision as to their course of action and immediately proceed to travel the escapeway either to an RA or out of the mine. Taking into account that miners working on faces with long travel distances have additional SCSRs available to them and that miners in a disaster situation would assemble and make a decision about their course of action, it is reasonable to assume that miners will generally not use more than 15 minutes of their available 120 minutes of SCSR breathable air time in the course of face area traveling, assembly, and decisionmaking.

3. *SCSR Switchover.* Working with a breathable air time of 120 minutes assumes that miners will switch from their original SCSR to a new one. In a worst-case scenario, the maximum switchover time would be 5 minutes. In cases where a miner starting out with a 20-minute SCSR has to accomplish a switchover to a new 60-minute SCSR before traveling to a BIP RA, the extra 5 minutes required for the additional switchover would be more than made up for by the initial 20 minutes of breathable air from the 20-minute SCSR.
4. *RA Preparation and Entry.* When using current mobile RA designs, preparation and entry time can be considerable. According to 30 CFR 7.505, which defines the structural components of an RA, the process of deploying an RA once it is reached by

²⁵ Some longwall mines provide additional SCSRs at the tailgate and mid-face. In some mines, miners have 20-minute SCSRs, which they wear on their person, but have additional 60-minute units available to them at face locations, which results in the miners adding additional breathing time to their available 120 minutes. Additional SCSRs could be mandated on faces where travel times on the face to the escapeway exceed 15 minutes.

trained persons, without the use of tools, must be achieved within 10 minutes of the RA being reached. The removal of harmful gases for RAs is covered in 30 CFR 7.508, which states that the time between deployment of and entry into the RA cannot exceed 20 minutes. Summing these two amounts, currently available mobile RA units could require up to 30 minutes for preparation and entry.²⁶

Under this assumed worst-case scenario as outlined above, the sum of the non-escapeway travel activities is *30 minutes* as shown in Table 2. In this assumed worst-case scenario, if miners use 30 of their 120 minutes of SCSR time to carry out the activities described above, this leaves 90 minutes for travel time from the face to the RA. Note that this worst-case scenario assumes the longest time needed to accomplish each of the tasks. Appendix B presents a statistical analysis to establish a realistic range of times for miners to accomplish these four tasks.²⁷

Table 2. Summary of non-escapeway travel activities based on worst-case SCSR usage times

Nontravel activity	Worse-case SCSR usage times
SCSR donning	5 min
Face area travel, assembly, decisionmaking	15 min
SCSR switchover	5 min
RA preparation and entry	5 min
Total	30 min

In addition to this 30-minute requirement for non-escapeway travel activities, knowing the time available for escapeway travel is critical in determining how far from the working face a BIP RA can be placed. In the published literature, there is a great deal of discussion about how smoke-filled airways reduce travel speeds, but few concrete numbers are published. Some available information comes from Harteis et al. [2011], who conducted studies of travel times for miners in high coal (greater than 65-in entry height) through dense smoke and without lifelines.

²⁶ By contrast to this 30-minute time frame required for RA preparation and entry, the proposed new BIP RA designs can maintain the RA's inside atmosphere under positive pressure when not in use to ensure that the RA contains breathable air immediately upon entry. Further, these designs would likely only require that miners turn a compressed air valve to prepare the RA for use. Since no purging is needed, all miners can enter the RA immediately. For these BIP RAs, the maximum preparation and entry time should not exceed *5 minutes*. This should also result in simpler and more effective emergency training.

²⁷ Appendix B establishes that it is highly unlikely that a miner would require more than 26 minutes to accomplish the four tasks of SCSR donning; face travel time, assembly, and decisionmaking; SCSR changeover; and RA deployment and entry—with a mean time for miners of about *20 minutes*. This supports the argument that miners with two 60-minute SCNRs would have at least 90 minutes of travel time in the escapeway to the RA. Another consideration is that this worst-case scenario assumes that miners don their SCNRs before starting to leave their work location. Depending on the circumstances, they may not actually don their SCNRs until after they have traveled the face, assembled, and chosen a course of action, which would increase the SCNR available breathing time for traveling the escapeway to the RA.

The study of 53 miners found that the average miner could travel *77.9 feet per minute* (fpm) in heavy smoke. In MSHA's 30 CFR 75.1714-4(c)(2)(ii), it is assumed that an average miner can travel *5,700 feet in 30 minutes* in high coal in clean air. This is a travel rate of 190 fpm.

Taking these two pieces of information into account, one can calculate that travel in smoke-filled airways without lifelines results in miners traveling only about 40% as fast as in clean airways ($77.9 \text{ fpm}/190 \text{ fpm} = 41\%$). This would indicate that travel rates in heavy smoke are reduced by about 60%. This 60% reduction is further confirmed by the work done by Kriel et al. [1995], which stated that without lifelines travel rates in smoke-filled airways are reduced to about 40% of normal travel rates.

Emerging from the above discussion is Table 3, which calculates 90-minute travel distances in smoke-filled escapeways based on entry height. This table combines three pieces of information: the regulations in 30 CFR 75.1714-4(c)(2)(ii) for 30-minute travel distances in various entry heights; the fact that smoke-filled airways reduce travel times by about 60%; and the above-outlined worst-case scenario evidence that escaping miners should have 90 minutes of SCSR breathing time available to them for travel from the face to an RA.

**Table 3. Calculated 90-minute travel distances in smoke-filled
escapeways based on entry height**

Average entry height	90-minute travel distance with 60% reduction	90-minute travel distance with lifeline (assuming a 40% reduction)*
<40 in	2,640 ft	3,960 ft
>40-<50 in	3,960 ft	5,940 ft
>50-<65 in	5,280 ft	7,920 ft
>65 in	6,840 ft	10,260 ft

*This column assumes that with a lifeline in the escapeway, miners would be able to travel at 60% of their travel speed in clean air. This 60% travel rate with lifelines is conservative with respect to the findings of Kriel et al. [1995], who reported that miners wearing SCRs and traveling in very low visibility move at approximately 75% of normal travel speeds when aided by a lifeline.

Approach 3: Based on NIOSH and U.S. Bureau of Mines Established Travel Times and Escape Probabilities

Approach 3 uses travel times established by recent OMSHR research from actual miners traveling in airways filled with dense smoke in high coal (greater than 65-in entry height) without lifelines [Harteis et al. 2011], and U.S. Bureau of Mines (BOM) research from 1990 that considers the probability of making a successful mine escape in high coal with a single SCSR [BOM 1990].

Looking solely at the OMSHR research from the 2011 study, which measured travel times for 53 miners, the findings were that the average miner could travel 77.9 fpm, while the slowest miner traveled at 73.2 fpm. In the 90 minutes of available SCSR breathing time arrived at in Approach 2, the average travel distance would be over 7,000 feet, while the slowest travel distance would be over 6,500 feet. These two travel distances fall just above and below the 6,840

travel distance established in Approach 2, Table 3, for high entry heights in smoke-filled airways. This evidence further justifies the argument that RAs can be located further from the face based on entry height.²⁸

The 1990 U.S. Bureau of Mines research showed that miners who were proficient in donning and using an SCSR had a high probability of escaping up to 2,000 meters (approximately 6,000 feet) employing a single SCSR, walking bent over (assuming a 50- to 65-in entry height), and traveling without lifelines. This 6,000-feet travel distance is significantly higher than the 4,400-feet travel distance suggested in Approach 1, and is somewhat higher than the 5,280-feet travel distance arrived at in Approach 2. These findings from the U.S. Bureau of Mines study clearly support the argument for locating RAs at greater distances from the working face.

Discussion of Three Approaches to Locating BIP RAs Further from the Face

Taking into account the findings from the three approaches discussed above, conservative maximum distances from the face to the RA for the various entry heights can be established (Table 4). Table 4 assumes that all other factors from approach 2 remain the same—i.e., SCSR donning and switchover times; time to travel the face, assemble, and make a decision; and time to prepare and enter the RA. Therefore, Table 4 is grounded in the assumption that miners have 90 minutes of available travel time in the escapeway (based on available SCSR breathing time) to reach the RA.

Table 4. Maximum distances of refuge alternatives from the face

Average entry height	Maximum distance of RA from the face	Maximum distance between SCSR storage locations
<40 in	2,000 ft	2,200 ft
>40–<50 in	3,000 ft	3,300 ft
>50–<65 in	4,000 ft	4,400 ft
>65 in	5,000 ft	5,700 ft

The travel distances to RA locations based on entry height in Table 4 closely correspond to the distances between SCSR cache locations in 30 CFR 75.1714-4(c)(2)(ii)—therefore, it would be practical to use the same travel distances for both. Using the same travel distances to both SCSR caches and RAs, as well as locating SCSR caches in the same place where possible, would be logical given the following facts:

1. Additional SCSCRs would be located at the RA.
2. Miners would have unused SCSCRs at the RA should they have issues with RA deployment.

²⁸ As noted in an earlier discussion, it is also important to point out that a person traveling with a lifeline to the RA would normally travel at a faster rate than without a lifeline.

3. Miners would have a specific and clearly defined decision point—“Grab another fresh SCSR and go on” or “Deploy RA.”²⁹
4. The compliance distance requirement would be a single number for both SCRs and RAs.
5. Firebosses would be able to examine both the RA and SCRs at the same location.
6. Storage of the SCRs could potentially be incorporated inside the BIP RA, providing them with additional protection from explosive forces.

Expanding on the argument of defining travel distances to RA locations based on entry height and using the same travel distances to both SCSR caches and RAs, Figures 1 and 2 offer perspective on the number of underground coal mines and underground coal miners that would be positively affected by this approach. Figure 2 shows that of the 45,099 coal mine employees in underground mines, almost 65% (29,191) work in mines with seam heights greater than 65 in, and almost 84% (37,721) work in mines with seam heights greater than 50 in.³⁰ Therefore—comparing the data from Table 4 and Figure 2—based on seam height, the vast majority of underground coal miners would be able to travel at least 4,000 feet to RAs given the available SCSR breathing time.

Considering the most conservative maximum distance of the RA from the face as defined in Table 4, OMSHR believes that mines could locate built-in-place refuge alternatives at distances from the working face according to the guidance provided in Table 4. This is further discussed in the report section, “Considerations for Facilitating the Use of BIP RAs.”

Finally, it should be noted that while BIP RAs may not be practical for all underground coal mine applications, OMSHR believes that they should play an important role in the available suite of RA options. For example, a consideration would be to locate a BIP RA with a borehole to the surface or a protected compressed air line at the mouth of each section. The BIP RA would be built in a crosscut or blind cutout with seals at the ends set back to better survive possible explosion forces. Depending on the distance to the face, the RA could be the first one that miners travel to from the face or could be an additional outby RA. Also, the BIP RA being at the mouth of the section could provide miners a good location at which to decide on a further course of action with respect to escape or refuge.

²⁹ Having a clear decision point can be an important factor in an emergency circumstance. In this case, because miners will have already traveled some distance and can better assess their abilities and limitations, they may be in a better position to make an informed decision about the next steps to either self-escape or take refuge.

³⁰ Figures 1 and 2 show MSHA data based on coal mine seam heights. The entry heights in coal mines, especially lower coal mines, are always equal to or greater than the actual coal seam height. Therefore, the numbers reporting that almost 65% of underground coal miners work in mines with seam heights greater than 65 in and almost 84% work in mines with seam heights greater than 50 in are conservative.

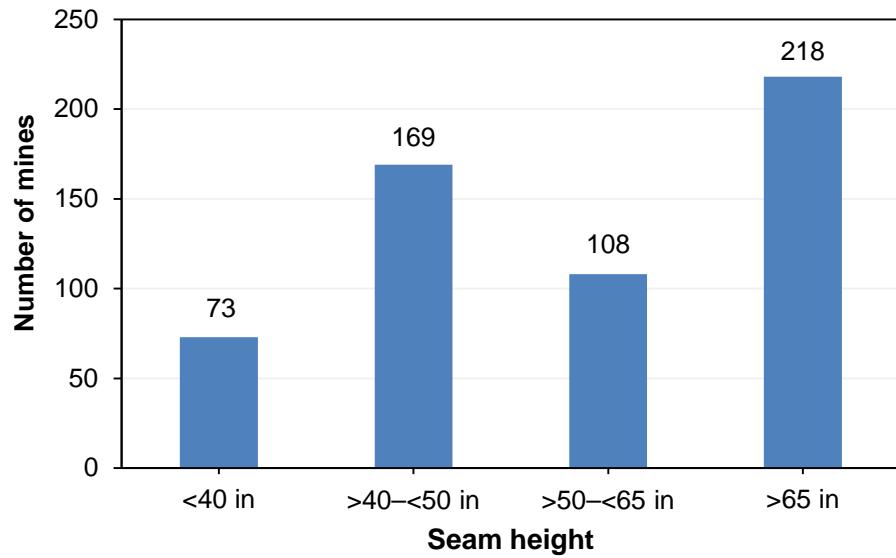


Figure 1. Number of active underground coal mines by seam height, 2012. (data source: MSHA 2013)

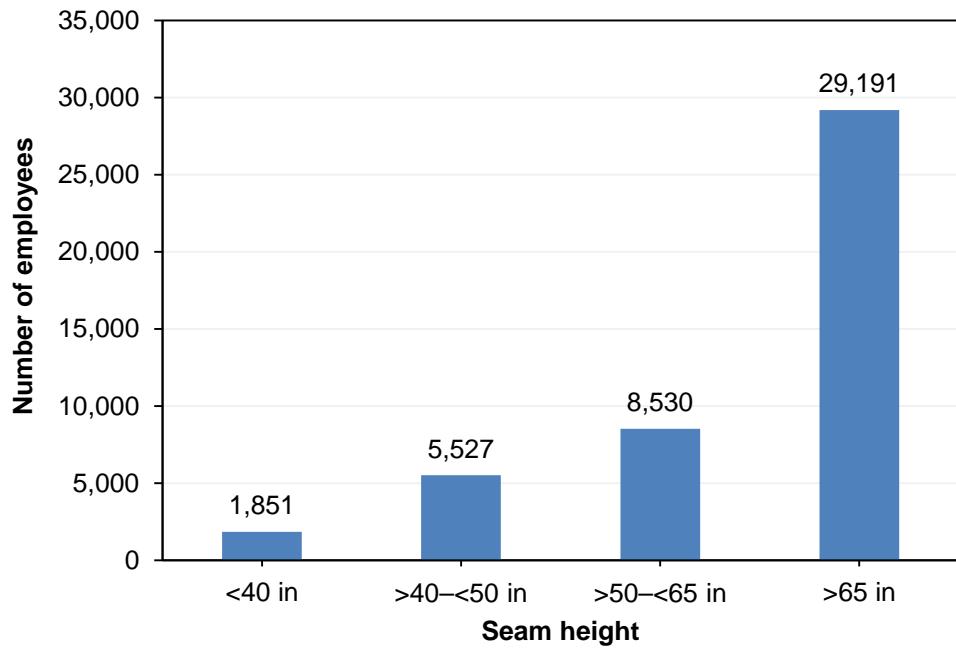


Figure 2. Number of coal mine employees working at underground locations by seam height, 2012, excluding office employees. (data source: MSHA 2013)

Discussion of How Locating BIP RAs Further from the Face Impacts RA Moves

Using the maximum distances for locating BIP RAs from the face presented in Table 4, it is possible to estimate the frequency of BIP RA moves as compared to currently employed mobile RAs. The most rapid face advance would generally occur with a three-entry continuous miner development entry, where advance rates would range from about 1,000 to 1,300 feet per month. Currently employed mobile RAs are moved about every 500 feet of advance in order to comply with the regulation to keep them within 1,000 feet of the working face. Therefore, they would need to be advanced two to three times per month. In high coal, if a BIP RA could be located up to 5,000 feet from the working face as proposed in Table 4, its construction could be started about 500 feet from the working face. Assuming a very conservative construction time of two weeks and an advance rate of 500 feet during that time, the BIP RA would be located about 1,000 feet from the working face when it is ready for use. The working face could then be advanced another 4,000 feet before a new BIP RA nearer to the face would be needed. Therefore, a new BIP RA—with construction completed within 1,000 feet of the original working face—would not be needed for another 3 to 4 months depending on the face advance rate.

Design and Approval of RA Stoppings

Structural Design Considerations for RA Stoppings

Refuge alternative stoppings³¹ are the essential life-critical component of a BIP RA—put simply, if the stoppings fail, then lives are at risk. To understand the significant structural design considerations of RA stoppings, a literature review outlining explosion pressure considerations provides a useful beginning. Regarding the magnitude of explosion pressure that an RA stopping that is constructed in a crosscut and out of line with the direction of explosion propagation could be subjected to, there are two important factors to consider: (1) explosion pressure estimates from past mine disasters, and (2) the durability of the human body, as measured from experimental studies.

Explosion pressures from past mine disasters are documented in the literature in a recent report by Foster-Miller [2007], which summarized the characteristics of 12 underground coal mine disasters that occurred in active mining (non-sealed) areas between 1970 and 2006. These explosion pressures are estimates based on observed damage by accident investigators and are not actual measurements of explosion pressures. Post-explosion overpressure estimates are

³¹ An RA stopping is a hand-built barrier designed to create and isolate a BIP RA in either a crosscut or a cutout of an underground coal mine. It must include a built-in door at the front end of the RA constructed in a crosscut or a cutout to allow entry into the RA. It can also be a uniform stopping with no door as could be used at the back end of a BIP RA constructed in a crosscut. Some BIP RAs constructed in crosscuts have doors in the RA stoppings at both ends of the RA. Either the uniform stopping or the stopping/door combination must meet the MSHA criteria for RA stoppings of surviving a 15-psi explosion with a 0.1-second rise time and a 0.1-second fall time. These criteria are specified in 30 CFR 7.505 and further clarified in the April 29, 2009, section of the document, "[Questions and Answers: MSHA's Refuge Alternatives Requirements](#)".

primarily from the study of damage to stoppings that were located in crosscuts perpendicular to direction of the explosion propagation. Of those 12 disasters, 9 were explosions and 3 were fires. Two of the explosions occurred within sealed areas that affected the active area of the mine. The estimated explosion overpressure within 1,000 feet of the source was 15 to 20 psi in one case, 2 to 5 psi in two cases, and low (< 2 psi) in the remaining six cases. The estimated explosion pressure within 2,000 feet of the source was 2 to 5 psi in three cases, and low (< 2 psi) in six cases.

Three recent coal mine disasters not considered in the above report are the Willow Creek Mine explosions [MSHA 2000], the Jim Walter Resources No. 5 Mine explosions [MSHA 2001], and the Upper Big Branch Mine explosion [MSHA 2010]. Four explosions occurred at the Willow Creek Mine with pressures of about 5 psi near the origin at the face, decreasing to about 2 psi some 500 feet away where ventilation control devices were destroyed. Four injured survivors remained in the mine after the first explosion, and they were rescued within four hours before the subsequent explosions occurred [MSHA 2000].

The first explosion at Jim Walter Resources No. 5 Mine originated about 400 ft from a development face, and its pressure was estimated at about 4 psi near the source. The second explosion originated about 1,000 feet from the face and had an estimated peak pressure of about 12 psi near the source [MSHA 2001].

The explosion at the Upper Big Branch Mine developed overpressures³² ranging from 6 to 25 psi depending on location and local conditions in the mine. Near the source of the explosion in the tailgate near the longwall panel, the explosion pressure is believed to have been about 14 psi. Along the longwall face, the explosion pressure is believed to have ranged from 7 to 14 psi. Elsewhere in the mine, explosion pressures may have reached 20 to 25 psi. In the Headgate 25 area, calculations indicated pressures on the order of 52 to 65 psi, and these pressures could have resulted in reflected overpressures up to 105 psi [MSHA 2010].

To detail the effects of blast pressures, Table 5—based on Department of Defense data from Glasstone and Dolan [1977] and Sartori [1983]—summarizes the effects of progressively increased blast pressures on various structures and the human body. These data originate from weapons tests and blast studies and provide some guidance on the possible effects of mine explosions on miners.

The human body can survive relatively high blast overpressure without experiencing barotrauma, which is injury caused by changing air pressure. A 5-psi blast overpressure will rupture eardrums in about 1% of subjects, and a 45-psi overpressure will cause eardrum rupture in about 99% of all subjects. The threshold for lung damage occurs at about 15 psi blast overpressure. A 35-psi to 45-psi overpressure may cause 1% fatalities, and a 55-psi to 65-psi overpressure may cause 99% fatalities [Glasstone and Dolan 1977; TM 5-1300 1990; UFC 3-340-02 2008].

³² The pressures discussed in this report are static overpressures above atmospheric pressure and acting in all directions. A dynamic overpressure in the direction of the explosion wave propagation is associated with the static overpressure, and it can also have significant magnitude. Reflected blast waves at normal incidence can be several times the incident explosion wave overpressure, which is the combined static and dynamic overpressure.

Table 5 also shows the maximum wind speed associated with a given overpressure. In mine explosions, as in war-related explosions, it is the blast wind resulting from the blast overpressure that leads to injuries and fatalities. The human body may be thrown violently into objects and receive blunt force trauma; conversely, large objects may be thrown into persons resulting in crush injuries, or projectiles launched by the blast wind may penetrate the body. The susceptibility of personnel to blast effects depends on their proximity to nearby objects and possible projectiles. Miners standing in the open and away from projectiles may survive higher blast overpressures than those standing near a solid wall or object. Personnel sitting within the confines of mining machines may receive some protection from both blunt force trauma and projectiles. While it is impossible to determine the exact correlation between blast wave overpressure and fatality rate for personnel in an active underground mine, the data in Table 5 provide useful guidance.

Table 5. Effect of various long duration blast overpressures and the associated maximum wind speeds on various structures and the human body (based on data from Glasstone and Dolan [1977] and Sartori [1983])

Peak overpressure	Maximum wind speed	Effect on structures	Effect on the human body
1 psi	38 mph	Window glass shatters	Light injuries from fragments occur
2 psi	70 mph	Moderate damage to houses occurs (windows and doors blown out and severe damage to roofs)	People are injured by flying glass and debris
3 psi	102 mph	Residential structures collapse	Serious injuries are common, fatalities may occur
5 psi	163 mph	Most buildings collapse	Injuries are universal, fatalities are widespread
10 psi	294 mph	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
20 psi	502 mph	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

The above review of recent explosion disasters shows that maximum explosion pressures in the active parts of coal mines generally do not appear to exceed 15 to 20 psi.³³ This same estimated pressure range of 15 to 20 psi was reported within 1,000 feet of the explosion origin at the Darby Mine explosion [MSHA 2006]. The recent explosion at Upper Big Branch produced estimated explosion pressures up to 25 psi, and possibly higher in some locations. According to Table 1, miners are unlikely to survive an explosion with pressure greater than 10 psi and therefore would be unable to reach a nearby RA unassisted. Consideration of recent explosions such as Willow Creek Mine in 2000, the Jim Walter Resources No. 5 Mine in 2001, and others mentioned in the Foster-Miller report [1983], suggests that secondary explosions are a very real concern. Therefore, if miners are inside an RA, it should protect them from a secondary explosion that could develop. The pressures developed by secondary explosions are not well understood, but they too have not been observed to exceed 15 to 20 psi.

Based on the above literature review and known structural design considerations for RA stoppings, the following needs emerge for designing stoppings that can withstand the expected explosion pressures:

1. A recommended design pressure-time curve for an RA stopping.
2. Criteria for designing an RA stopping and approval of RA stopping designs.
3. Suggested guidelines for an RA stopping design application.
4. An example design for RA stoppings meeting the proposed design criteria.

Recommended Design Pressure-Time Curve for an RA Stopping

The essential structural design criteria for an RA stopping are the pressure-time curve and elasticity of design applied to (1) the RA stopping structure itself; (2) the RA stopping foundation or anchorage; and (3) the entrance door. All components must meet the design pressure-time curve requirements and remain within the linear elastic range of their materials. The RA stopping foundation must have adequate preparation to develop favorable support conditions.

Based on the considerations detailed in the previous section, a 15-psi pressure-time curve with a 0.1-second rise time, 0.1-second fall time, and 0.2-second duration is suggested for the design of RA stoppings.³⁴ Because of the slow rise time, this pressure-time curve is expected to have a dynamic load factor (DLF) of 1.0 and therefore an equivalent static design pressure of 15 psi for the anticipated BIP-RA designs. Figure 3 shows the recommended design pressure-time curve along with the pressure-time history from an experimental gas explosion conducted at the

³³ It should be stressed that, in relation to worst-case explosion pressures, if an initial small mine explosion disrupts or destroys much of the ventilation system, it is conceivable that large volumes of flammable methane-air mixtures could accumulate. If these mixtures were ignited, it is possible that explosion pressures greater than 120 psi could develop.

³⁴ It should be noted that this recommended pressure-time curve is less conservative than the curve developed by Foster-Miller [1975; 1983] in its reports. These prior studies recommended a 20-psi instantaneous rise time curve with an equivalent static pressure of 40 psi.

former NIOSH Lake Lynn Experimental Mine (LLEM). This pressure-time history was measured near the explosion source. This recommended pressure-time design curve is identical to an earlier one presented by NIOSH OMSHR in its report to Congress on refuge alternatives [NIOSH 2007].

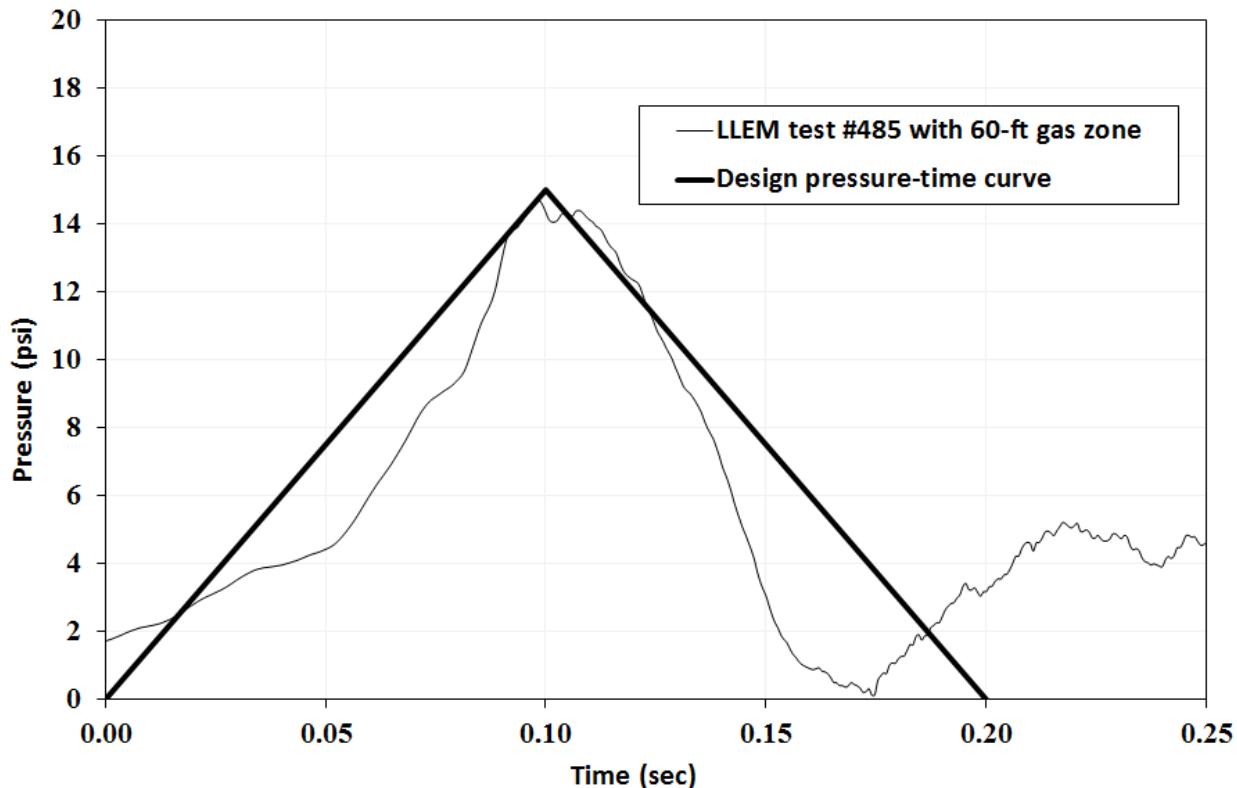


Figure 3. Recommended design pressure-time curve for refuge alternative stoppings.

The recommended pressure-time curve³⁵ with slow rise time is characteristic of an explosion pressure-time history near the explosion source. However, as an explosion wave propagates from its source, two phenomena occur that affect the character of the wave: first, a shock wave with near instantaneous rise time tends to form; second, the magnitude of the pressure wave tends to decrease.

Shock wave development occurs because the speed of a pressure wave depends in part on gas density. At the leading edge of an explosion wave near its source, gas density is less and wave speed is slower than at the point of peak pressure or beyond in the trailing part of the explosion wave where the gas density is greater. Therefore, the point of peak pressure in the explosion

³⁵ The design pressure-time curve is a static overpressure curve above atmospheric pressure. Because reflected blast wave overpressure can be several times greater than the static overpressure, BIP-RAs must be located out of the direct path of a likely explosion wave such as a crosscut or a similar side passageway to minimize the effect from reflected explosion waves.

wave gains on the leading edge of the wave until a shock wave forms with near instantaneous rise time. This process of explosion wave steepening (or “shocking up”) is well understood in the gas dynamics and blast wave effects community [Gamezo et al. 2008; Sapko et al. 2000].

Figure 4 shows the recommended design pressure-time curve along with the pressure-time histories recorded at 10, 526, and 782 ft from the origin for LLEM gas explosion # 485. As the pressure-time curve from the gas combustion propagates from its source, shock waves with near instantaneous rise times begin to form while the peak pressure tends to decrease.

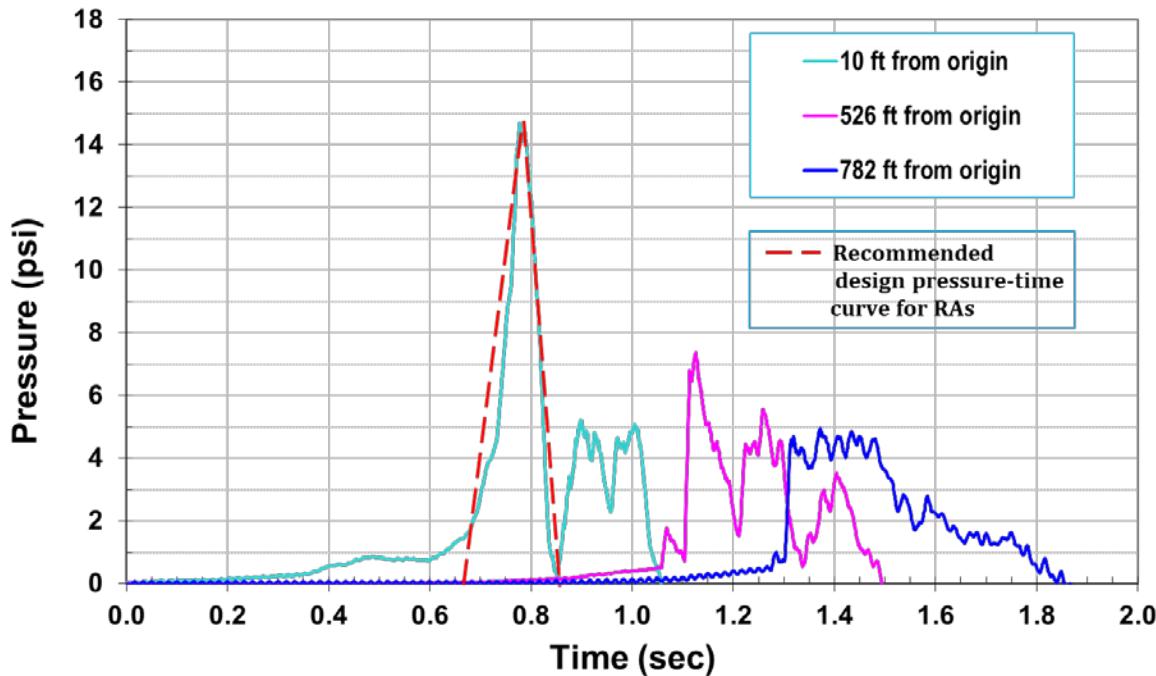


Figure 4. Pressure-time curve showing pressure decay with distance and shock wave development from LLEM test #485 with 60-ft gas zone.

The recommended 15-psi pressure-time curve with a slow rise time, a dynamic load factor of 1.0, and an equivalent static pressure of 15 psi is representative of the expected pressure-time history close to an explosion source. A 7.5-psi maximum pressure at 526 feet with an assumed instantaneous rise time, a dynamic load factor of 2.0, and an equivalent static pressure of 15 psi is dynamically identical to the recommended curve, and is representative of the pressure-time history further from an explosion.

Criteria for Designing an RA Stopping and Approval of RA Stopping Designs

Given the analysis provided in the previous subsection, the issues that emerge in relation to design and approval of RA stoppers are structural design criteria, foundation design, location, leakage, and quality control.

Structural Design Criteria

1. *Pressure-time curve.* The required pressure time-curve has a 15-psi constant pressure, 0.1-second rise time, 0.1-second fall time, and 0.2-second duration. This pressure-time curve is expected to have a DLF of 1.0 for most practical BIP RAs because of its slow rise time. The equivalent static design pressure is therefore 15 psi.
2. *Elasticity of design.* The RA stopping structure must resist the equivalent static design pressure of 15 psi and remain within the linear elastic range of its component materials. The RA stopping structure must return to its original shape with no permanent deflection when subjected to the 15-psi equivalent static design pressure. This elasticity of design requirement is identical to requirements used for the design and approval of coal mine seals under the 2008 regulations in 30 CFR 75.335.
3. *Entrance door.* The entrance door through the RA stopping must have a least dimension of 2 feet and meet the same design pressure-time curve requirements.
4. *Support conditions.* The support conditions for the RA stopping structure must match the mine conditions. The expected support conditions are simple supports with zero moment on all four edges in most practical mining conditions. Fixed support conditions with moment are possible to develop if the foundation is prepared. The design should consider the stopping using simple supports unless the designer provides detailed calculations and drawings to demonstrate that the fixed condition is a realistic assumption.

Foundation Design

As to foundation design considerations, the RA stopping must be adequately anchored to the surrounding strata. The relevant criteria to consider are:

1. *Adequate anchorage capacity.* The RA stopping anchorage system must resist the shear load around the perimeter of the RA stopping induced by the design pressure-time curve.
2. *Elasticity of design.* The RA stopping anchorage system must resist the induced shear load and remain within the linear elastic range of its component materials.
3. *Support preparation.* The RA stopping foundation must have sufficient preparation to justify the support conditions assumed for the RA stopping structure.

Location

1. The RA stopping must be located in a crosscut or a similar side passageway to minimize the magnitude of reflected explosion wave overpressure acting on the structure.

Leakage

Given the possibility of leakage, the RA stopping structure and the surrounding strata must enable maintenance of a life-supporting atmosphere within the facility. The leakage criteria to consider are:

1. *Pressure.* There must be an ability to maintain a measurable positive pressure inside the facility of at least 0.1-in water gauge.

2. *Sealant.* The RA stopping structure and the nearby roof and rib strata must be coated with an approved sealant for fire resistance and leakage control.
3. *Repair.* Fresh containers of an approved sealant must be kept inside the facility for emergency repair of any leaks.

Quality Control

In relation to quality control, the design of an RA stopping structure and its foundation must be considered a life-critical facility. Therefore, design, construction, and subsequent maintenance must follow the highest quality control practices. The practices are similar to those used for coal mine seals since adoption of the 2008 regulations prescribed in 30 CFR 75.335. Quality control criteria to consider are:

1. *Certification by a licensed professional engineer.* A design submitted to MSHA for approval must be certified by a licensed professional engineer.
2. *Construction of the RA stopping and its foundation.* Mine management must certify that the RA stopping and its foundation were built according to the design specifications of a licensed professional engineer and as approved by MSHA.
3. *Maintenance of the RA stopping and its foundation.* Mine management must periodically inspect the RA stopping and its foundation to verify that the facility will perform as expected.

Guidelines for Effective RA Stopping Design

Design engineers must submit RA stopping designs for approval under the requirements of MSHA's Refuge Alternatives for Underground Coal Mines [Federal Register 2008]. To assist them with that task, the list below for an RA stopping design application is adapted from guidelines compiled for coal mine seal design applications [MSHA 2008].³⁶ Using the MSHA guidelines as a model, an RA stopping design application should include the following elements and specifications.

1. Engineering drawings
 - a. Provide front, side, and plan views plus any details as needed at a reasonable scale for clarity.
 - b. Specify the maximum and minimum entry size for which the RA stopping design applies.
 - c. Provide a table giving entry height and width plus relevant structure details of the RA stopping design that will change with these dimensions such as thickness, amount and size of reinforcement, and anchorage requirements.

³⁶ These MSHA guidelines call for engineering designs that address the following categories: gas sampling pipes, water drainage systems, methods to reduce air leakage, pressure-time curve, fire resistance characteristics, flame spread index, entry size, engineering design and analysis, elasticity of design, material properties, construction specifications, quality control, design references, and other information.

2. Material properties descriptions
 - a. Provide engineering properties of the materials used in the RA stopping design such as compressive strength, yield strength, modulus values, and fire endurance properties of the materials. Fire endurance properties should at least be consistent with criteria codified in 30 CFR 75.333 Subpart D for the design of mine ventilation controls.
 - b. Provide laboratory test results for other materials including average and standard deviation.
 - c. Provide engineering properties of the roof and floor rock of the RA stopping site that justify the support conditions assumed in the analysis.
3. Engineering calculations
 - a. Provide a complete set of calculations for the RA stopping structure and its foundation. The calculations must demonstrate that the design is linear elastic and satisfies the elasticity of design criterion.
 - b. Explain all assumptions and justify the support conditions used in the structural design.
 - c. Cite references for all analysis methods used.
4. Cite applicable design codes followed such as the American Concrete Institute [ACI 318-08 2008], the American Institute of Steel Construction—Steel Construction Manual [AISC 2005], or the Unified Facilities Code [UFC 3-340-02 2008].
5. Leakage control measures
 - a. Demonstrate ability to maintain a measurable positive pressure inside the facility of at least 0.1-in water gauge.
 - b. Describe methods to control leakage out of the facility.
 - c. Specify sealants to be used.
6. Door specifications
 - a. Provide a complete set of calculations for the entrance door showing that it can meet the pressure-time curve requirements and remain linear elastic.
 - b. Alternatively, provide specifications for a commercially available door that meets ASTM Standard F2247-11 [2011] “Standard Test Method for Metal Doors Used in Blast Resistant Applications (Equivalent Static Load Method).”
7. Fire resistance and flame spread index
 - a. Specify any fire retardants used and their characteristics to meet fire endurance criteria of 30 CFR 75.333.
8. Construction specifications
 - a. Provide information on the site location and necessary site preparation for the RA stopping. Describe extra ground support to install in the area. Describe remediation procedures for any adverse ground conditions that could develop in the area.
 - b. Provide information on the RA stopping foundation such as rock bolt anchors, the depth of hitch, or the angle iron size and its anchorage.

- c. Provide information on internal reinforcement such as the diameter and spacing of horizontal and vertical reinforcement and stirrups.
 - d. Provide information on formwork if used.
 - e. Provide information on methods and equipment used to batch, mix, transport, convey, and place RA stopping materials.
 - f. Provide information on the fire resistance properties of the construction materials.
9. Quality control plan
- a. Describe how and by whom the site will be investigated prior to installation of an approved RA stopping.
 - b. Describe how and by whom the RA stopping foundation will be certified when it is built.
 - c. Describe how and by whom the RA stopping structure will be certified when it is built.
 - d. Specify how often the RA stopping should be inspected and maintained during its lifetime.
10. Summary of installation procedures
- a. Provide complete, standalone, step-by-step installation procedures for the RA stopping and its foundation.
 - b. Include drawings and other valuable information to help the installer construct the RA stopping according to the engineer's intent.

Example Design for an Effective RA Stopping

Based on the above guidelines, OMSHR developed an example design for an effective RA stopping that consists of a conventional rebar-reinforced concrete wall 12 in thick. The complete design calculation for this example is included as Appendix C.³⁷ The example RA stopping design is presented to illustrate the application of the proposed design guidelines in preparing a design submittal to MSHA District Managers for approval. Significantly different RA stopping/door systems for BIP RAs have already been approved by MSHA for use, and OMSHR believes that if BIP RAs become more commonly used in U.S. coal mines, then many more acceptable and economically viable stopping/door designs that meet the 15 psi static pressure criteria will be developed.

The design example presented here was developed by adapting recognized protective structure design principles in the Unified Facilities Criteria (UFC): Structures to Resist the Effects of Accidental Explosions [UFC 3-340-02 2008]. The design method follows three general steps: (1) design inputs where the design load and material properties are specified, (2) foundation design where an anchorage system for the stopping structure is designed, and (3)

³⁷ Additionally, Foster-Miller [1975] also presents some examples of RA stopping designs that would meet the proposed design criteria.

design of the stopping structure itself. In all cases, the design pressure-time curve is 15 psi with a 0.1-second rise time, 0.1-second fall time, and 0.2-second duration. The equivalent static design pressure is 15 psi, and the design remains in the linear elastic range under the design pressure. The entry dimensions for this example design are 20 ft wide by 8 ft high. The design example below follows conservative protective design principles used by the military. This example is not to limit alternative designs that may be more aggressive and economical, but only to convey the need to meet established performance standards and follow protective structure design principles.

This rebar-reinforced concrete wall design is 12 in thick. Steel reinforcement within the RA stopping wall consists of 5/8-in-diam (#5 bar) vertical and horizontal reinforcement bars on 12-in centers on both sides of the RA stopping wall. Shear reinforcement consists of 1/2-in-diam (#4 bar) stirrups at each intersection of vertical and horizontal reinforcement bars. The RA stopping wall is anchored to the surrounding rock with 5/8-in-diam (#5 bar) rock bolt anchors spaced every 1.5 ft around the RA stopping perimeter. The 5-ft-long anchors have 3 ft grouted into surrounding rock and 2 ft embedded in the RA stopping structure. The total number of rock bolt anchors required is 40. The yield strength for reinforcement steel is 60,000 psi. The compressive strength of the concrete is 3,000 psi. Figure 5 shows this rebar-reinforced concrete RA stopping design.

**Rock bolt anchors—5/8-in-diam, 1.5-ft centers,
3 ft into rock, 2 ft into wall**

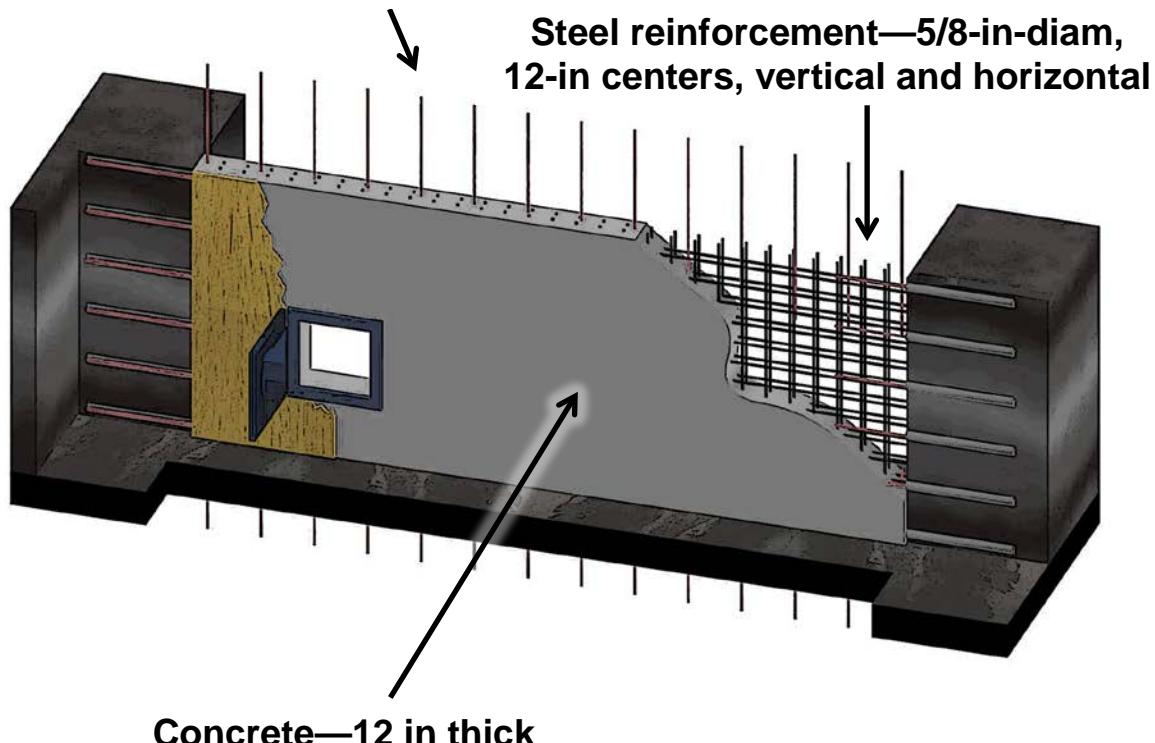


Figure 5. Design example for a 15-psi RA stopping using conventional rebar-reinforced concrete.

Delivering a Reliable Supply of Clean, Breathable Air to a BIP RA

Most of the advantages of a BIP RA disappear if the RA is not guaranteed a constant and highly reliable supply of clean, breathable air. A borehole from the surface to the BIP RA is the most highly desirable approach. Several breathable air supply units to be used in conjunction with a borehole directly into a BIP RA have been approved by MSHA. These consist of either air supply units permanently mounted at the borehole or of trailer-mounted units which can be brought from some central storage location to the mouth of the borehole in an hour or less in the event of a mine disaster. Both fan/blower type systems and compressed air type systems have been approved and are currently in use to provide air to outby BIP RAs. The compressed air units have dryers and oil and water separators to ensure the delivery of clean breathable air to the miners.

For some mining operations it will not be practical to employ boreholes to deliver air to BIP RAs due to drilling costs, difficult terrain, and surface rights issues. An alternative approach may be to provide air to the BIP RA via a protected compressed air line carrying clean, breathable air.

Some work has already been done to address this issue. MSHA has already granted approval to a compressed air supply system, including a protected compressed air line for use with BIP RAs.³⁸ This approval opens the door for providing a continuous supply of clean, breathable air to a BIP RA.

In order to guarantee a supply of clean, breathable air to BIP RAs in an emergency situation, a number of issues need to be considered with respect to the reliability and availability of the surface compressor station and the protected compressed air line. Considerations for the surface compressor station are as follows:

1. Accessibility to surface location.
2. Protection from weather and elements.
3. Whether the compressor station should be treated like a main mine fan—i.e., if the compressor is down more than 15 minutes, what steps would be taken.
4. The requirements for a backup compressor and power supply.

³⁸ The Hubble Breathable Air Units (Models HBA75, HBA 100, and HBA 250) have been approved by MSHA (Approval No. 07- LCA110001) for use in providing breathable air to an RA via a protected compressed air line. The main components of the Hubble Breathable Air (HBA) unit are the surface air supply unit and a compressed air pipeline system which carries air underground to a BIP RA. These components of the system have MSHA approval and are intended to be employed in conjunction with an approved BIP RA. The HBA unit consists of a rotary screw air compressor, a continuous flow breathing air purifier system, and a diesel-powered generator unit to provide backup power. There are three approved versions of the surface HBA unit (HBA 75, HBA 100, and HBA 250) which, respectively, supply 274 cfm (12.5 cfm per person = 21 people), 336 cfm (12.5 cfm per person = 26 people), and 977 cfm (12.5 cfm per person = 78 people). A continuous supply of breathable air can be delivered to the RA through a 2-in pipeline which is either buried in soft floor along the rib or anchored to hard floor along the rib and covered with waste material. A regulator valve, manifold valve system, flow measurement system, and a silencer are all located at the BIP RA.

5. Sizing requirements—i.e., the amount of air that is needed to be supplied to the RA, whether a single compressor system would provide air to one or more RAs.
6. Maintaining discharge air quality in terms of oil, moisture, filtration, etc.

Considerations for the protected compressed air line³⁹ are as follows:

1. Type of material to be used—*Carbon steel pipe*: ASTM A106, A53, ASTM A179, ASTM A192, DIN17175 ST45.8 ST35.8, *Alloy steel pipe*: ASTM A335, ASTM A213, *Stainless steel pipe*: ASTM A312, ASTM A213, *Line pipe and casing pipe*: API5L, API 5CT.
 2. Bending strength requirements of the compressed air line.
 3. Anchoring or protection of air line in the event of a mine explosion. The air line must survive 15 psi over 0.2 seconds with a 0.1-second rise and 0.1-second fall.
 - a. Whether it should be buried and to what depth.
 - b. If not buried, how much it should be anchored. Whether it can be covered with debris. If covered with debris, what type, how much, and how deep.
 - c. The air line's ability to survive an explosion and not be damaged by flying projectiles that would result from an explosion (concrete blocks, bolts, mine supplies, pieces of equipment, etc.).
 4. Drainage of water in long lines due to condensation.
 5. Whether additional filtration is needed at the RA.
 6. Procedures for extending and purging the air line.
 - a. While the air line is being extended, the original RA will need to be maintained.
 - b. The time requirement for the advancement window.
 - c. The time requirement for a “hardened line.”
 - d. Specifications/quality control on tightening connections.
 7. Distribution air manifold requirements at the RA location.
 8. Valve requirements of the air line at various locations including check valves, shutoff valves, and testing for leaks.
 9. Whether a continuous low volume of air can be provided to a BIP RA to keep it under positive pressure ~ 0.1 in water gauge. If so, how much would be needed [Foster-Miller 1983].
 10. How the air line is transitioned into the BIP RA itself and kept protected.
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³⁹ Through additional research and testing, it will be necessary to better define the requirements for the construction and survivability of compressed air lines for BIP refuge alternatives. As part of this process, the specifications, installation procedures, “best practices” for required maintenance and examinations, and testing criteria will be developed to establish the guidelines for use of these compressed air line systems OMSHR has already funded on-going contract research in this area.

11. Where best to locate protected compressed air lines under various mining scenarios (longwall development, continuous mining section, retreating longwall considerations, etc.).
12. Air delivery limits—i.e., how far air can be carried through a compressed air line before pressure losses become too great, how often a new borehole would be needed to keep the air supply at an acceptable distance from the RAs.

To assess how industry can meet the above requirements, research needs to be conducted to develop specific guidance.

Considerations for Facilitating the Use of BIP RAs

The NIOSH OMSHR 2007 report to Congress on refuge alternatives [NIOSH 2007] concluded that built-in-place refuge alternatives offer substantial advantages over mobile RAs, and that the strengths of BIP RAs compared to mobile RAs are so significant that consideration should be given to allowing extended distances from the face for the placement of BIP RAs. This Report of Investigations has argued that point more expansively, by first summarizing the potential advantages of BIP RAs, discussing three approaches to locating them further from the face, outlining design and approval guidelines for RA stoppings, and analyzing the issues involved in delivering a reliable supply of clean, breathable air to a BIP RA. Building on the above material, here OMSHR sets forth and analyzes several considerations for facilitating the use of BIP RAs in underground mines.

Locating BIP RAs at Greater Distances from the Working Face

Based on the three approaches undertaken by OMSHR researchers to determine how far from the face area miners could travel given the breathing time afforded by their available SCSRs, and combined with the travel distances to RA locations based on entry height and the distances between SCSR cache locations as outlined in Table 4, OMSHR believes that mines could locate built-in-place refuge alternatives at distances from the working face based on the guidance provided in Table 4.

Allowing mines to locate BIP RAs at greater distances from the working face introduces a number of advantages:

1. RAs located further from the face have a higher likelihood of avoiding damage from both primary and secondary explosions which occur at the face area of the mine. While the current 30 CFR 75.1506(c) regulation requires that RAs be located within 1,000 feet of the working face, in practice, mining logistics generally result in RAs being located much closer than the 1,000-feet requirement, making them and their occupants easily subject to effects from explosions at the face. Locations further from the face might also increase the likelihood that the communication system to the RA survives a disaster.
2. Locating BIP RAs further from the face would reduce the number of BIP RAs that would need to be constructed.

- Locating BIP RAs further from the face and thus reducing the frequency of RA moves will make it more practical to introduce a wider variety of BIP RA designs, which could improve the safety as well as the psychological and physiological comfort and mental well-being of confined miners, significantly improving the likelihood of survival.

Table 6 presents a summary of the three approaches. Using conservative rounded-down distances and combining the data from Table 4 results in potential maximum BIP RA distances from the face, which vary with entry height.

Table 6. Maximum distances of BIP RAs from the face

Entry height	Approach 1: Based on SCSR-mandated storage cache locations	Approach 2: Based on worst-case SCSR usage times	Approach 3: Based on NIOSH and BOM established travel times and escape probabilities	Maximum BIP RA distance from the face
<40 inches	2,200 feet	2,640 feet	NA	2,000 feet
>40–<50 inches	3,300 feet	3,960 feet	NA	3,000 feet
>50–<65 inches	4,400 feet	5,280 feet	6,000 feet	4,000 feet
>65 inches	5,700 feet	6,480 feet	6,500–7,000 feet	5,000 feet

Locating BIP RAs further from the face requires a trade-off of the advantages of locating an RA close to the face—such as the ability to easily assist injured miners in reaching the RA location and a shorter travel distance for miners to the RA—against the significant potential advantages gained from the use of a BIP RA. This argument is consistent with OMSHR’s position in its 2007 Report to Congress on refuge alternatives [NIOSH 2007]. Therefore, consideration should be given to allowing mines to locate RAs further from the face only if they employ new RA technologies that meet the following three criteria:

- Provide a constant supply of air to the RA either via a protected compressed air line into the RA or a borehole from the surface into the RA.
- Provide additional RA space per occupant. The original minimal space requirement of 85 ft³ per occupant as noted in the NIOSH report to Congress on refuge alternatives [NIOSH 2007] is recommended.
- Maintain the RA interior atmosphere under positive pressure when not in use to ensure that the RA contains breathable air immediately upon entry and to keep contaminated air from entering the RA with miner entry. It would be advantageous to have a differential pressure gauge on the RA which could be inspected regularly to ensure that the positive differential pressure is maintained. However, if it is not feasible to maintain the RA under positive pressure when not occupied, additional SCRSs must be available in the RA to sustain miners until the RA can be adequately purged of contaminated air by the air supply to the RA.

Importantly, it is possible that a protected compressed air line could be run to a mobile RA. This would eliminate the need for compressed air and O₂ cylinders in the RA itself, which could result in more occupancy space in the RA.

Designing RA Stoppings for MSHA Approval

Previous sections of this report have detailed structural design criteria for RA stoppings that could meet with MSHA approval, including an example design for an RA stopping constructed from a conventional rebar-reinforced concrete wall. OMSHR believes that the guidelines set forth in this report could be used by industry when submitting stopping design applications for approval by MSHA.

Based on findings from this Report of Investigations, the recommended design pressure-time curve for an RA stopping has a magnitude of 15 psi, a rise time of 0.1 seconds, a fall time of 0.1 seconds, and a duration of 0.2 seconds.⁴⁰ Because of the slow rise time, this pressure-time curve always has a dynamic load factor of 1.0 and an equivalent static design pressure of 15 psi. This design pressure-time curve is representative of the pressure-time history close to an explosion source. It is similar to observed explosion pressures in recent underground coal mine disasters, and is commensurate with the blast pressure tolerance of the human body. This curve is identical to that developed in OMSHR's 2007 report to Congress on refuge alternatives [NIOSH 2007].

Delivering Clean, Breathable Air to a BIP RA

As noted in this report, most of the advantages of a BIP RA disappear if the RA is not guaranteed a constant and highly reliable supply of clean, breathable air. A borehole from the surface directly to the BIP RA is the most advantageous and reliable option. However, a borehole from the surface to the BIP RA is often impractical due to such factors as drilling costs and surface rights issues. Using a protected compressed air line carrying clean, breathable air to a BIP RA is emerging as a practical and achievable goal.⁴¹ OMSHR believes that a constant supply of clean, breathable air can be provided to BIP RAs either from a borehole to the surface or through a protected compressed air line system. Several efforts to develop and test such systems are already being undertaken by private companies.

Considering Economic Drivers when Designing New BIP RAs

Currently, there are approximately 30 BIP RAs with a constant air supply (all via borehole to the surface) and MSHA-approved stopping and door systems in U.S. underground coal mines. These BIP RAs are all located outby the face areas. These RAs range in volume from 1,800 ft³ to 10,000 ft³ and are designed to house from 20 to over 100 occupants given the requirement of

⁴⁰ These criteria are specified in 30 CFR 7.505 and further clarified in the April 29, 2009, section of the document, "[Questions and Answers: MSHA's Refuge Alternatives Requirements](#)."

⁴¹ The Hubble Breathable Air Units (Models HBA75, HBA 100, and HBA 250) have already been approved by MSHA (Approval No. 07-LCA110001) for use in providing breathable air to an RA via a protected compressed air line.

12.5 ft³/min of breathable air per occupant in 30 CFR 7.506 and the current space requirement of 15 square feet of floor space per person in 30 CFR 75.1506. Each of these BIP RAs provides more than the 85 ft³ of space per occupant recommended in the NIOSH report to Congress on refuge alternatives [NIOSH 2007].

The costs of these existing BIP RAs range from \$50,000 to \$150,000, depending mainly on stopping and door system costs and borehole costs. Given these costs, it does not appear to be economically viable to provide these types of RAs within 1,000 feet of the working face of mines. However, if BIP RAs that advance with the face become an accepted practice, it is likely that much more cost-effective stopping and door systems, which could be disassembled and advanced or be inexpensive enough to abandon in place, will be developed and made available. Some work in this area is already being undertaken by private companies.

In the context of economic drivers, design needs for new BIP RAs that can be advanced with the face are as follows:

1. BIP RA designs are needed to employ stopping and door systems that are inexpensive enough to build and leave in place or stopping and door systems that are designed to be quickly and easily disassembled, moved, and reassembled.
2. Novel BIP RA concepts that provide more space and breathable air per occupant and can be easily moved with the face are needed. An example would be a series of bolt- or clamp-together steel box modules that could be moved with the face and easily assembled into a single larger steel box (modular design). The smaller individual boxes could be moved easily in the mine (possibly with a scoop) and assembled into the larger unit in a crosscut or cutout. This would allow for an RA that could provide significantly more space per occupant.
3. Breathable air would most likely be provided to any of the above RA designs through a protected compressed air line. Therefore, there is an economic driver to provide a protected compressed air line that supplies breathable air to the RA occupants and can be advanced with the face. The compressed air source could be located on the surface and distributed to the RA via a borehole and a protected underground compressed air line.

Another economic consideration is to develop ways to reduce RA stopping and door costs by requiring only one stopping and door system per RA. This could be done by locating RAs in crosscuts that are not completely cut through or by locating them in cutouts in long pillars that originate halfway through a crosscut. The development of improved air supply and cooling systems employing technologies such as liquid O₂ systems, or cryogenics could also reduce the cost of advancing more habitable RA designs with the face.

If there is a willingness to accept new BIP RA design concepts for advancement with the face, competition could bring new economically viable BIP RA designs into the marketplace.

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Appendix A—An Overview of Built-in-place Refuge Alternatives in U.S. Underground Coal Mines

Introduction

This Appendix discusses the current use of BIP RAs in U.S. underground coal mines. This includes statistics on the number of BIP RAs currently in the Nation's underground coal mines, the number of coal companies and mines employing the BIP RAs, how BIP RAs are currently used, and their role as part of a mine's comprehensive escape and rescue plan. The MSHA regulatory requirements for design and provision of BIP RAs are presented. This Appendix also provides a review of site-specific information obtained during mine visits by OMSHR researchers to view BIP RAs. The site-specific BIP RA information includes construction, location, air supply, and RA provisions and inventories. The characteristics of an ideal BIP RA are assessed, in addition to other acceptable but less desirable attributes.

Review of Refuge Alternatives

RAs are intended to provide a post-disaster safe place of refuge for miners that have exhausted all attempts at escaping. In the face area they replace barricading which traditionally was the method miners used to isolate themselves from the post-disaster noxious gases. There is a history of miners successfully utilizing barricades to survive post-disaster, but most of the successful barricading occurred in distant years past. In fact, since 1958, only 11 miners have survived by building a barricade. Table A1 illustrates the success and failures of barricading from 1900 to 1998. It does not include the Sago miners who perished behind a barricade.

Table A1. Historical review of mine barricading efforts as a result of fires and explosions in coal mines

Outcome for miners	1900–1958*	1958–1998**
Fatally injured	4,084	421
Escaped	2,835	588
Rescued	381	23
Survived after barricading	880	11
Died after barricading	189	22

Sources: *BOM Bulletin 586; **Misc. BOM Information Circulars

In outby mine areas, RAs can serve as places of refuge for outby workers if escape is cut off or as waystations as miners escape for short-term rest and regrouping before continuing escape. RAs provide miners with the basic necessities to survive including a breathable atmosphere (oxygen, compressed air, and/or carbon dioxide scrubbing) and food and water. They can be of two types, either mobile RAs or BIP RAs. Table A2 presents a comparison of the characteristics of the two different RA concepts.

Table A2. Comparison of characteristics for mobile RAs and BIP RAs

Characteristic	Mobile Tent-Type Inflatable	Mobile Rigid Steel	BIP RA
Size	Smaller than mine opening	Smaller than mine opening	Utilizes mined opening
Number of occupants	36 maximum	20–24 maximum	Limited only by size and space/volume requirements of 30 CFR 75.1506 (b)(1)
Breathable air supply	Oxygen bottles	Oxygen bottles	Borehole compressed air, borehole blower system, compressed air line
Amount of air	1.32 ft ³ /hr O ₂ per person	1.32 ft ³ /hr O ₂ per person	12.5 cfm air per person
Designed duration of occupancy (hr)	96	96	96 +
Carbon dioxide scrubbing	Lithium hydroxide or soda lime curtains or canisters	Lithium hydroxide or soda lime curtains or canisters	None
Airlock	Yes, required	Yes, required	Probably not required
Food, water, supplies	Minimum as required by law	Minimum as required by law	Generally more than required by law
Approximate cost*	\$100K–\$200K	\$100K–\$200K	\$80K–\$150K

*It should be noted that the mobile RAs (both inflatable and rigid) are reusable.

Mobile RAs

Mobile RAs are designed to be moved frequently as the mining face advances, and by regulation, are to be kept within 1,000 feet of the active mining face. This frequent moving requirement necessitates that they “fit” within the mined openings; thus their dimensions are less than the height and width of the opening. The result is limited space, both for occupants and supplies. There are two types of mobile RAs, inflatable tent-type or rigid steel. The tent-type RAs are comprised of a steel container that protects their contents which include the tent, inflation, purge and breathing air bottles, and all supplies. To deploy this type of RA, a door on one end is opened, the tent is manually rolled out, and then inflation is initiated by pulling or turning an activation valve. Inflation air, contained in high-pressure compressed air bottles, is released into the tent’s internal supporting structure. Tent-type RAs can accommodate up to 36 occupants. A rigid steel RA is simply a structurally reinforced box constructed from steel with one or more entrance/exit doors. The breathing air, purge air, and all supplies are stored inside the RA. Rigid steel RAs typically have a lower occupancy, at most up to 24 miners. Most mobile RAs are equipped with an airlock that must be purged of contaminated air (primarily carbon monoxide (CO) and methane (CH₄)) before miners can enter the main RA chamber. A few are designed for the entire main RA chamber to be purged after miners enter. In addition, both types of mobile RAs must provide breathable air to sustain each occupant for 96 hrs. Information

obtained from MSHA [Shumaker 2014] places the approximate number of mobile RAs manufactured and shipped as of February 2012 at 1,660 units, of which nearly 80% were inflatable tent-type and the remaining 20% rigid steel. Currently it is believed that there are over 1,700 mobile RAs at the Nation's underground coal mines, with about 1,400 of them in active usage.

BIP RAs

BIP RAs are known by many names including waystations, safe rooms, safe havens, refuge rooms, bulkhead-based refuge stations, and in-place shelters. BIP RAs use the mine structure as the refuge area where miners can retreat to when escape is not possible. Typically, BIP RAs are hardened rooms located in a crosscut or stub (butt) heading cut into a coal or barrier pillar within the coal seam, with the resulting room serving as a protected secure space with an isolated atmosphere. The mine ribs serve as two or three of the walls of the BIP RA, and one or two explosion-resistant stoppings are constructed to isolate the area from the rest of the mine. Entrance doors are provided in one or both of the stoppings. In most cases, additional roof and rib support is provided to strengthen the roof and ribs. Spraying of the mine area with a cement-based sealant such as shotcrete is common as well as setting timbers against the ribs in higher seams. All currently employed BIP RAs provide fresh air to the miners through a borehole from the surface, as well as food, water, and other supplies the miners will need inside the RA. The main advantage of a BIP RA is space. Because the whole mined opening is utilized, and the length can be virtually as long as desired or practical based on crosscut length, considerably more space can be provided for each occupant as compared to a portable RA. In addition, depending on the breathable air supply system employed, the number of occupants can be much greater. From unofficial information obtained by OMSHR from all MSHA Districts, there are approximately 30 BIP RAs in U.S. underground coal mines, operated by six mining companies. All of these BIP RAs employ boreholes to the surface.

Current Role of BIP RAs

Currently, all BIP RAs are located outby the active mining faces and are designed and approved for use by the outby workers only when seeking refuge in case escape is not possible. Face workers are expected to use the mobile RAs on the sections if they decide to refuge. The BIP RAs located outby have occupancies that are selected to "accommodate persons reasonably expected to use it" according to 30 CFR 75.1506(b)(3). Most of the mines visited by OMSHR researchers as part of this study allowed for escaping face workers to utilize the outby BIP RAs.

Built-in-place Shelters as Part of a Comprehensive Escape and Rescue Plan

RAs can be extremely useful to facilitate escape from the mine (when the RA is used as a waystation) as well as to serve as a safe haven of last resort. Such an approach would be far superior to one in which RAs are simply placed into the mine to comply with a regulation [NIOSH 2007]. As part of a comprehensive escape and rescue plan, BIP RAs could be used in a number of specific situations including those detailed below.

1. As a rest stop or waystation during escape for miners to take a short break, get a drink of water, communicate with the outside, review maps and escape routes, plan their next escape path, change out their self-contained self-rescuers (SCSRs), then resume escape.

2. Give aid to injured workers, then resume escape or to refuge and wait for rescue if non-injured miners have lost their strength and ability to continue escaping, and help injured miners escape, or if continued escape would negatively impact the chance of survival for both the injured and non-injured workers.
3. As a place to retreat to and to seek refuge if further escape becomes impossible.
4. For use as a possible advanced fresh-air base by mine rescue teams trying to reach unaccounted-for or refuged miners.
5. As originally intended—to serve as a place of refuge for outby miners who have exhausted all attempts to escape.

Regulatory Requirements for BIP RAs

MSHA uses the term refuge alternative (RA) to refer to both BIP RAs and portable RAs. For use in underground coal mines they both must satisfy the MSHA requirements for refuge alternatives as listed in 30 CFR 7 and 30 CFR 75. There are two key issues with respect to MSHA allowing the use of BIP RAs, as detailed below.

1. BIP shelters can have boreholes to the surface or an MSHA-approved protected compressed air line as the source of the RA's continuous supply of fresh breathing and purging air, or the RA can be built without either boreholes to the surface or a compressed air line supply and employ the same type of purging air, breathing air, and carbon dioxide scrubbing components as portable RAs employ. Depending on the method of breathable air and purge air supply, the BIP RA may or may not be required to have an airlock. When boreholes or compressed air lines are used and a positive pressure is created within the RA, no airlock is required as per 30 CFR 7.505(a)(3). If the BIP RA relies on oxygen bottles for breathable air and compressed air tanks for purging, an airlock is required according to 30 CFR 7.505(a)(3). In both cases, harmful gas removal requirements that must be satisfied are found in 30 CFR 7.508.
2. The stopping walls and door of a BIP RA must meet the MSHA explosion criteria of withstanding a 15-psi overpressure for 0.2 seconds as stated in 30 CFR 7.505(a)(4). This is basically a 15-psi static pressure and is identical to what a portable RA must withstand. In addition, stopping materials must meet the non-combustibility criteria codified in 30 CFR 75.333 Subpart D, based on the ASTM Standard E119-14 [2014] fire endurance test. This endurance test consists of a one-hour exposure of up to ~ 1,652°F, whereas the portable RA must pass exposure to a flash fire consisting of a three-second exposure at 300°F. Mining companies or stopping vendors requesting approval for their designs must submit the designs to the MSHA District Manager in the district where the BIP RA will be built. The District Manager generally submits the design to MSHA Technical Support for its analysis of the design. In general, submitters must design their own RA stopping and door plan, do the engineering calculations to show they meet MSHA's 15-psi overpressure criteria, and have the design certified by a professional engineer.

Summary of Mine Visits

General Information on BIP RAs Observed

OMSHR researchers visited underground coal mines to view BIP RAs and discuss with mine officials why they employ BIP RAs. Information concerning the construction, location, capacity, air supply, and provisioning was obtained. Mines visited were selected to obtain a cross section of the industry including high and low coal and eastern and western coal mines. The mines were located in the following states: Colorado, Kentucky, Montana, and New Mexico. Table A3 summarizes the information obtained by OMSHR researchers, while the sections that follow include details of the specific BIP RA characteristics observed.

Table A3. Summary of in-mine observations of BIP RAs

Characteristic	Mine 1	Mine 2	Mine 3	Mine 4
State	CO	KY	MT	NM
Number of BIP RAs	2	5	1	8
Distance apart (ft)*	Less than 6,000	8,000	5,700	6,000
Area (sq ft)	715; 850	1,000	360	1,000
Mining height (in)	104; 132	63	120	105
Volume (ft)	6,197; 9,350	5,250	3,600	8,750
Design number of occupants based on supplies provided	50	6	15	20
Potential number of occupants based on volume of air supplied	62; 68	120	104	100
Maximum number of occupants based on mining height and unrestricted volume requirement of 30 CFR 75.1506(b)(1)	103; 156	87	60	146
Stopping and door	MICON	MICON	MICON	Mine-designed
Number of doors	2	1	2	2
Door locations	Front and back stopping	Front stopping	Front and back stopping	Front and back stopping
Breathable air supply	Borehole, permanent blower	Borehole, portable blower	Borehole, permanent compressed air	Borehole, portable compressed air
Amount of air (cfm)	770; 850	1,493	1,300	250 to 1,500
Borehole depth (ft)	Less than 600	Less than 450	220	Less than 900
Borehole diameter (in)	10	6	6	7
Carbon dioxide scrubbing	None	None	None	None
Airlock	No	No	No	No
Approximate cost	\$150K	\$100K	\$80K	\$80K
Separate toilet area, size (sq ft)	Yes, 22.5 and 90	No	No, brattice cloth provided, must be hung	Brattice cloth in place for privacy

*Distance apart refers to the actual distance the outby BIP RAs are from each other or—in the case of Mine 3, which has only one BIP RA—the distance selected by the mine operator for placement of a second BIP RA in the future.

BIP RA Stopping Construction

The stopping and door systems used for BIP RAs were of two types, either a MICON⁴²-designed and MSHA Technical Support-approved RA stopping and door system (Figure A1) or a mine-developed and MSHA-District Manager-approved⁴³ RA stopping and door design (Figure A2). To date, MICON provides the only MSHA Technical Support-approved RA stopping and door system for BIP RAs. Stopping design and certification is performed by MICON for each BIP RA. Initially, a mine provides MICON with a location for the BIP RA, and then MICON checks the shear strength of the surrounding strata and measures the cleaned opening. Once the opening is cleaned and measured, MICON uses the design chart to determine the thickness of the stopping necessary to withstand 15 psi overpressure, with a safety factor of 2. MICON RA stoppings can be built up to 14 ft high and 28 ft wide. The steel door is designed to withstand a 50-psi explosion pressure.



Figure A1. Example of a MICON built-in-place refuge alternative stopping and door system.

⁴² MICON is a company that provides specialty ground control and contracting services to the mining industry.

⁴³ This specific design was approved by the MSHA district manager for use only in one specific mine in that district.



Photo by NIOSH

Figure A2. Mine-designed and MSHA District Manager-approved built-in-place refuge alternative stopping and door system.

The MICON BIP RA stoppings are constructed with concrete block and polyurethane bonding adhesive that is applied to both sides of the blocks, between blocks as they are laid, and on the perimeter between the blocks and the roof and ribs. The perimeter expands upon curing, leaving an impermeable membrane with virtually no leakage. The blocks are a concrete masonry unit (CMU) with a minimum of 1,800 psi compressive strength which meets the C140 ASTM standard [ASTM 2012]. MICON BIP RA stoppings are typically 2 to 5 blocks thick. They can be flush mounted at the edge of the crosscut, but are typically installed a foot or two from the corners for an added safety factor. The stoppings are designed for a higher safety factor than what is required by regulation to account for the degradation over time. The doors are usually installed on top of the first layer of block, and steel expansion pieces are used if the stopping is more than a few rows thick. Each mine decides on the whether a door will be installed in each stopping. Many mines have only one door to reduce the cost. Construction by MICON personnel can take as little as two days in lower coal seams and up to a week in the thicker seams.

There is presently only one mine-designed and MSHA District Manager-approved BIP RA stopping and door design. This RA stopping is built using 16-in-thick solid blocks dry stacked with each row laid at 90° from the previous (the first row of blocks is laid with the long side perpendicular to the ribs and the next row is laid with the long side parallel to the ribs). The stopping's perimeter is pressurized using packsetter pressurized pre-stressing bags between the blocks and the roof and ribs. These bags are of a heavy impermeable material and are filled with

a quick-setting grout under pressure of about 50 psi. The grout slightly expands causing a tight fit around the perimeter and filling all voids. This loads the stopping and keeps it airtight. Finally, both sides of the stopping are sealed with trowel grade cement plaster.

Supplemental Support

The roof and ribs in the BIP RAs are normally provided with some additional support simply because the RAs have an anticipated long life and must remain stable and safe for the occupants. Most mines visited by OMSHR researchers installed wire mesh on the roof to prevent small rocks from falling. In the higher seams, the ribs were usually wire meshed and bolted and then covered with a pneumatically applied concrete-based sealant for long-term stability. The mine roof was sprayed in this manner as well in many of the shelters. Also in the higher seams, posts or jacks were installed along both ribs to help eliminate rib roll problems (Figure A3).



Figure A3. Posts and chain link fence placed to prevent rib rolls in a higher seam built-in-place refuge alternative.

Location (Distance Apart) for BIP RAs

The location for BIP RAs, which were all built outby the face areas, was determined by actual walking trials. 30 CFR 75.1506(c)(2) states that RAs shall be “spaced within one-hour travel distances in outby areas where persons work such that persons in outby areas are never more than a 30-minute travel distance from a refuge alternative or safe exit.” Mine operators determined the appropriate distance through simple walking trials under normal mine conditions. Depending on the seam height, mine conditions, slope or gradient of the entries, etc., one-hour walking distances ranged from 5,000 to 15,000 ft. The mine operators elected to build their BIP RAs at distances less than the maximum walking distances determined. Several factors influenced location selection including in-mine site conditions, surface availability, and of course, walking distance.

Location (Physical/Actual) of BIP RAs

The actual physical location of the BIP RAs, which were all built outby the face areas, varied from mine to mine. Most were located in a crosscut off the primary (intake) escapeway and were attached by a branch lifeline to the main lifeline. Others were located in a crosscut between the intake and return air course. The locations were somewhat dictated by the availability of locating the borehole—i.e. terrain, surface rights, power availability, etc.

Breathable Air Supply Systems for BIP RAs

Breathable air was supplied to the BIP RAs through a borehole from a permanent compressed air supply or blower (Figures A4 and A5) or through a borehole from a portable compressed air supply or blower (Figure A6). Most boreholes were from 6 to 10 inches in diameter, cased, and equipped with a muffler for noise reduction or diffuser for improved airflow at the termination end inside the BIP RA. Some boreholes were just a hole in the roof as shown in Figure A7. 30 CFR 7.506(c), which requires that a minimum flow rate of 12.5 cfm of clean air per person be supplied when breathable air is supplied via compressed air from fans or compressors. All borehole air systems visited by OMSHR researchers exceeded this standard. All systems must satisfy 30 CFR 7.506(a), which states that “only uncontaminated breathable air shall be supplied to the refuge alternative.”



Photo by NIOSH

Figure A4. Permanent blower air supply system.



Photo by NIOSH

Figure A5. Connection to borehole for a permanent air supply system.



Photo by NIOSH

Figure A6. Portable, diesel-powered blowers for borehole air supply systems.



Photo by NIOSH

Figure A7. Breathable air supply borehole opening into a built-in-place refuge alternative with no collar.

Occupancy/Capacity

All of the BIP RAs visited by OMSHR were located in outby areas of the mines. 30 CFR 75.1506(b)(2) states that “each refuge alternative for outby areas shall accommodate persons reasonably expected to use it.” This is interpreted as the outby BIP shelters only needing to be sized to accommodate the number of outby persons reasonably expected to use the RA, since face workers deciding to refuge are expected to use the portable RAs located on the active mining sections. Occupancy is limited by the amount of breathable air provided, the size of the RA, and/or the amount of food and water available. The design occupancy of the BIP RAs examined was limited by the supplies provided and ranged from 6 to 50 occupants. Table A3 also shows that based solely on the volume of breathable air supplied, the occupancy could be as many as 120 occupants. Finally, BIP RAs must also meet the mining-height-based unrestricted volume requirement of the table presented in 30 CFR 75.1506(b)(1). Table A3 shows that the design occupancy of all the BIP RAs visited as part of this research satisfies this regulation and could be in the range of 60 to 156 occupants.

RA Supplies

The supplies provided varied widely from one BIP RA to the next. All the BIP RAs observed during the mine visits provide food and water that satisfies the requirements of 30 CFR 75.1507(d)(1) for the number of persons expected to use the RA. In many instances extra food and water was provided. Other basic supplies included were those required by regulation such as a first aid kit (30 CFR 75.1507(d)(4)), fire extinguisher (30 CFR 75.1506(j)), communications (30 CFR 75.1600-3(a)), repair materials and tools (30 CFR § 75.1507(d)(3)), air monitoring equipment (39 CFR 7.507), and lighting sufficient for persons to perform tasks (30 CFR 75.1507(a)(10)). Generally, the quantity of supplies in the BIP RAs was greater than in portable RAs because of the extra space provided by the BIP RAs. Additional items not normally found in portable RAs that have been provided in BIP RAs include extra first-aid supplies and stretchers,

foldable cots, blankets, face wash, emergency eye wash stations, hand sanitizer, disposable coveralls, hand and foot warmers, and self-contained self-rescuers (SCSRs). The borehole used for the breathable air supply delivery can also serve as a point of introducing supplies, communications, medicines, etc., if the size of the borehole is adequate and is configured such that supplies can be introduced without jeopardizing the airflow.

Waste (Toilet) Facilities in BIP RAs

A means to effectively contain human waste and minimize objectionable odors must be provided as specified in 30 CFR 7.504(c)(3). A range of waste facilities/areas was observed that are designed to comply with this standard. In the larger BIP RAs, a folding toilet and disposable toilet bags were one option supplied. Waste bag disposal was normally accomplished by placing the bag in a trash can and tightly closing the lid. Other options included camp toilets, or marine-type flushable toilets (Figure A8) that expel the waste outside of the RA. One mine actually built urinals out of polyvinyl chloride (PVC) pipe and shutoff (obviously with only male miners in mind) that would allow miners to urinate, then open the shutoff and let the fluid flow out the pipe, through the stopping and onto the mine floor outside the back of the RA. Neither of these last two systems are the most sanitary systems, but they do eliminate bags full of human waste. Most of the BIP RAs had an area within the RA that was designated as the “toilet area.” Some RAs required the occupants to hang brattice curtain at first use; others had the curtain already in place; some had concrete block walls or walls constructed from metal stoppings and a door to isolate the toilet area (Figure A9).



Photo by NIOSH

Figure A8: A marine-type flushable toilet.



Photo by NIOSH

Figure A9: A mine-constructed isolation room for a toilet.

Internal Facilities

A range of internal facilities was observed. These included benches (Figure A10), picnic tables, folding chairs, and storage shelves (Figure A11). The supplies were stored in the original manufacturer's cardboard boxes and/or various types of plastic storage boxes (Figure A12). Some mines experienced long-term problems with cardboard boxes and wood shelving developing mold, which necessitated using plastic storage boxes and non-wood shelving, benches, chairs, and tables.



Photo by NIOSH

Figure A10. Metal benches in a built-in-place refuge alternative.



Photo by NIOSH

Figure A11. Storage shelves in a built-in-place refuge alternative.



Photo by NIOSH

Figure A12. Typical storage boxes in a built-in-place refuge alternative.

Appendix B—Statistical Analysis of Times to Complete Needed Actions in a Mine Emergency

Approach

As part of this Report of Investigations, estimates were made of the minimum and maximum time in minutes miners would need to complete the following activities required to travel to and access a BIP RA:

1. SCSR Donning (1 min to 5 min)
2. Face Travel Time, Assembly, and Decisionmaking (5 min to 15 min)
3. SCSR Changeover (2 min to 5 min)
4. RA Deployment, RA Entry and Purging (2 min to 5 min)

It is reasonable to assume that the distribution of time to complete each activity would be approximately normal.

The specifications for the four activities are shown in Table B1 below. Based on the symmetric property of the normal distribution, the mean time was posited to be midpoint between the minimum and maximum time. The values of the standard deviation were derived on the basis of a rule of thumb which states that dividing the range by 4 produces a reasonable estimate of the standard deviation.

Table B1. Specifications for generation of simulated data for four activities required to travel to and access a refuge alternative

Phase	Minimum	Maximum	Mean	Range	SD
SCSR donning	1 min	5 min	3.00	4	1.00
Face travel time, assembly, decisionmaking	5 min	15 min	10.00	10	2.50
SCSR changeover	2 min	5 min	3.50	3	0.75
RA deployment, RA entry, and purging	2 min	5 min	3.50	3	0.75

It was decided that a sample of 500 cases per phase would be adequate. The STREAMINIT and RAND procedures in SAS [Wicklin, 2013] were used to generate samples of 530 random cases from each of four normal distributions, respectively, with the specifications listed in Table B1. The 30 additional cases were generated to allow for exclusion of the small proportion of cases that fell below or above the minimum time or maximum time specified. It is known that normal distributions encompass extreme values although such values rarely occur.

As the next step, the random values generated by SAS for each sample were written to Excel files. Public domain software accessed through the Research Randomizer Web page⁴⁴ was used to determine which observations from each sample to exclude in order to arrive at the target sample size of 500. Observations were identified by the sequence in which they were generated—e.g., 1 for the first observation, 2 for the second observation, etc. The four columns of data (observations 1–500) from the four data files (a file for each of the four phases) were combined into a single master data file. Table B2 shows the first 12 cases from the master data file as an illustration. The four values in each row of data were summed to compute a total time requirement.

Table B2. First 12 cases in master data file that correspond to data from Table B1*

Seq	SCSRdon	Trvl/Dec	SCSRchgovr	RAdeploy
1	3.81 min	11.41 min	3.87 min	3.39 min
2	1.96 min	6.30 min	3.48 min	4.51 min
3	1.94 min	5.07 min	3.31 min	4.01 min
4	1.25 min	10.51 min	3.13 min	3.71 min
5	3.57 min	14.66 min	2.44 min	2.58 min
6	1.54 min	11.88 min	2.76 min	3.35 min
7	3.26 min	10.46 min	3.63 min	2.33 min
8	2.35 min	10.19 min	2.70 min	4.78 min
9	3.42 min	9.00 min	3.36 min	4.40 min
10	2.94 min	8.63 min	2.70 min	2.65 min
11	1.17 min	5.20 min	3.02 min	3.42 min
12	2.93 min	8.31 min	3.48 min	4.82 min

*Rounded to 2 significant figures.

⁴⁴ The Research Randomizer is a computer software package (version 4.0) developed by Geoffrey C. Urbaniak and Scott Plous. Retrieved on July 19, 2013, from <http://www.randomizer.org/about.htm>.

Results

Descriptive statistics on the simulated data values (time in minutes) for each of the four phases are shown in Table B3 below. It can be seen in Table B3 that the means, minimum values, and maximum values are very close to the specified values shown in Table B1. The standard deviations for all phases are smaller than the specified value, but this can be explained by the exclusion of extreme values.

Descriptive statistics for total time are shown in Table B4. Table B5 presents a frequency table for total time rounded to the nearest minute, and Figure B1 displays the frequencies in a histogram.

As shown in Table B4, the average observed value for total time was approximately 19.92 minutes, and the maximum observed value for total time was 26.49 minutes. Review of the “Cumulative Percent” column in Table B5 shows that 99.6% of the values were 25 minutes or less, and 100% of the values were 26 minutes or less.

Table B3. Descriptive statistics on simulated values for four phases required to travel to and access an RA

Statistic	SCSR donning	Face travel time	SCSR changeover	RA deployment
Mean	3.00 min	9.93 min	3.51 min	3.49 min
Lower bound, 95% CI for mean	2.93 min	9.74 min	3.45 min	3.43 min
Upper bound, 95% CI for mean	3.08 min	10.12 min	3.56 min	3.55 min
5% trimmed mean	3.00 min	9.93 min	3.51 min	3.49 min
Median	2.96 min	9.92 min	3.50 min	3.45 min
Variance	0.72 min	4.80 min	0.43 min	0.47 min
Std. deviation	0.85 min	2.19 min	0.66 min	0.69 min
Minimum	1.06 min	5.02 min	2.06 min	2.01 min
Maximum	4.98 min	14.66 min	4.93 min	4.99 min
Range	3.91 min	9.65 min	2.87 min	2.98 min
Interquartile range	1.22 min	3.26 min	0.96 min	0.99 min
Skewness	0.01	0.02	-0.06	0.05
Kurtosis	-0.55	-0.66	-0.66	-0.66

Table B4. Descriptive statistics on simulated values for total time to travel to and access an RA

Mean	19.92 min
Lower bound, 95% CI for mean	19.70 min
Upper bound, 95% CI for mean	20.15 min
5% trimmed mean	19.93 min
Median	19.85 min
Variance	6.41 min
Std. deviation	2.53 min
Minimum	13.53 min
Maximum	26.49 min
Range	12.96 min
Interquartile range	3.69 min
Skewness	-0.03
Kurtosis	-0.57

Table B5. Frequency distribution for total time to travel to and access an RA*

Time (min)	Frequency	Percentage (%)	Cumulative Percentage (%)
14	9	1.8	1.8
15	7	1.4	3.2
16	29	5.8	9.0
17	46	9.2	18.2
18	56	11.2	29.4
19	76	15.2	44.6
20	64	12.8	57.4
21	66	13.2	70.6
22	59	11.8	82.4
23	44	8.8	91.2
24	30	6.0	97.2
25	12	2.4	99.6
26	2	0.4	100.0

*Rounded to the nearest minute.

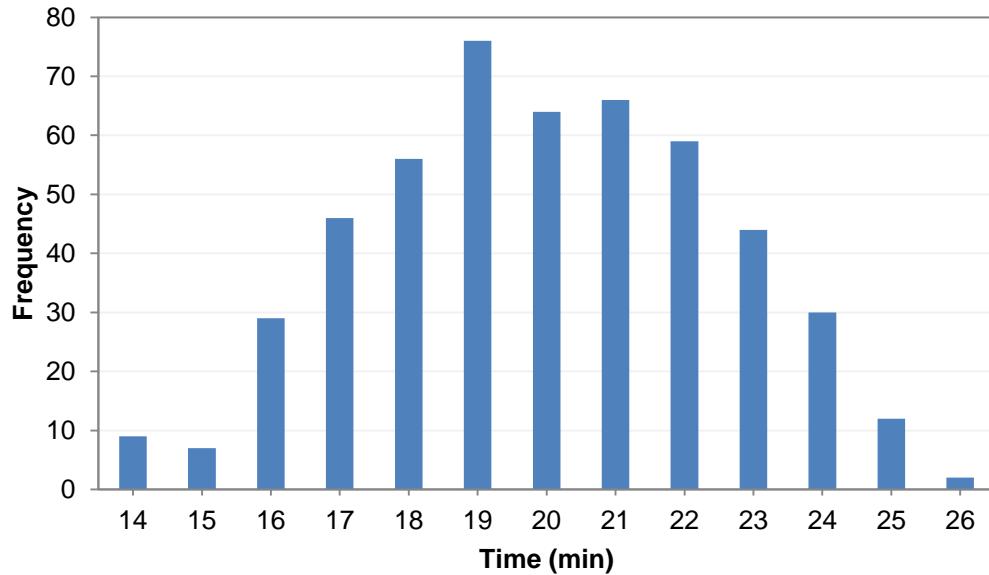


Figure B1. Histogram of simulated values for total time to travel to and access an RA (rounded to the nearest minute).

To validate the results described above, the simulation was repeated with different starting values for random number generation. Results were similar to those for the original simulation. For example, the mean total time was 20.15 minutes in the second simulation compared to 19.92 minutes in the first simulation. In the dataset generated by the second simulation, 97.8% of the values were less than 25 minutes, and 99.6% of the values were less than 26 minutes. For easy comparison, in Figure B2, a histogram for the second simulation is juxtaposed to the histogram for the first simulation.

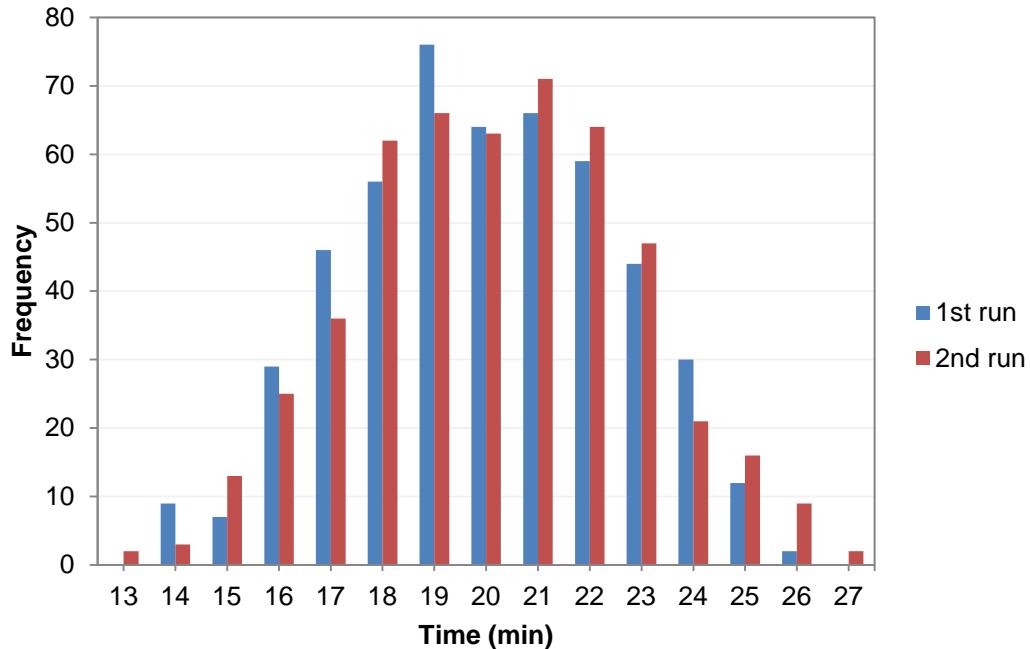


Figure B2. Comparison of frequency distributions for total time to travel to and access an RA in first and second simulation runs.

To achieve a larger sample size, and hence a more precise estimate of the population proportion, the two simulated datasets of 500 cases each were combined into a single dataset of 1,000 cases, and a one-sided 95% confidence interval for the population proportion was constructed. If the process of simulating 1,000 cases were repeated an infinite number of times, there is a 95% probability that at least 99.6% of the values would be less than or equal to 26 minutes. Therefore, it is highly unlikely that a miner would require more than 26 minutes to access the refuge alternative.

Appendix C—Design Example for a 15-psi RA Stopping Using Rebar-Reinforced Concrete

The following design example for an RA stopping using rebar-reinforced concrete follows recognized protective structure design principles in the Unified Facilities Criteria (UFC): Structures to Resist the Effects of Accidental Explosions [UFC 3-340-02 2008]. The design method follows three general steps: (1) design inputs where the design load and material properties are specified; (2) foundation design where an anchorage system for the stopping structure is designed; and (3) design of the stopping structure itself.

Design Inputs

Specify design load

Peak pressure— $P = 15 \text{ psi}$

Rise time—0.1 sec

Fall time—0.1 sec

Duration— $T = 0.2 \text{ sec}$

Specify allowable failure

The design must remain linear elastic—“elasticity of design.” No failure or permanent deformation of the RA stopping structure or the RA stopping foundation is allowed.

Specify safety factor

$\Phi_p = 1.0$

The adjusted peak dynamic pressure is

$$P_d' = P_d \cdot \varphi_p = 15 \cdot 1.0 = 15 \text{ psi} \quad (1)$$

Determine dynamic load factor (DLF)

The rise time, T_r , of the design load is 100 ms. The natural period, T_N , of the RA stopping structure is unknown currently, but will likely range from 1 to 10 ms. Because the rise time is likely to be much greater than the natural period, the ratio T_r/T_N is also always greater than 10. From Figure 3-51 [UFC 3-340-02 2008, page 619], the dynamic load factor is 1.0. The equivalent static pressure is

$$P_s = P_d' \cdot \text{DLF} = 15 \cdot 1 = 15 \text{ psi} \quad (2)$$

Specify coal mine entry geometry

Height— $H = 96 \text{ in (8 ft)}$

Length— $L = 240 \text{ in (20 ft)}$

Determine support conditions

The RA stopping is simply supported on four sides. It can resist translation, but it cannot resist moment at the supports. The foundation rocks surrounding an RA stopping are invariably weak or low strength and unlikely to provide any rotational (moment) resistance to the RA stopping structure. This simple support condition on all four sides is sometimes designated (SSSS). The RA stopping wall is a two-way wall, meaning that it can resist bending in both directions—rib-to-rib and roof-to-floor.

Specify material properties

The rebar-reinforced concrete RA stopping will use ordinary concrete, steel reinforcement bar, and steel rock bolt anchors.

Steel yield strength— $f_y = 60,000 \text{ psi}$

Concrete compressive strength— $f'_c = 3,000 \text{ psi}$

Determine dynamic increase factor

The steel and concrete strengths are adjusted upwards to account for the small increase in strength when dynamic loads are applied (using Table 4-1 [UFC 3-340-02 2008, page 1,068]).

Type of stress	Rebar	Concrete
Bending	$f_{dy.m} = 1.17^* 60,000 = 70,200 \text{ psi}$	$f'_{dc.m} = 1.19^* 3,000 = 3,570 \text{ psi}$
Direct shear	$f_{dv.s} = 1.10^* 60,000 = 66,000 \text{ psi}$	$f'_{dc.v} = 1.10^* 3,000 = 3,300 \text{ psi}$
Compression	$f_{dy.c} = 1.10^* 60,000 = 66,000 \text{ psi}$	$f'_{dc.c} = 1.12^* 3,000 = 3,360 \text{ psi}$

Foundation Design (RA Stopping Anchorage)

Determine approximate yield line location

The UFC uses yield line theory to calculate maximum shear and moment in one- and two-way walls that are either free, simple, or fixed supports on any of the four sides. For two-way walls with four edges supported, UFC 3-340-02 [2008] provides relations for the ultimate resistance of the wall in terms of its geometry and moment capacity [UFC 3-340-02 2008, page 574]. These equations can be combined and solved for an estimate of the yield line location x^* . An estimate of the horizontal location of the yield line is the real root of the following cubic equation:

$$0 = 2 \cdot x^{*3} - 6 \cdot L \cdot x^{*2} - 5 \cdot H^2 \cdot x^* + \frac{15}{4} \cdot H^2 \cdot L \quad (3)$$

$$0 = 2 \cdot x^{*3} - 6 \cdot 240 \cdot x^{*2} - 5 \cdot 96^2 \cdot x^* + \frac{15}{4} \cdot 96^2 \cdot 240 \quad (4)$$

$$x^* = 63.861 \text{ in} \quad (5)$$

Determine approximate shear forces

The approximate shear forces per foot along the perimeter at the roof, floor, and ribs of the RA stopping are found using Table 3-11 [UFC 3-340-02 2008, page 582].

$$V_{SVr}^* = \frac{3 \cdot P_s \cdot y \cdot (2 \cdot L - 2 \cdot x^*) \cdot 12}{(6 \cdot L - 2 \cdot x^*)} = \frac{3 \cdot 15 \cdot (96/2) \cdot (2 \cdot 240 - 2 \cdot 63.861) \cdot 12}{(6 \cdot 240 - 2 \cdot 63.861)} = 6.958 \text{ kips/foot} \quad (6)$$

$$V_{SVf}^* = \frac{3 \cdot P_s \cdot (H - y) \cdot (2 \cdot L - 2 \cdot x^*) \cdot 12}{(6 \cdot L - 2 \cdot x^*)} = \frac{3 \cdot 15 \cdot (96 - 96/2) \cdot (2 \cdot 240 - 2 \cdot 63.861) \cdot (12)}{(6 \cdot 240 - 2 \cdot 63.861)} = 6.958 \text{ kips/foot} \quad (7)$$

$$V_{SH}^* = \frac{3 \cdot P_s \cdot x^* \cdot 12}{5} = \frac{3 \cdot 15 \cdot 63.861 \cdot 12}{5} = 6.897 \text{ kips/foot} \quad (8)$$

The maximum shear force per foot is

$$\text{maximum shear } V_u^* = \max\{V_{SVf}^*, V_{SVf}^*, V_{SH}^*\} = 6.958 \text{ kips/foot} \quad (9)$$

As a check, the average shear force per foot is found by dividing the total applied explosion force by the RA stopping perimeter.

$$V_{ave} = \frac{P_s \cdot L \cdot H}{(2 \cdot L + 2 \cdot H)} = \frac{15 \cdot 240 \cdot 96}{(2 \cdot 240 + 2 \cdot 8)} = 6.171 \text{ kips/foot} \quad (10)$$

This simple average shear force method usually underestimates the maximum shear force around the perimeter by about 10% to 15% depending on the wall geometry.

Determine number of rock bolt anchors

The shear strength of steel is usually taken as 60% of its yield strength. The shear strength of a single rock bolt anchor is

$$F_{nv} = \mu_{RB} \cdot f_{yRB} = 0.6 \cdot 60,000 = 36,000 \text{ psi} \quad (11)$$

Choose rock bolt anchor diameter = 5/8 in = #5 bar and spacing SRB = 12 in. The area of a rock bolt anchor is

$$A_{\theta d} = \frac{\pi \cdot \theta_d^2}{4} = \frac{\pi \cdot (5/8)^2}{4} = 0.307 \text{ in.}^2 \quad (12)$$

The approximate number of rock bolt anchors per foot of wall is

$$N_{\theta d}^* = \frac{V_u^*}{(F_{nv} \cdot A_{\theta d})} = \frac{6,958}{(36,000 \cdot 0.307)} = 0.630 \quad (13)$$

Space the rock bolt anchors no more than $12/0.630 = 19.1$ in apart around the RA stopping perimeter. For simplicity, space the rock bolt anchors every 1.5 ft around the perimeter, including the roof, floor, and ribs. Use 5/8-in (#5 bar) 60 ksi steel.

RA Stopping Structure Design

Estimate reinforcing steel requirements

The horizontal and vertical positive moment capacities are [UFC 3-340-02 2008, page 574]

$$M_{VP}^* = M_{HP}^* = \frac{P_s \cdot x^{*2}}{5} = \frac{15 \cdot 63.861^2}{5} = 12,235 \frac{\text{lb-in}}{\text{in}} \quad (14)$$

For an initial trial design, assume that the RA stopping is 12 in thick. The reinforcement must have at least 2 in of concrete cover. The approximate distances of the extreme compression fiber to the centroid of tension reinforcement are

$$d_V^* = T_c^* - 2.5 \text{ in} = 12 - 2.5 = 9.50 \text{ in} \quad (15)$$

$$d_H^* = T_c^* - 3.5 \text{ in} = 12 - 3.5 = 8.50 \text{ in} \quad (16)$$

The approximate area of vertical tension steel reinforcement per foot of section is determined by solving the ultimate moment capacity equations iteratively [UFC 3-340-02 2008, page 1076].

The minimum area for flexural reinforcement is [UFC 3-340-02 2008, page 1092]

$$A_s = 1.875 \cdot \frac{\sqrt{f'_c}}{f_y} \cdot b \cdot d = 1.875 \cdot \frac{\sqrt{3,000}}{60,000} \cdot 12 \cdot 9.5 = 0.195 \text{ in}^2 \quad (17)$$

Assume $\rho_V = 0.00200$

$$A_{Vs}^* = \frac{M_{VP}^* \cdot b}{(f_{dy} \cdot d_V^*)} \cdot \frac{1}{\left[1 - 0.59 \cdot \rho_V \cdot \frac{f_{dy}}{f'_{dc}}\right]} = \frac{12,235 \cdot 12}{(70,200 \cdot 9.5)} \cdot \frac{1}{\left[1 - 0.59 \cdot 0.00200 \cdot \frac{70,200}{3,570}\right]} = 0.225 \text{ in}^2 > 0.195 \text{ in}^2 \text{ OK} \quad (18)$$

$$\rho_V = \frac{A_{Vs}^*}{(b \cdot d_V^*)} = \frac{0.225}{(12 \cdot 9.5)} = 0.00197 \approx 0.00200 \quad (19)$$

The approximate area of horizontal tension steel reinforcement per foot of section is also determined iteratively.

Assume $\rho_H = 0.00250$

$$A_{Hs}^* = \frac{M_{HP}^* \cdot b}{(f_{dy} \cdot d_H^*)} \cdot \frac{1}{\left[1 - 0.59 \cdot \rho_H \cdot \frac{f_{dy}}{f'_{dc}}\right]} = \frac{12,235 \cdot 12}{(70,200 \cdot 8.5)} \cdot \frac{1}{\left[1 - 0.59 \cdot 0.00250 \cdot \frac{70,200}{3,570}\right]} = 0.253 \text{ in}^2 > 0.195 \text{ in}^2 \text{ OK} \quad (20)$$

$$\rho_H = \frac{A_{Hs}^*}{(b \cdot d_H^*)} = \frac{0.252}{(12 \cdot 8.5)} = 0.00248 \approx 0.00250 \quad (21)$$

The computed areas of vertical and horizontal reinforcement are per linear foot of wall. Number 5 bar reinforcement (5/8-in-diam) has an area of 0.307 in².

Specify RA stopping wall thickness of 12 in. Specify #5 reinforcement bars (0.625-in-diam) for vertical and horizontal reinforcement on 12-in centers on both sides of the RA stopping wall.

Determine diagonal shear reinforcement

The shear strength of unreinforced concrete is [UFC 3-340-02 2008, page 1079, or ACI 318-08 2008, Section 11.11.3.1]

$$v_c = 2 \cdot \sqrt{f'_{dc}} = 2 \cdot \sqrt{3,300} = 115 \text{ psi} \quad (22)$$

$$v_c = [1.9 \cdot \sqrt{f'_{dc}} + 2,500 \cdot \rho] \leq 3.5 \cdot \sqrt{f'_{dc}} = [1.9 \cdot \sqrt{3,300} + 2,500 \cdot 0.002] = 114 \text{ psi} \leq 3.5 \cdot \sqrt{3,300} = 201 \text{ psi} \quad (23)$$

Choose $v_c = 114$ psi. The shear resistance of unreinforced concrete per foot of wall is

$$V_c = 12 \cdot v_c \cdot T_c^* = 12 \cdot 114 \cdot 12 = 16,416 \text{ pounds per foot} = 16.416 \text{ kips per foot} \quad (24)$$

From a prior calculation, the maximum shear force per foot in the concrete is $V_u^* = 6.958$ kips / foot.

Since V_u^* is less than V_c , no additional shear load must be resisted by shear reinforcement. However, the UFC specifies minimum shear reinforcement for slabs as “at least one stirrup must be located at each bar intersection” [UFC 3-340-02 2008, page 1082]. Therefore, use minimum shear reinforcement from the front to back side of the RA stopping wall at each horizontal and vertical reinforcement bar intersection.

Specify # 4 reinforcement bar stirrups (0.500-in-diam) on 1-ft centers.

Determine actual vertical moment capacity

The actual area of vertical tension reinforcement steel per foot of wall is 0.307 in^2 provided by 1 number 5 bar reinforcement (5/8-in-diam) on 12-in centers. The actual distance from the extreme compression fiber to the centroid of the vertical tension reinforcement is

$$d_V = T_c - \left(CC_w + \varphi_{sw} + \frac{\varphi_{vw}}{2} \right) = 12 - \left(1.5 + 0.5 + \frac{0.625}{2} \right) = 9.69 \text{ in} \quad (25)$$

The actual reinforcement ratio for vertical tension reinforcement steel is

$$\rho_V = \frac{A_{Vs}}{(b \cdot d_V)} = \frac{0.307}{(12 \cdot 9.69)} = 0.00264 \quad (26)$$

To ensure against sudden compression failures, the maximum reinforcement ratio ρ must not exceed 0.75 of the ratio ρ_b which produces balanced conditions at ultimate strength [UFC 3-340-02 2008, page 1077].

The maximum allowable reinforcement ratio ρ_b is

$$K_1 = 0.85 - 0.05 \cdot \left[\frac{(f'_{dc} - 4,000)}{1,000} \right] = 0.85 - 0.05 \cdot \left[\frac{(3,750 - 4,000)}{1,000} \right] = 0.8625 \quad (27)$$

$$\rho_b = \left(0.85 \cdot K_1 \cdot \frac{f'_{dc}}{f_{dy}} \right) \cdot \left[\frac{87,000}{(87,000 + f_{dy})} \right] = \left(0.85 \cdot 0.8625 \cdot \frac{3,570}{70,200} \right) \cdot \left[\frac{87,000}{(87,000 + 70,200)} \right] = 0.02063 > 0.00264 \quad (28)$$

The minimum vertical reinforcement ratio $\rho_{s,min,V}$ is [UFC 3-340-02 2008, page 1091]

$$\rho_{s,min,V} = \frac{1.25 \cdot \sqrt{f'_{dc}}}{f_{dy}} = \frac{1.25 \cdot \sqrt{3,570}}{70,200} = 0.00106 < 0.00264 \text{ OK} \quad (29)$$

The actual vertical reinforcement ratio meets the minimum and maximum reinforcement ratio conditions.

$$\rho_{s,min,v} = 0.00106 \leq \rho_v = 0.00264 \leq \rho_b = 0.02086 \quad (30)$$

The vertical ultimate moment capacity per foot of wall is [UFC 3-340-02 2008, page 1076]

$$a_v = \frac{(A_{Vs} \cdot f_{dy})}{(0.85 \cdot b \cdot f'_{dc})} = \frac{(0.307 \cdot 70,200)}{(0.85 \cdot 12 \cdot 3,570)} = 0.59184 \text{ in} \quad (31)$$

$$M_{Vu} = \left(A_{Vs} \cdot \frac{f_{dy}}{b} \right) \cdot \left(d_v - \frac{a_v}{2} \right) = \left(0.307 \cdot \frac{70,200}{12} \right) \cdot \left(9.69 - \frac{0.59184}{2} \right) = 16,871 \frac{\text{lb-in}}{\text{in}} \quad (32)$$

Determine actual horizontal moment capacity

The actual area of horizontal tension reinforcement steel per foot of wall is 0.307 in^2 provided by 1 number 5 bar reinforcement (5/8-in-diam) on 12-in centers. The actual distance from the extreme compression fiber to the centroid of the horizontal tension reinforcement is

$$d_H = T_c - \left(CC_w + \varphi_{sw} + \varphi_{vw} + \frac{\varphi_{hw}}{2} \right) = 12 - \left(1.5 + 0.50 + 0.625 + \frac{0.625}{2} \right) = 9.06 \text{ in} \quad (33)$$

The actual reinforcement ratio for horizontal tension reinforcement steel is

$$\rho_H = \frac{A_{Hs}}{(b \cdot d_H)} = \frac{0.307}{(12 \cdot 9.06)} = 0.00282 \quad (34)$$

The maximum allowable reinforcement ratio ρ_b is

$$K_1 = 0.85 - 0.05 \cdot \left[\frac{(f'_{dc} - 4,000)}{1,000} \right] = 0.85 - 0.05 \cdot \left[\frac{(3,750 - 4,000)}{1,000} \right] = 0.8625 \quad (35)$$

$$\rho_b = \left(0.85 \cdot K_1 \cdot \frac{f'_{dc}}{f_{dy}} \right) \cdot \left[\frac{87,000}{(87,000 + f_{dy})} \right] = \left(0.85 \cdot 0.8625 \cdot \frac{3,570}{70,200} \right) \cdot \left[\frac{87,000}{(87,000 + 70,200)} \right] = 0.02063 > 0.00282 \text{ OK} \quad (36)$$

The minimum horizontal reinforcement ratio $\rho_{s,min,H}$ is

$$\rho_{s,min,H} = \frac{1.25 \cdot \sqrt{f_{dc}}}{f_{dy}} = \frac{1.25 \cdot \sqrt{3,570}}{70,200} = 0.00106 < 0.00282 \text{ OK} \quad (37)$$

The actual horizontal reinforcement ratio meets the minimum and maximum reinforcement ratio conditions.

$$\rho_{s,min,H} = 0.00106 \leq \rho_H = 0.00282 \leq \rho_b = 0.02086 \quad (38)$$

The horizontal ultimate moment capacity per foot of wall is [UFC 3-340-02 2008, page 1076]

$$a_H = \frac{(A_{Hs} \cdot f_{dy})}{(0.85 \cdot b \cdot f'_{dc})} = \frac{(0.307 \cdot 70,200)}{(0.85 \cdot 12 \cdot 3,570)} = 0.59184 \text{ in} \quad (39)$$

$$M_{Hu} = \left(A_{Hs} \cdot \frac{f_{dy}}{b} \right) \cdot \left(d_H - \frac{a_H}{2} \right) = \left(0.307 \cdot \frac{70,200}{12} \right) \cdot \left(9.06 - \frac{0.59184}{2} \right) = 15,740 \frac{\text{lb-in}}{\text{in}} \quad (40)$$

Determine static properties of the design

Specify modulus of elasticity and Poisson's ratio for steel as 29,000,000 psi and 0.30.

The modulus of elasticity for concrete is [UFC 3-340-02 2008, page 1070]

$$E_c = w_c^{1.5} \cdot 33 \cdot (f'_c)^{0.5} = 150^{1.5} \cdot 33 \cdot (3,000)^{0.5} = 3,321,000 \text{ psi} \quad (41)$$

The modular ratio is [UFC 3-340-02 2008, page 1070]

$$n = \frac{E_s}{E_c} = \frac{29,000,000}{3,321,000} = 8.732 \quad (42)$$

The average reinforcement ratio is

$$\rho = \frac{(\rho_V + \rho_H)}{2} = \frac{(0.00264 + 0.00282)}{2} = 0.00273 \quad (43)$$

The moment of inertia for a slab of unit width is [UFC 3-340-02 2008, page 1071]

$$I_g = \frac{T_c^3}{12} = \frac{12^3}{12} = 144 \text{ in}^4 \quad (44)$$

Using Figure 4-12 of the UFC with $\rho = 0.00273$ and $n = 8.732$, the cracked concrete coefficient (F) is determined [UFC 3-340-02 2008, page 1074].

$$F = 0.015$$

The cracked moment of inertia is [UFC 3-340-02 2008, page 1071]

$$I_c = F \cdot \left[\frac{(d_V + d_H)}{2} \right]^3 = 0.015 \cdot \left[\frac{(9.69 + 9.06)}{2} \right]^3 = 12.36 \text{ in}^4 \quad (45)$$

The averaged moment of inertia is

$$I_a = \frac{(I_g + I_c)}{2} = \frac{(144 + 12.36)}{2} = 78.18 \text{ in}^4 \quad (46)$$

The flexural rigidity of the slab is [UFC 3-340-02 2008, page 528]

$$D = \frac{(E_c \cdot I_a)}{(1 - v^2)} = \frac{(3,321,000 \cdot 78.18)}{(1 - 0.17^2)} = 2.674 \times 10^8 \text{ lb-in} \quad (47)$$

The height-to-length ratio of the RA stopping structure is

$$\frac{H}{L} = \frac{96}{240} = 0.400 \quad (48)$$

Using Figure 3-36 of UFC, the moment and deflection coefficients, β_{1V} , β_{1H} and γ_1 , for a two-way wall with all edges simply supported are [UFC 3-340-02 2008, page 566]

$$\beta_{1V} = 0.12$$

$$\beta_{1H} = 0.043$$

$$\gamma_1 = 0.012$$

Determine actual yield line location and ultimate resistance

The actual moment capacities found earlier are $M_{Vp} = 26,882$ lb-in and $M_{Hp} = 25,615$ lb-in. The following equations are solved simultaneously for the ultimate resistance r_u and the actual yield line location x [UFC 3-340-02 2008, page 574].

$$r_u = \frac{[M_{Vp} \cdot (6 \cdot L - 2 \cdot x)]}{\left[\left(\frac{H}{2}\right)^2 \cdot (3 \cdot L - 4 \cdot x)\right]} \quad (49)$$

$$r_u = \frac{5 \cdot M_{Hp}}{x^2} \quad (50)$$

The system of equations reduces to

$$0 = 2 \cdot M_{Vp} \cdot x^3 - 6 \cdot L \cdot M_{Vp} \cdot x^2 - 5 \cdot H^2 \cdot M_{Hp} \cdot x + \frac{15}{4} \cdot H^2 \cdot L \cdot M_{Hp} \quad (51)$$

$$0 = 2 \cdot 16,871 \cdot x^3 - 6 \cdot 240 \cdot 16,871 \cdot x^2 - 5 \cdot 96^2 \cdot 15,739 \cdot x + \frac{15}{4} \cdot 96^2 \cdot 240 \cdot 15,739 \quad (52)$$

$$x = 62.070 \text{ in} \approx 63.861 \text{ in} \quad (53)$$

The ultimate elastic resistance of the RA stopping structure is

$$r_u = \frac{[M_{Vp} \cdot (6 \cdot L - 2 \cdot x)]}{\left[\left(\frac{H}{2}\right)^2 \cdot (3 \cdot L - 4 \cdot x)\right]} = \frac{[16,871 \cdot (6 \cdot 240 - 2 \cdot 62.070)]}{\left[\left(\frac{96}{2}\right)^2 \cdot (3 \cdot 240 - 4 \cdot 62.070)\right]} = 20.43 \text{ psi} \quad (54)$$

$$r_u = \frac{5 \cdot M_{Hp}}{x^2} = \frac{5 \cdot 15,739}{62.070^2} = 20.43 \text{ psi} \quad (55)$$

The elastic deflection of the RS stopping structure at ultimate elastic resistance is [UFC 3-340-02 2008, page 528]

$$X_e = \frac{\gamma_1 \cdot r_u \cdot H^4}{D} = \frac{0.012 \cdot 20.43 \cdot 96^4}{2.674 \times 10^8} = 0.078 \text{ in} \quad (56)$$

The elastic stiffness of the RA stopping structure is [UFC 3-340-02 2008, page 529]

$$K_E = \frac{r_u}{X_e} = \frac{20.43}{0.078} = 261.9 \frac{\text{psi}}{\text{in}} \quad (57)$$

Determine direct shear capacity of concrete

The direct shear capacity of the concrete near the supports is [UFC 3-340-02 2008, page 1083]

$$V_d = 0.16 \cdot f'_{dc} \cdot b \cdot d_H = 0.16 \cdot 3,300 \cdot 12 \cdot 9.06 = 57,404 \text{ lbs/foot of wall} \quad (58)$$

The actual shear forces per foot of wall at the roof, floor and ribs are [UFC 3-340-02 2008, page 582]

$$V_{sVr} = \frac{3 \cdot P_s \cdot y \cdot (2 \cdot L - 2 \cdot x) \cdot 12}{(6 \cdot L - 2 \cdot x)} = \frac{3 \cdot 15 \cdot 96/2 \cdot (2 \cdot 240 - 2 \cdot 62.070) \cdot 12}{(6 \cdot 240 - 2 \cdot 62.070)} = 7,010 \text{ lbs/foot of wall} \quad (59)$$

$$V_{sVf} = \frac{3 \cdot P_s \cdot (H - y) \cdot (2 \cdot L - 2 \cdot x) \cdot 12}{(6 \cdot L - 2 \cdot x)} = \frac{3 \cdot 15 \cdot (96 - 96/2) \cdot (2 \cdot 240 - 2 \cdot 62.070) \cdot 12}{(6 \cdot 240 - 2 \cdot 62.070)} = 7,010 \text{ lbs/foot of wall} \quad (60)$$

$$V_{SH} = \frac{3 \cdot P_s \cdot x \cdot 12}{5} = \frac{3 \cdot 15 \cdot 62.070 \cdot 12}{5} = 6,704 \text{ lbs/foot of wall} \quad (61)$$

The maximum shear force per foot of wall is

$$V_u = \max\{V_{SVr}, V_{SVf}, V_{SH}\} = 7,010 \text{ lbs/foot of wall} \quad (62)$$

The direct shear capacity of the concrete is greater than the shear forces in the concrete.

$$V_d = 57,404 \geq V_u = 7,010 \quad (63)$$

Determine dynamic response of the RA stopping structure

The maximum dynamic displacement of the RA stopping structure and its natural period of vibration are determined based on the RA stopping geometry, its properties, and its ultimate resistance. The elastic load mass factor, $K_{LM_elastic}$, is determined using Table 3-13 of UFC [UFC 3-340-02 2008, page 595] and the RA stopping dimensions L and H. For all RA stopping structures, the four sides are simply supported.

The length-to-height ratio of the RA stopping structure is

$$\frac{L}{H} = \frac{240}{96} = 2.500 \quad (64)$$

From Table 3-13 of UFC, the elastic load mass factor for a two-way wall with all sides simply supported is [UFC 3-340-02 2008, page 595]

$$K_{LM_e} = 0.79$$

The yield line location to length ratio of the RA stopping structure is

$$\frac{x}{L} = \frac{62.070}{240} = 0.259 \quad (65)$$

From Figure 3-44 of UFC, the plastic load mass factor for a two-way wall with all sides simply supported is [UFC 3-340-02 2008, page 593]

$$K_{LM_p} = 0.595$$

The effective load mass factor is the average of the elastic and plastic load factors.

$$K_{LM} = \frac{(K_{LM_e} + K_{LM_p})}{2} = \frac{(0.79 + 0.595)}{2} = 0.693 \quad (66)$$

The effective unit mass is

$$m_e = \frac{\rho_c \cdot T_c}{g} \cdot K_{LM} = \frac{150 \frac{\text{lb}}{\text{ft}^3} \left(\frac{1 \text{ ft}}{12 \text{ in}}\right)^3 \cdot 12 \text{ in}}{32.2 \frac{\text{ft}}{\text{sec}^2} \frac{12 \text{ in}}{1 \text{ ft}} \left(\frac{1 \text{ sec}}{1000 \text{ ms}}\right)^2} \cdot 0.693 = 1,868.2 \frac{\text{psi-ms}^2}{\text{in}} \quad (67)$$

The natural period of vibration is [UFC 3-340-02 2008, page 591]

$$T_N = 2 \cdot \pi \cdot \left(\frac{m_e}{K_E}\right)^{0.5} = 2 \cdot \pi \cdot \left(\frac{1,868.2}{261.9}\right)^{0.5} = 16.8 \text{ ms} \quad (68)$$

Response chart parameters are calculated as follows.

$$\frac{r_u}{P_d} = \frac{20.43 \text{ psi}}{15 \text{ psi}} = 1.362 \text{ and } \frac{T_r}{T_N} = \frac{100 \text{ ms}}{16.8 \text{ ms}} = 5.95 \quad (69)$$

From Figure 3-58 of UFC, the ratio X_m/X_e is found as 0.75 [UFC 3-340-02 2008, page 626]. The maximum dynamic displacement is

$$x_m = x_e \cdot \frac{X_m}{X_e} = 0.078 \cdot 0.75 = 0.059 \text{ in} \quad (70)$$

The maximum dynamic displacement is less than or equal to the maximum elastic displacement, and therefore, the design is elastic.



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