Mining, Metallurgy & Exploration (2022) 39:2311–2331
https://doi.org/10.1007/s42461-022-00682-1

REVIEW

Evaluation on Underground Refuge Alternatives and Explosion Survivability: a Review

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Received: 18 March 2022 / Accepted: 20 September 2022 / Published online: 24 September 2022

Abstract
Underground mining environments bring occupational health and safety issues with some severe dangers such as mine disasters like explosions. During such events, miners might escape using main access openings, or find a safe haven like refuge alternatives (RAs) to wait and be rescued and evacuated to the surface. In this paper, RAs are explained with their early and current applications. A classification as permanent and portable is explained depending on the conditions and their abilities. This classification is followed by the utilization and survivability of RAs with the requirements and recommendations of the main mining countries. Based on the utilization and survivability constraints, basic human requirements, waiting for a rescue team, and the required physical specifications of RAs during the events are analyzed in detail for various countries with their regulations. Among these, the specification, resistance to the explosion, is discussed in particular, and the studies in the literature are examined in terms of structural deformation. The highest deformed zones, the beneficiation of reinforcing steel components such as stiffeners, and the simulation approaches are investigated through this review.

Keywords Refuge alternatives · Refuge chamber · Built-in place · Mine explosion · Numerical analysis

Abbreviations

ALE	Arbitrary Lagrange-Eulerian algorithm
BIP	Built-in-place
CABA	Compressed air breathing apparatus
CO_2	Carbon dioxide
CO	Carbon monoxide
FSI	Fluid-solid interaction
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety & Health
O_2	Oxygen
RA	Refuge alternative
SCSR	Self-contained self-rescue device
USBM	US Bureau of Mines
WVOMHST	West Virginia Office of Miners' Health, Safety, and Training

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1 Introduction

Underground mining environments bring with them the issue of occupational health and safety. Accidents and emergency events in underground mines can result in serious worker injury or fatality, with underground mine fires, explosions, and floods posing the most severe risks to worker occupational safety and health worldwide [1–4]. Underground mine fires and explosions can vary greatly in intensity and duration depending on the mining conditions. In metal/stone mines, the major fuel source for fires or explosions is equipment that can only burn with the presence of fuel, tires, and other combustible materials, which means the duration of danger will not last for more than a few hours. After the combustibles were consumed and ventilation has removed the products of combustion, the mine will resume having a livable environment [2, 5, 6].

However, the mine fire and explosion events might be more severe in coal mines, as the coal itself can be a nearly unlimited source of fuel to sustain fires for a long duration. The spontaneous combustion of methane gas from coal seams poses an additional hazard for underground mine workers, as methane gas is combustible at certain concentrations when introduced to the mine atmosphere. Underground mines, especially coal mines, are inherently hazardous, thus posing a risk to worker's health and safety. For this reason, emergency response plans with a systematic self-escape plan and self-rescue strategy are needed for underground mining operations to increase the survivability of workers during emergency events such as fires and explosions. In the events where the mine environment is hazardous, miners may be in a position of disarray or injury; thus, the escape strategy plays a crucial role in preventing fatalities or injuries to miners [2]. Gaab [7] indicates that time, on the order of minutes, is very important during mine evacuations for the miners to be able to escape safely. Miners usually have two options to survive: main access openings like ramps, mine shafts, or other underground mine ways to escape, or some form of artificial safe area, RA, which can provide a habitable environment for some limited time for rescue teams to reach the trapped miners and evacuate them to the surface. Plans for self-escape from mines must be included in emergency response protocols, as well as rescue plans that allow miners to pass through environments that might not be able to support life within the scope of evacuation plans. Miners must put on their breathing equipment to self-escape to the surface so they can breathe clean air. Miners must switch to a new SCSR or refill their CABA at changeover/refill stations located along the escape route because SCSR and CABA both have a limited air supply that lasts, on average, 1 h [6]. Mine safety laws mandate that all mines must have usable escapeways to support this escape plan. They must be kept apart from one another so that miners can still self-escape through the other escapeway in the event of an incident in the first. To accomplish this, all crosscuts or cut-throughs that connect these escapeways must have stoppings [8]. It is stated by the refuge station report [2] that self-escape systems should be firstly considered for the miners to reach the surface of the underground mine or any other place rather than rescue plans. On the other hand, the report [2] also points out that, in such an emergency, a miner's natural instinct is to "run" and find safety as quickly as possible (such as a fresh air base or the surface), which is considered to be typically the best course of action. This is particularly important in an underground coal mine because, in the event of a fire, the coal seam walls of underground roadways are themselves fuel and may burn for a very long time once ignited. Nevertheless, miners evaluate their own conditions and the possible scenarios they may face and opt for whichever alternative they perceive as the best for them. Also, Hall and Margolis [8] state that miners did not always have the chance of escaping from a mine accident, and that it was not always possible to reach the trapped miners by rescue teams within a sufficient time to ensure their survival. Hence, the need for a safe place in underground mines that provides some necessities to miners such as time, rest, life-saving equipment, and communication until they are rescued stands out as a problem to be solved and developed in cases where self-escape is not a realistic option. The circumstances may depend on various parameters; for example, the location of the miners and safe havens due to large areal extents of mines. Although refuge havens are acceptable and oftentimes useful areas during emergency events, the opinions of miners themselves tend to favor self-escape over waiting in a safe haven, since it is often believed that rescue efforts may be unlikely or impossible in deep/large mines, or those with explosive or toxic gasses [1].

As the concept and implementation of RAs have evolved through multiple periods, countries, and mining districts, there are many iterations of distinct designs and sizes which are intended to provide a sealed, safe shelter that is separate from the hazardous mine environment during an emergency. The term "refuge alternative" is a blanket term that refers to the following, among others: mine refuge, refuge chamber, rescue chamber, mine safe haven, designated place of safety, gathering point, and staging area used by various countries, states, and mines [3].

A classification of RAs is also defined by the Office of Mine Safety and Health [9] as chambers and BIP shelters covering safe havens, safe rooms, and bulkhead-based refuges. To this report, chambers are used for rigid or inflatable vessels manufactured off-site and placed at a strategic point according to an emergency plan, however, in place-shelters can be built in the mine through the construction of bulkheads that separate an allocated part of the mine openings from the potentially hazardous environment.

2 Refuge Alternatives

Safe places for miners to survive during emergencies are known as RAs; refuge stations, havens, or bays, which could be preplanned and located in certain areas according to the emergency response plans, as well as barricades that could be constructed spontaneously during emergency events [2].

Barricading is the practice of creating a suitable isolated area apart from the polluted atmosphere due to mine fires, explosions, or inundations of gasses by changing the ventilation flow pattern, often constructed by miners themselves during an emergency (Fig. 1). Barricades may consist of concrete block walls, lumber, or sandbags with claying of joints, or in the form of brattice cloth fastened to the ribs, roof, and floor, with the intent of achieving a sub-section of the mine with a breathable atmosphere [2, 9, 10].

The concept of safe havens in underground mining was first put forward by the USBM to tackle a mine fire, over a hundred years ago [12, 13]. Miners were trained how and where to build a barricade with training programs by USBM specialists and some operators to increase their familiarity with mine fire and explosion events [10, 14]. Surveys between the years 1940 and 1980 show that 127 miners had

Fig. 1 A brattice cloth barricade with a foam sealing agent at the boundaries [11]

been saved by barricading; thus, it was deemed as a significant shelter for entrapped miners [14]. However, the MSHA report of the investigation indicates that improper barricading is one of the reasons behind the Sago mine fatalities and only one miner survived while CO poisoning killed 11 barricaded miners. It is also stated by Halim and Brune [6] that miners would suffocate to death from CO_2, even if it is airtight and suitably located in the fresh air. Therefore, barricading was not effectively thought of as a reliable RA [15].

Technological improvements led to the improvement of the barricading technique to include more advanced constructions for refuge areas to increase the survival time of miners waiting for rescue. It is reported that some coal mines operating in the late 1930s and 1940s successfully utilized small refuge chambers which aided in the rescue of several miners [16, 17]. In the early 1970s, a team leader of the Gold Fields Mine in South Africa utilized the compressed air line at the end of a development tunnel to create a positive-pressure, fresh air haven for a team of miners during an underground mine fire. After this event, the use of refuge systems has grown and evolved in South Africa. By the 1970s and 1980s, the use of refuge stations had become commonplace in the metal mines of Ontario, Canada, and by this time, a total of 12 refuge chambers were designated in England [2].

Several reports, the 1972 Robens report in the UK, the 1995 Leon Commission in South Africa, and the 1996 Wardens Inquiry in Australia catalog mine incidents and fatalities, the inferences of which highlight the lack of legislation and regulations for this time period regarding miner escape and rescue strategies [8, 18, 19]. However, owing to the observed benefits of the emerging use of refuge chambers and safe havens, certain countries had set up some regulations to be followed by underground mines regarding the compulsory utilization of RAs. Apart from the other main countries discussed subsequently, Canadian legislators changed the Mining Act in 1932, 2 years after the Hollinger Fire disaster, which resulted in 39 worker fatalities. This new Act requires the construction of a RA only if the chief inspector of mines considers it to be necessary [20]. The RA provision was then adopted by the various provinces (Ontario, Alberta, British Columbia, Nova Scotia, New Brunswick) in different years (between 1980 and 2003). South Africa governed a similar mandatory regulation in late 1986 after the Kinross disaster. In 1994, Japanese lawmakers signed the Coal Mine Safety Regulation into law [4]. In 2001, a related regulation has been introduced also in Queensland, Australia [2] while the first signals of needs towards the rescue operations were noticed after the case at Moura no. 2 mine in 1994 [1]. In the USA, three accidents occurred with a total of 47 fatalities in a row in the year 2006; these were the Sago Mine Explosion (West Virginia), the Aracoma Alma Mine Fire (West Virginia), and the Darby No. 1 Mine Explosion (Kentucky) [21]. These disasters triggered the construction of the Miner Act of 2006, requiring that breathable air must be supplied to all miners for 96 h after the accident [5, 22]. This regulation was followed by a law passed by WVOMHST in 2007 with the provision for the use of refuge shelters [23]. In China, the requirements of refuge systems for the safety of underground coal miners were regulated for the construction of a complete safety framework, known as the "six systems" (covering underground monitoring systems, precision positioning of underground workers, emergency escape systems, compressed air self-rescue systems, water supplies, and communication networks) by the State Administration of Coal Mine Safety in China by 2010 [24].

3 Permanent and Portable Safe Havens

RAs can be considered in two main categories: permanent (fixed) (Fig. 2) and portable safe havens (mobile) (Figs. 3 and 4) in underground coal mining [10] or, according to Jakeman [1], static and portable. If this classification is scrutinized, the Office of Mine Safety and Health [9] expresses the building up of permanent ones such that they are in-place shelters, and there are two methods to establish a permanent safe haven: (1) via the installation of bulkheads at both ends of a crosscut or (2) installing a bulkhead to enclose dead-end heading, creating an isolated area with steel bulkheads, grout walls, and block walls [1]. Workplace Safety North [20] stipulates in the mine rescue refuge station report that they must be excavated in the competent rock and must be sealed to prevent any possible connection through joints, cracks, or fissures in the walls. Some crucial needs (like fresh air, food, water, carbon dioxide scrubbers, and toilet) must be provided for the waiting duration of the miners and can be supplied by a borehole drilled from the surface to the

Fig. 2 Permanent safe haven [25]

Fig. 3 Steel-structured safe haven [29]

Fig. 4 Inflatable safe haven [28]

sealed and isolated area, while fresh air can be ensured via compressed air lines [2]. In cases where a surface borehole is not practical, some essentials (food, water, etc.) are required to be stocked in the refuge station. Regulations of different countries vary in the recommendation of minimum time to provide some necessities; for example, the Office of Mine Safety and Health recommends a minimum of 96 h for such kinds of needs [9]. In addition to those survival needs, the structure has to be some certain resistance and strength to withstand the events of mine fires and explosions. These requirements will be discussed in detail in the following parts of this study.

Portable safe havens are the other alternatives that offer some flexibilities to mine operators as portable refuge stations have the advantage of mobility and ease of placement. The location of portable refuge stations can be arranged according to the production schedule and underground mine design. Movable refuge stations have the added advantage of limiting the costly and time-intensive construction associated with BIP RAs, as they can be used repeatedly in different areas within the mine, and require less space for installation [10]. Mobile refuge chambers have similar basic requirements to their permanent counterparts. According to Workplace Safety North [20], to ensure that portable refuge stations will remain stationary, they should be positioned on solid ground with a sturdy base. A portable station can be thought of as "permanent" in status, but logistically they are moveable. The features and contents are the same as in a permanent refuge station. In some countries, portable or temporary shelters are used as first aid stations or as minor points to help miners reach permanent safe havens in mines [2]. Despite the advantages of mobile refuge chambers, significant expertise is required, as well as practical knowledge in the design and use of these systems during the dynamic working area to maintain a sustainable environment in case of an emergency event [26].

Portable safe havens are in two types commonly: one is steel-structured walk-in chambers with certain explosion resistance, and the other is manufactured rigid or inflatable vessels placed in a steel skid container that allows it to be moved around in an underground coal mine [9]. Mitchell [5] describes the two types of mobile refuge chamber as hard-walled, having walled constructed from A46 steel, and soft-walled, consisting of flame-retardant inflatable material (see Figs. 3 and 4). Those chambers were claimed as a new technology by Margolis et al. [27] for the date 2011 among RAs to reduce the risks of severe injuries and losses during underground mine emergencies with the same objectives of providing essential needs for up to 96 h such as fresh air, food, water, temperature, humidity, communications, and light. While hard-walled refuge chambers have the significant advantage of explosion resistance to some extent depending on the size of surface area, the reinforced steel walls may increase the cost dramatically when compared to their inflatable counterparts, and the decision between the two options is generally a function of the mining environment and intended usages for the refuge chamber.

In the utilization of these RA types, there are some advantages and disadvantages to define the RA preferences according to mining conditions. In this manner, Trackemas et al. [30] indicate these positive and negative aspects of permanent and portable RAs over each other due to the construction differences, space available, clean air supply, and greater quantities of supplies. Some potential positive aspects in comparison, which come with the utilization of BIP RA, are as follows [30]:

- In order to guarantee that the refuge has breathable air upon entry and to prevent contaminated air from entering the refuge when miners enter, it is crucial to keep the refuge's interior under positive pressure when it is not in use. Certain alternative refuge designs could contaminate the main chamber upon entry. Purging is a typical requirement to prevent fire or explosions where explosive and flammable materials are present. Purging the airlock and main chamber is necessary to test the removal of harmful gasses. Before people remove their breathing apparatus after entering, the interior volume must be purged to reduce the harmful gas concentrations to a tolerable level. Since the supply of fresh air is the primary concern in that assessment, the need for RA purging is likely to be reduced or eliminated in a BIP RA with a constant supply of fresh breathable air. Prior to entering the shelter, it may be possible to create positive pressure with clean breathable air, which would eliminate the need for purging. Also, CO_2 scrubbing is not required in a BIP RA with a continuous supply of fresh breathable air, as it is in an occupied portable RA with minimal or no air exchange capability. Consequently, in compared to a mobile RA, the number and order in which miners arrive at a BIP RA are far less crucial because purging is rarely required, and thus the availability of purge air is not as critical as it would be for a mobile RA.
- Learning how to operate a RA for a miner is an important issue: thus, BIP RAs with a steady supply of breathable air have less operating requirements than portable refuge options; thus, it is easier to learn how to use them for the miners.
- Communication and personal supplies are also other concerns on benefit and drawback comparison of RAs; A BIP RA's communication system can be built to have a higher chance of surviving an explosion or fire. A reliable communication system could, for example, be provided to the BIP RA from the surface via a borehole or a protected compressed air-line. BIP RAs can be made larger and provide more available room for refuged miners than mobile RAs, allowing more food, water, and personal comforts to be included in the shelter.
- Compared to a mobile RA, the number and sequence of miners arriving at a BIP RA are much less crucial because purging is typically not necessary and the availability of purge air is not as crucial as it would be for a mobile RA. In addition, even if some contaminated air from outside enters the RA during miner departure, there is enough breathable air available to keep the RA habitable in the event that some miners must leave a BIP RA while others must remain.

On the other hand, there are some potential drawbacks of BIP RAs over portable RAs, as follows [30]:

- In comparison to using mobile RAs, the cost of current BIP RA designs would be prohibitive if they had to be kept within 1000 feet of the active mining face. However, much more cost-effective designs will likely emerge if the use of BIP RAs is more widely accepted.
- BIP RA stopping/door devices that are either inexpensive enough to be abandoned in place or that can be disassembled, transported, and rebuilt at a new BIP RA site closer to the face will need to be designed. However, it should be noted that this disadvantage brings with the positive outcome of that many RAs left behind are needed and can be used as way stations.
- The advantage that BIP RAs have continuous clean air might require detailed planning and significant cost while the supply of air is provided via a protected compressed air line and a borehole to the surface.
- Locating BIP RAs further away from the face than the present requirement of 1000 feet or fewer could make it more difficult for injured miners to go to the RA on their own or with help.

4 Survivability of Safe Haven

Some certain conditions and factors must be met to provide a survivable and sustainable area for the miners in the case of several hazardous conditions in addition to fires or explosions, such as blasting, flooding, inadequate ventilation, mud-rush and water rush, gas outbursts, geotechnical stability and seismicity, dust, and contaminated atmosphere. As discussed earlier, the emergency plans should cover both self-escape and rescue plans, and the self-escape systems should be firstly taken into account to reach the surface; thus, it cannot be concluded that the use of an RA is superior to the escape option for any abovementioned circumstances. The safety of a miner in the context of RA utilization can be examined in two stages: firstly, the period up which a miner can reach a RA, and secondly, the process of entering and waiting within a RA. The first stage requires the training of the miners to safely travel to the RA area in case of an emergency event, known as a "muster point" by Jakeman [1]. This phase covers the necessary accessibility and high visibility associated with reaching and finding the RA in low visibility conditions via cone/lanyard ropes, audio-visual systems, and signage with fluorescent directional signs in the openings [1, 20].

Once sheltered within the RA, several design parameters are necessary to ensure (1) the miners are protected from the impacts of events outside the RA, and (2) the needs of the miners are met while inside the RA.

While waiting for the arrival of a rescue team, the miners will need some basic human requirements, which a RA should include, such as an SCSR, first aid equipment, firefighting equipment, food, potable water, chemical toilets, blankets, power supply, lighting, spare lamps, communication by intercoms or telephones, environmental control units (air conditioner or heater, humidity absorbent), escape plan of the mine, atmospheric monitoring equipment, nails, brattice, some housekeeping items including garbage cans and bags, towels, soap, cups, small fridge, microwave, and toaster oven depending on the space [1, 2, 4, 6, 9, 20, 31–33] (see Fig. 5).

According to Western Australia Guidelines [35], the status of a refuge chamber can be described with three levels: (1) standby, (2) externally supported, and (3) stand-alone. Chambers go into standby mode when there is no emergency, and there are no survival systems turned on. The emergency power pack is kept charged, and chamber monitoring and communication systems are turned on if they are available. When there is an emergency but no disruption to normal electrical, pneumatic, or potable water systems, a chamber is expected to operate under externally supported conditions. These services, if offered, are available for the chamber's continuous support. When a chamber is cut off from usual exterior services, it is said to be "stand-alone." The RA should be completely self-contained to secure the life of its occupants in the least stressful way possible.

In addition to the requirements inside, RAs must have acceptable outer design specifications to protect the miners from the impacts of events outside the RA [1, 2, 9, 20, 39]. The Office of Mine Safety and Health [9] states these specifications address the following issues: establishing and maintenance of an environment that will support life, maintaining of structural integrity through an initial explosion and any potential subsequent explosions, as well as location and positioning of RA. Other than the "strength" parameter, the Office of Mine Safety and Health [9] gives a list of these specifications based on the literature values, the results of practices in other countries, and the information obtained from the experience of other non-mining disciplines. The strength parameter, on the other hand, depends on the explosion tests performed for this purpose at the Lake Lynn Laboratory of NIOSH. The Western Australia Guidelines [35] and Workplace Safety North [20] have additionally taken into consideration robustness, sealing, capacity, and duration.

A breathable atmosphere needs to be established and maintained to support the life in a RA even if the environment outside the RA is non-respirable for workers. Workplace Safety North [20] asserts different methods for ensuring the maintenance of a breathable atmosphere within the RA, such as stipulating a minimum dead air space volume, oxygen candles, air recirculation to remove the undesirable gasses (CO, CO_2, H_2O, etc.), and O_2 supplies. However, some other parameters, such as the duration of sheltering for workers, entrance, capacity, and structural integrity, are indirectly related to providing a suitable atmosphere.

Duration is the time that a RA is capable of providing a safe and livable environment for miners at maximum capacity. The duration requirements of RAs vary with the country's regulations and recommendations: 24 h in Canada, 36 h in Western Australia, and 96 h in the USA and China [9, 20, 35, 37].

Robustness is the term used in the Australian guideline to explain the mountings of the chamber and its equipment. A refuge chamber should be built to accommodate the

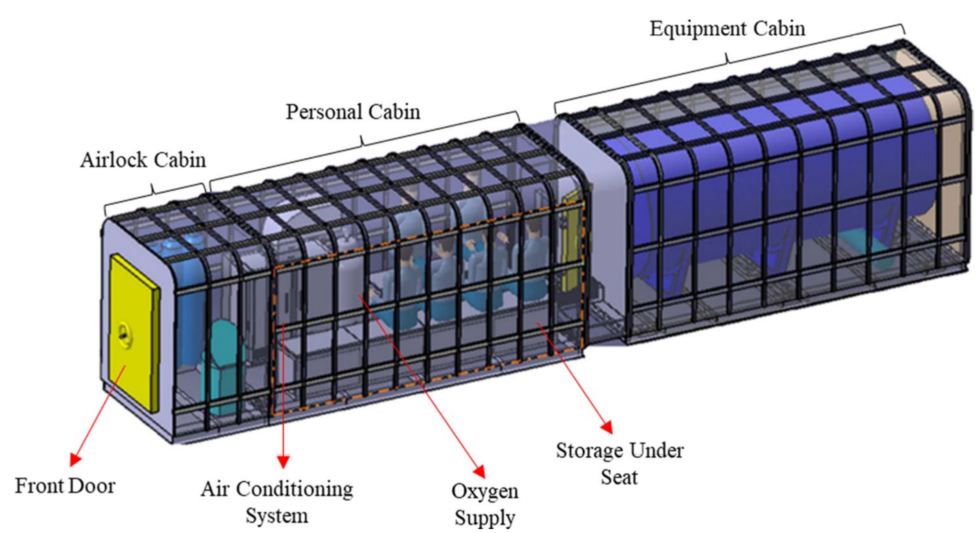

Fig. 5 A schematic view of a refuge chamber [34]

situations under which it will be utilized and transported. Because underground roadways are sometimes rough, and the equipment installed inside and attached to the chamber is frequently damaged by sudden movement, the chamber and its equipment mountings should be sturdy [35].

The capacity of a refuge station should be determined by the maximum number of people expected to work or visit in the region. Additional numbers that may visit the location at different times should be taken into account (e.g., geologists, visitors, inspectors, trainees, and mine management). To meet the possibility of such people being in the region from time to time, the station should have at least double the number of locally operational staff, or a policy (e.g., shift plan, entrapment tagboard) should be created to limit personnel in the area so that all trapped personnel should find seating in the chamber [20, 35].

Workplace Safety North [20] affirms a series of requirements for the entry of steel-structured RA. A double entrance door system with an airlock should be used for entry. The airlock allows for a simple and safe transition from a contaminated to a clean environment. Steel doors and door frames that open and close properly and are fastened are required. Doors must be airtight, and if a pressure leak occurs, clay or another sealant must be readily available to reestablish the refuge station's airtight seal from the outside environment. Refuge stations must have the ability to sustain both positive pressure and hold a vacuum. The airlock and the doors should be large enough to provide simple access [20]. According to Workplace Safety North [20], the pressure within the airlock should not exceed 500 Pa. To relieve air pressure and expel stale air from the refuge chamber, doors should be supplied with a small vent that can be sealed and opened by hand.

The Western Australia Guidelines [35] point out that the chamber construction may bend during movement among underground locations, causing door frames to distort and welded seams to break. The structure of the chamber should be robust enough to withstand this flexing and the harm it can cause. The sealing of a chamber can also be affected if it is damaged by contact with mine vehicles. The use of substantial bollards or pillars will preclude close access to permanent and portable chambers. In addition to the sealing feature of the refuge chamber door, in this guideline, a window is a prerequisite on a refuge chamber's door as a practical and basic addition, allowing for visual contact between the inside and outside of the station; for example, it allows personnel inside the station to observe someone attempting to enter and aid if necessary [20, 35].

One of the most essential features of RAs is maintaining structural stability during explosion and fire events. As stated by the Office of Mine Safety and Health [9], it is difficult to define an optimal design for an RA due to numerous factors associated with mine emergency events, especially those involving explosions. Mine explosions are complex events, our knowledge of which is subject to, the interaction between explosions and mine environment, conflicting data in the literature, and the limitation of observations in the environment after explosions. Therefore, the Office of Mine Safety and Health [9] proposed a requirement that RAs be constructed to withstand a blast overpressure of 15 psi for 0.2 s before deployment and be able to withstand a temperature of 300°F for 3 s in the initial explosion. On the other hand, in Canada, the recommendation towards fire resistance indicates that the material to construct a permanent refuge station should be made up of material with a 1-h fire-resistance rating and should resist burning and be able to withstand high temperatures [20].

The effects of these emergency events are significantly dependent on the distance between the hazard (fire, explosion) and the RA; that is why another issue regarding these havens is the selection of the most suitable location for installation [38]. The RA is a part of or is located within the existing mine infrastructure, and as such, the relative location of the RA to the mine workers is a critical element of a mines' escape and rescue plan. The travel time of workers from their normal working areas, excavation dimensions, and the expected level of smoke during a fire event all must be considered when placing an RA [39]. The position of each active face's RA is critical, but pinpointing the right location is difficult. It would appear that placing the refuge option as near to the face as possible would be helpful, in terms of reducing the time and effort required for miners to reach it; however, locating the RA closer to a potential explosion source increases the risk of damage by overpressure or flying debris from the initial explosion. It is also proposed that the RA should be located further away from the face to encourage and facilitate escape instead of choosing an RA. In addition to the initial explosion, the impacts of potential subsequent explosions with varied and possible locations must be considered, Office of Mine Safety and Health [9]. If it is possible, the RAs should be placed away from the intake or return escape way and in crosscuts rather than in dead-ends or entries. The relationship between the likely path of a miner to an RA and the ventilation circuit must be taken into account when placing RAs and devising the safety action plan to ensure miners have the ability to reach the RA while traveling in clean air. It is recommended that the RA should be placed at a minimum distance of 1000 feet from the face, and 2000 feet for some exceptional cases, or 30–60 min of the projected time of travel due to some undesired conditions like the presence of smoke, which take into account slower travel circumstances, by the experimental results of the explosions conducted at NIOSH's Lake Lynn Experimental Mine.

While the Office of Mine Safety and Health [9] provides the distance requirements based on walking tests in mines, the Western Australia Guidelines [35] and Workplace Safety North [20] use fire events to decide safe distances. It is expressed by Workplace Safety North [20] that though a full risk assessment should be used to determine the maximum distance between an active working area and a refuge station, it is advised that a worker traveling at a moderate walking pace take no more than 30 min to reach the nearest RA. The Western Australia Guidelines [35] recommend that a risk assessment should take into account how far a person can walk at a normal pace for the 50% duration time of an SCSR to arrive at the nearest located refuge. However, there is no minimum safe distance stated in either document.

5 Study Areas of Refuge Alternatives

Halim et al. [6] state that the feasibility of using refuge chambers in hard rock and coal mines is significantly impacted by the differences between fires in those mines. Because fires in hard rock mines tend to be short-lived and miners can leave the mine as soon as the fire is out and the mine's air quality has been restored through ventilation, using refuge chambers may be a successful strategy. It is much riskier to seek refuge and wait for rescue in coal mines because of the ongoing fire and explosion risk, raising the question of whether miners should even use the refuge chambers at all. The mine rescue teams might not be able to enter the mine and rescue the miners from the refuges if there are fire or explosion hazards. For instance, during the Pike River disaster in New Zealand in 2010 [40] and the Moura No. 2 disaster in the State of Queensland, Australia, in 1994 [41], numerous secondary explosions prevented rescue efforts. While Halim et al. [6] point out that refuge chambers might not be the best course of action in circumstances like Moura No. 2 and Pike Rive, they also claim that one could argue that the mine rescue teams were able to enter the mine in less than 96 h in other disasters like Upper Big Branch [42]. Halim et al. [6] also exemplify that, however, in the case of Upper Big Branch, most of the miners close to the longwall died instantly from a direct explosion, burn trauma, CO exposure, and were unable to enter refuge chambers. Eight miners attempted to escape by rail, but their mantrip became stuck in the explosion debris, and seven of them succumbed to CO. The 8th miner was able to escape on foot. If the seven miners had been able to find shelter in a refuge chamber, they might have survived. Similar to how the tragedies in Australia and New Zealand show that it might not be possible for miners to enter a refuge chamber, it might also not be possible for mine rescue teams to reach the zone to save sheltered miners.

As the dimensions of the openings and extents of the mines increase, which leads to more complicated emergency plans are required; for example, the rate of survival probability decreases dramatically with the exceeding distance of 2000 m for escape [43]. It should be noted that this study was a computational study, which took into account training (Did the miner don the SCSR properly?), SCSR integrity (Did the SCSR function, or did the miner decide to abandon it?), and oxygen consumption (Did the SCSR provide enough oxygen) so that the simulation was conducted with each change over to another SCSR based on a questionable training success in 1992. This estimated distance can change depending on better training today since the number of SCSR changeovers was the problem. However, it can be inferred that a certain distance might still be a limit for the rate of survival probability, as it is currently 2000-feet distance between the surface and working face to provide an RA according to MSHA's final rule. Due to the varying circumstances of the mine and miners during the events, the details of the safety action plan (RA locations, escape pathways) should be determined through a risk assessment of each mine [44]. Although escape and rescue efforts are becoming more difficult due to excessive distances and egress is the major focus area for emergency management, the utilization of the RA option has increasingly significant importance in such events [4]. Therefore, RAs are a required subsystem of survival tactics and should be improved to provide a reliable provide [26], but it should be noted that self-assisted escape is the primary goal.

In order to make RAs a more reliable and effective tool for miners during emergency events, some uncertainties and risks around the development of RAs should be eliminated. The primary components which constitute a RA have been extensively examined by Huang and Huang [37], who offered a risk analysis model for chamber design. Four main factors were defined in relation to the refuge chamber: (1) general performance parameters, (2) the complexity of operating, (3) the flexibility of the product, and (4) investment cost. It is noted that involving a risk factor of any cost is questionable regarding a topic directly related to human health and safety according to the author's point of view. Within general performance parameters, there are sub-factors, such as structure (physical dimensions, capability of withstanding overpressure and flash fire exposure), respirable air sustenance (harmful gas removal and air monitoring), temperature control, power sustenance, and overall weight. The steps are identifying weights in issues with numerous attributes, evaluating the importance of each attribute's weight, assessing the level of achievement of each attribute, and risk assessment with the goal of evaluating the factors that influence the risk associated with each of the prioritized attributes. This study demonstrates that the capability of withstanding overpressure, the temperature control, the flexibility of the product, and the investment cost are the most essential parameters that are linked to the product development risk and should be given more consideration in technology design. It is also indicated that the capability of oxygen sustenance, carbon dioxide scrubbing, and carbon monoxide scrubbing are very crucial to the effectiveness of the chamber and must be satisfied in all cases.

Various studies have been conducted which relate to the effective design of RAs considering one of the four main factors stated by Huang and Huang [37]. The conducted studies were classified based on their research of interest. While the sustainable atmosphere is the most commonly used research topic for RA improvement [5, 22, 45–51], the other fields regarding RAs are heat-insulating capacity of the chamber and energy consumption of the cooling system [52], buckling analysis of the shell of a refuge chamber [53], optimization and decision-making methodology in design [54], system design [24, 54, 55], phase change according to the heat-dissipating capacity [56], outside environmental monitoring system [57, 58], thermal protective properties of chambers [59, 60], the efficiency of air curtain system barriers [61], heat stress and thermal environment [47, 62], identification of infrared image of refuge chamber [63], and psychology of the miners [64, 65].

As indicated in the study of Huang and Huang, [37], the ability of a RA to withstand overpressure is one of the most critical design parameters and is both directly related to the physical protection of the miners inside the chamber, as well as some indirect consequences. Hence, Li et al. [66] state that to withstand the massive shock waves created by explosions and devastation caused by high temperatures, the refuge chamber's construction must be of explosion and fireproof materials. Refuge chamber doors should be installed to ensure that the chamber can resist sufficient damage in case that a refuge chamber undergoes shock and stress. Thus, during the design and manufacturing stages, some tests should be repeated to ensure that the structure is able to withstand such damages. The exposure of doors to explosion pressures may have indirect consequences as well, for example, sealing can be damaged after the explosion so that the breathable atmosphere might be affected, exposing miners to contaminated air. While explosion doors have been studied in navy ships and submarines disciplines, there are few specific studies directly related RA doors, and it can be said that the deformation of refuge chambers under shock waves due to explosion is a necessary study area for future research considering the unique environment of coal mine explosions.

6 Explosions in Underground Coal Mines

A gas explosion frequently necessitates the simultaneous presence of five components: a flammable gas, fuel entrainment, confinement, oxygen, and a source of ignition [67]. In an underground coal mine, flammable gas commonly refers to methane. As the coal seam is mined out gradually, methane continues to leak into the underground working areas, posing a considerable explosive risk to mine operators in some areas [68]. Methane and coal dust are the two most common types of coal mine explosions. When a buildup of methane gas comes into contact with a heat/ignition source and there is not sufficient air to dilute the gas below the explosion point, a methane explosion occurs. Similarly, fine coal dust particles at a certain concentration in contact with a source of heat can be explosive. Hybrid explosions with a mixture of methane and coal dust are also possible [69]. The explosion process occurs at such a fast rate that it is essentially adiabatic, resulting in a pressure build-up in the local region rapidly rising to a peak value before being released by air expansion. This causes a shock wave to spread in all possible directions [68].

Zipf and Cashdollar [38] stated that within a mine, multiple methane explosions with or without coal dust could occur. A first explosion could happen on the working face, either longwall or room-and-pillar, (2) within a sealed area, or (3) outside the working face, such as at the shaft bottom, bleeder system, or along with the mains. This first explosion has the potential to significantly damage the ventilation system, allowing actively liberating methane gas from the coal seam to build up with no means of dilution, creating a secondary fuel source that is potentially explosive. The subsequent explosions will most likely happen near to the initial one, but they might also happen at long distances from the primary explosion. Zipf and Cashdollar [38] explain this by giving the examples of the Willow Creek mine disaster in 2000, which involved four separate explosions, and the Jim Walters Resources mine disaster in 2001, which involved two explosions. The majority of the fatalities in both cases happened during the second and subsequent explosions and noted that the rescuers died while they tried to reach out to an RA. The size of an explosion is determined by a number of elements, the most important of which are the amount of methane gas available to ignite the explosion and the amount of coal dust involved. Zipf and Cashdollar [38] defined a 3-level criteria as that a "small" explosion has flame travel of fewer than 100 feet, a "medium" explosion has flame travel of several hundred feet, and a "large" explosion has a flame travel of over 1000 feet. Small and medium explosions are likely to disrupt only one working sector, while a large explosion could have a far-reaching impact across the mine. Methane explosions at the face or outby usually range in size from small to medium and travel hundreds of feet. If coal dust is present, the explosion might become "large" and spread thousands of feet.

The crew's chances of surviving an explosion and getting to a refuge chamber — or, ideally, escaping completely — depend on how close they were to the blast. This research [38] is based on the assumption that a medium or large explosion less than 1000 feet away will probably instantaneously kill or severely disable the crew, negating the necessity for the refuge chamber. At any working face, longwall, or room-and-pillar, the same scenario could happen. It is assumed [38] that most of the crew will probably live to enter the refuge chamber if a small to medium explosion happens distant from the crew, which is defined as more than 1000 feet away. The aim is to demonstrate how the initial location of a mine worker can dramatically affect their survival outcomes during an explosion event, along with the intermediate status of the miners for each area (fatal injury, escape, safely entered refuge chamber) (see Table 1).

The study conducted by Zipf and Cashdollar [38] is crucial and fundamental research for understanding the behavior and potential damages of the explosion. In a quantitative aspect of damage on RAs, as mentioned before, the final rule of MSHA [39] requires that US refuge chambers be built to withstand explosion pressure of up to 15 psi (0.1 MPa). According to the Office of Mine Safety and Health report [9], a number of factors make it challenging to design refuge chambers in a way that prevents secondary explosions. The complexity of mine explosions and the way the explosion interacts with the surrounding environment are two examples of these factors. To the report, the most likely locations of an initial explosion can be predicted with some degree of certainty and if there is an ignition source, there could be subsequent explosions, although the location and strength of these are more difficult to forecast [70]. The final rule does not include strength requirements with regard to a second explosion because it is challenging to predict the likelihood and strength of a secondary explosion [70].

Referring to a 15-psi (0.1 MPa) pressure, a free-standing chamber with a cross-sectional area of 4 m^2 may experience a 400-kN force for a brief period of time if it is exposed unilaterally to such an explosion pressure. Weiss et al. [71] tested a 700-kg battery charger under full-scale mine explosion conditions at a static pressure of roughly 0.2 MPa. The charger was thrown approximately 24 m and received a force of 200 kN. Its cross-sectional area was approximately 1 m^2. This experiment casts doubt on any refuge chamber's ability to withstand the direct impact of a mine explosion, especially one that is mobile [6]. The Sago mine explosion was simulated using computational fluid dynamics (CFD) by the US Army Corps of Engineers. According to the simulations, the pressure in a passageway outside of the seal location is greater than 50 psi (0.345 MPa) [72]. In the USA, Germany, and Poland, experimental mine explosion pressure measurements were examined by Zipf et al. [73]. These findings demonstrate that explosions in coal mines can produce pressures higher than 145 psi (1 MPa). There is a chance that a mine explosion will completely destroy both stationary and movable chambers at such high pressures. Considering the circumstances that RA is the last chance for the miners, and since the damage on the RA is more importantly related to the survivability of the miners, the deformation of the chambers at the time of the explosion is one of the required and quantitative research topics for the protection of mine workers. As the researchers in this field agreed on the aforementioned statements, most of the researchers directly focused on quantification of the deformation of RA during the explosion. These studies provide a better understanding of RA response for such a mine disaster consequence as presented in the following section.

7 Deformation Analyses of Refuge Chambers

As the response of RA under explosion is considered critical by several researchers, different approaches have been applied to understand that deformation behavior. These approaches might cover analytical, experimental, and numerical studies. An actual explosion in a full-size roadway might be used in physical explosion experiments. The degree of damage to the refuge chamber following an explosion can be determined, as well as its ability to resist explosion blast pressures. However, it can be costly or unsafe to see the RA's deformation process throughout the experiment. Furthermore, a theoretical understanding of the deformation

Table 1 The relationship between the locations of miners and explosion during mine explosion events and the potential effects on the miners [38]

Crew location	Location of "medium" explosion			
	Longwall (at or near face)	Longwall development (at or near face)	Mains development (at or near face)	Other location along primary escapeway
Longwall	Fatal	Chamber or escape	Escape	Chamber or escape
Longwall development	Chamber or escape	Fatal	Chamber	Chamber or escape
Mains development	Chamber or escape	Chamber or escape	Fatal	Chamber or escape
Inby the explosion	Not applicable	Not applicable	Not applicable	Chamber
Outby the explosion	Escape	Escape	Escape	Escape

process is also difficult to describe [74, 75]. Therefore, it can be considered that a numerical analysis of deformation under explosion might be a robust and advantageous tool to overcome some drawbacks of experimental and theoretical studies.

There are limited studies regarding the deformation of RAs under explosion by numerical analyses in the literature. These studies include an analysis of the general deformation behavior of only refuge chambers as well as some components, such as one segment of the structure separately. The main structural components of a conceptual refuge chamber are indicated in Figs. 6 and 7. It should be noted that the geometry of the chamber was inspired by the one built in the USBM experimental mine in the 1970s. The aim is to demonstrate the main components discussed within the scope of this section; the drawing may exclude some parts which are not in concern of this study. Current designs may differ from this conceptual drawing, for instance, in terms of door geometry, stiffener design, and relief valve.

The analyzed refuge chambers differ in terms of analysis type mainly, and also the parameters involved like the material types and stiffener configuration (Fig. 8). The analysis types might be handled under two methods: these are static and dynamic analyses of the deformation. Stress analysis is studied to analyze structures as part of the general design process. The numerical methods are used for computational analysis. Static analysis is frequently used because it is simple to use to determine the failure status. However, in actual physics, dynamic forces are imposed. Real forces, therefore, behave dynamically. Real and precise phenomena of structures subject to dynamic loads are revealed by transient analysis. However, transient analysis is very expensive and complex by computational means. Therefore, static analyses are preferred for dynamic loading problems as well [76]. In addition to the analysis of RAs, the researchers dealt with either the fully assembled body or only one component focused to be the side-wall, door, and effect of stiffeners on these walls and doors.

It can be easily observed and understood that static loading analysis has received less attention than dynamic analysis since the loading is actually in dynamic mode. The difference in results of dynamic and static loading is discussed

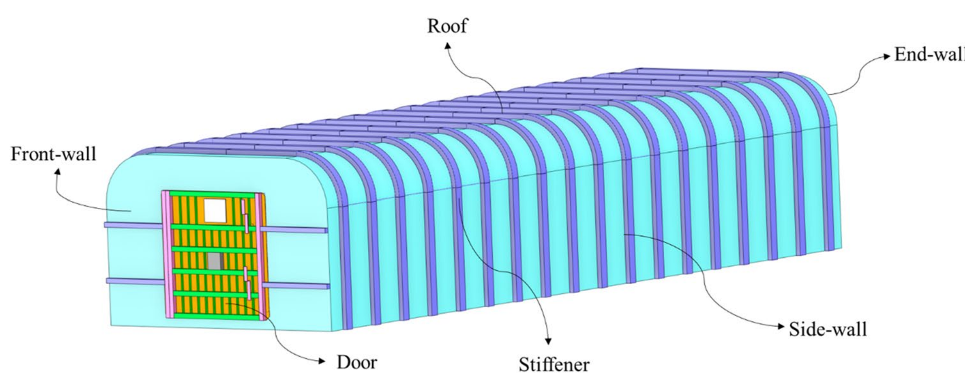

Fig. 6 A schematic view of a refuge chamber with structural components

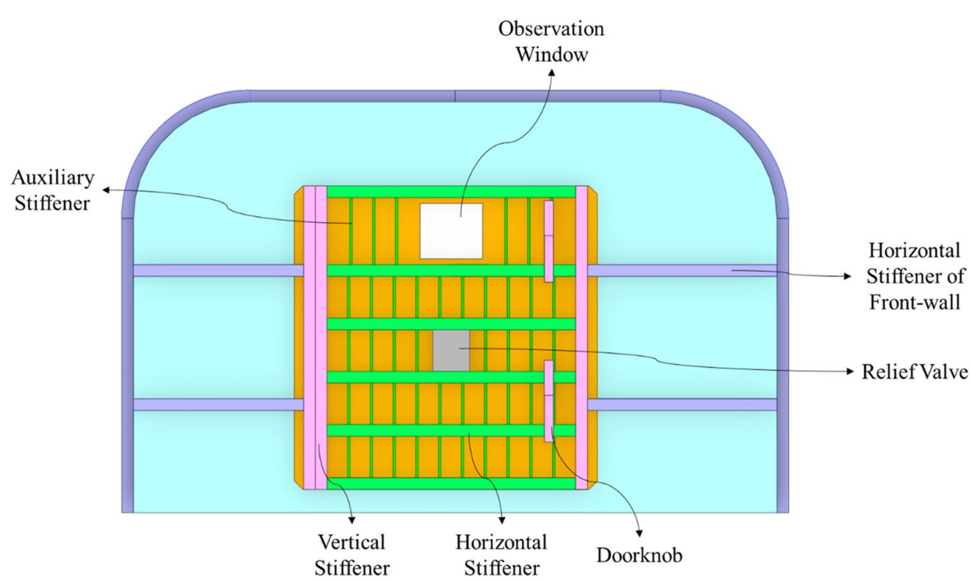

Fig. 7 A schematic view of a refuge chamber door with structural components

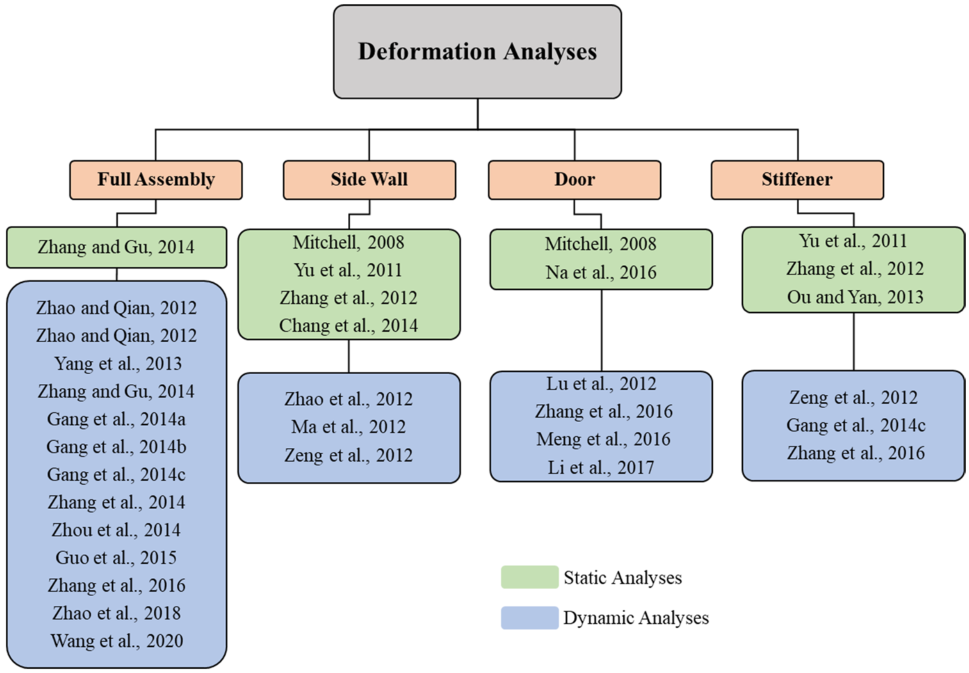

Fig. 8 A classification of the studies contributed to the literature on the deformation analyses of refuge chambers based on the components and analysis type

in the following sections. Most of the studies kept on the fully assembled body of the refuge chamber in a dynamic loading environment. However, a few pieces of research have been conducted on the focused part of the refuge chambers. The door, sidewall, and stiffeners have not been the main concern, which has been inferred that they are crucial components which will be discussed further in the following section as well.

7.1 Static Analyses

Mithcell [5] analyzed the structure of portable safe havens using an analytical solution. This study covers the investigation of both hard and soft walled chambers by the assumption of simply supported beams and flat plates with uniformly distributed loads to examine whether the RAs are capable of withstanding a 15-psi overpressure due to explosion, which is NIOSH's recommendation. A-50 steel components with yielding stress of 50,000 psi are subjected to 15 psi of overpressure, and the results are given in terms of factor of safety calculations. It is found out that they all could meet the requirements of the WVOMHST and MSHA. However, this study can be considered as a preliminary study for the deformation analyses.

Lei et al. [34] conducted numerical analyses of the structural strength of the refuge chamber under various scenarios in China. Three different cases of refuge chamber wall structures (two-layered, single-layered with stiffeners outside, and single-layered with stiffens inside) were investigated to observe and optimize the structure with the goal of producing a lightweight and high-strength structure. A 0.3 MPa of pressure is applied at the side-wall of the chamber with Q-460 steel using MSC Nastran finite element model. The results of the study show that a two-layer wall structure is a promising design for withstanding a single explosion; however, the two-layer structure may prove insufficient for subsequent explosions, as there is less insulation with this construction. In terms of stress and displacement, the results of the study indicate that the chamber wall design with stiffening elements outside the chamber is more effective than designs with stiffening elements inside the chamber walls. In addition, the arc-shaped design for the top of the chamber was found to be advantageous for its ability to resist high pressures and to facilitate drainage of standing water from the roof.

Stiffeners on the refuge chamber structure have been also examined by Zhang et al. [77]. The strengthening effect of stiffeners with different patterns, including no stiffener, parallel to end-wall stiffener only, vertical to end-wall stiffener only, and a combination of both vertical and horizontal stiffeners. It is deduced that horizontal to end-wall structures have better results than vertical ones, and it is also indicated that the best design, as well as the heaviest, is the grid structure with both patterns.

Another effort to simulate the shock wave effect of the explosion in terms of static analysis is performed by Zhang et al. [78] using Solidworks: the refuge chamber which is exposed to a uniform external pressure of 2 MPa on all surfaces, excluding the bottom surface of the chamber. The maximum deformation is obtained to be 21.72 mm at the side-wall of the structure with Q-345 steel. According to the results, it is stated that the side-wall elements had yielded due to the applied external pressure; thus, the simplified static simulation of explosion just demonstrates the effect of external stress on the refuge chamber.

The other investigation on refuge chamber structural stiffeners using the static analysis method was conducted by Ou and Yan [79]. The effect and comparison of T-shaped, rectangular, and square tube-shaped stiffeners on the ability of the chamber to withstand static loading conditions are considered. Q-345 steel-structured sheets with dimensions similar to those of the refuge chamber walls are subjected to a uniform load of 0.15 MPa using ANSYS-Workbench finite element analysis. While maximum stresses are seen on the stiffeners, the maximum deformation results are obtained in the central region of the sheets. The significant outcome of this research is that a refuge chamber wall structure with square tube-shaped stiffeners is the most suitable type of structure to be used in refuge chambers with better bending performance.

Chang et al. [80] studied a new chamber structure with a combined square and circular Q-345 steel and four types of simplified cabin models: (1) square chamber with one end closed and one end of the square flange, (2) square chamber with the square flange at both ends, (3) square chamber with one end of the square flange and one end of round flange, and (4) circular chamber with the round flange at both ends. The models of the cabins are exposed to 0.3 MPa of uniform static loading using ANSYS-Workbench. While the highest maximum deformation and stress are observed in the square chamber with one end closed and one end of the square flange and square chamber with one end of the square flange and one end of the round, the lowest values are obtained in the circular chamber model.

Zhang and Gu [81] investigated the difference between segmented and uniform loading in static analysis using Solidworks with an external pressure of 0.6 MPa. It ıs claimed that the results of the study indicate that the segmented loading scenarios give closer deformation results to those of the dynamic analysis method than uniform loading scenarios. The inference is that the segment loading static analysis method is superior to the uniform loading static analysis method.

Gao et al. [46] analyzed the behavior of refuge chamber doors for the capability of withstanding explosion pressure using static analysis. Flat and curved protective door shapes are compared with two different analytical solutions [82–85], and put forth that while the curved door is more successful in terms of impact, they both meet the 0.3 MPa of blast-resistance requirement stipulated by the State Administration of Coal Mine Safety in China. In addition to the analytical solution, 1-MPa external pressure simulations are performed with the material type of 16 Mn steel using ANSYS static structural analysis. The central part of the door structure shows the highest deformation, similar to the previous studies.

7.2 Dynamic Analyses

The analysis of refuge chambers subjected to dynamic loading conditions is an emerging field, with the oldest available research published in the early 2010s. The limited research studies regarding this topic mainly cover different loading levels and pulse widths, material types, software packages, and various approaches for the simulation of explosions. This section will point out the main objectives and crucial findings of studies involving the dynamic analysis of refuge chambers in the literature, given in chronological order. In addition, comparisons of the studies are summarized in Table 2, including the utilized loading levels, pulse widths and methods, material types, and software codes.

Zhao et al. [86] investigated the effect of shock waves on five sides of a refuge chamber using dynamic analysis in 3D geometry. While five sides of the refuge chamber are subjected to loading, including the capsule and door of the structure at one end. The analysis results show that capsules and doors meet the structural requirements, but the authors suggested an increase of bolt connections and the use of magnetic force for door seals. In addition, a low alloy steel material is recommended for use in cabin and emergency doors.

Ma et al. [87] worked on the resistance of the refuge chamber construction in an explosion is simulated using the explicit time-integration finite element method. The study aims to develop a simulation that serves as a theoretical guide for structural design optimization and enhancement. Based on the results acquired, the parameters of the refuge chambers: the span of the support structure, the thickness of support structure in the side, the amplitude of wave sheet, and the length of wave sheet are found to be important for the explosion resistance.

Zhao and Qian [88] studied the difference in explosion resistance of two distinct types of refuge chambers (single piece and segmented chambers) using 3D models. The results of the study suggest that the central parts of the front and back shells of the single-piece refuge chamber design, where the doors would be located, are the weakest regions and the central parts of sides of the segmented refuge chamber are the weakest zones. The authors state that the one-piece model has a size limitation, and experiences more displacement during dynamic loading events than the segmented type, but does not have the sealing problem between the connections of different segments. The study suggests the use of arc structures and thicker material for the walls to enhance the ability of refuge chambers to withstand dynamic loading.

Table 2 List of the researches regarding the dynamic analysis of the refuge chamber and components under explosion with the main parameters

The studies	Applied load (MPa)	Pulse width (ms)	Loading approach	Material type	Code
Zhao and Qian [86]	0.80	300	Triangular	Q-345	ANSYS LS-DYNA
Ma et al. [87]	1.50	5	Triangular	Q-235A	ABAQUS
Zhao et al. [88]	1.20	300	Triangular	Q-235	ANSYS LS-DYNA
Ceng et al. [89]	0.30	300	Triangular	Q-235	LS-DYNA
Luo et al. [90]	0.60	300	Triangular	Q-460	ANSYS LS-DYNA
Yang et al. [91]	0.60	300	Trapezoidal	Q-235	ABAQUS
Zhang and Gu. [92]	0.60	-	-	Q-345	SOLIDWORKS
Gong et al. [93]	0.60	7	Triangular	Q-235 – Q-345	LS-DYNA
Gong et al. [94]	0.60	7	Triangular	Q-345	LS-DYNA
Gong et al. [95]	0.60	7	FSI	Q-235	ANSYS-AUTODYN
Zhang et al. [96]	0.71	360	FSI	Q-235 – Q-345	ANSYS LS-DYNA
Zhou et al. [97]	0.60	300	FSI	Q-235 – Q-345	LS-DYNA
Guo et al. [98]	0.72	1000	FSI	Q-345	AUTODYN-LSDYNA
Zhang et al. [99]	0.64	500	FSI	Q-235B Q-345B Q-460B	ANSYS LS-DYNA
Meng et al. [100]	0.60	300	Triangular	Q-345	ANSYS LS-DYNA
Li et al. [101]	0.60	300	Triangular	Q-345B	ANSYS LS-DYNA
Zhao et al. [103]	0.60	300	FSI	Q-345B	ANSYS LS-DYNA-AUTODYN
Wang et al. [102]	0.60	2000	FSI	Q-235B	-

Ceng et al. [89] took into consideration only the cabin part, excluding the end sides, of the refuge chamber geometry to analyze the effects of stiffeners and their thicknesses. They suggest that increasing the thickness of the stiffeners and directly welding them to the structure will enhance the strength against explosion shock waves.

Luo et al. [90] focused on the door component of refuge chambers. Different door types are compared: flat-plate, arch, quadrangular, and spherical structure. The flat-plate type is chosen to analyze the dynamic behavior with different thicknesses, including the performances of sealing and stiffeners. According to the analyses results, the maximum deformation is seen on the central zone of the door, and the thickness is an essential parameter on the performance of the door. Some suggestions are also given that the door can be strengthened by changing the material and using stiffeners.

Another 3D geometry of a fully assembled refuge chamber is examined by Yang et al. [91]. In this work, they observe that the highest deformations are seen at the boundary of the front door and the cabin in the front panel, as well as in the central area of the door. In addition, the central zone in the door panel deforms from its original circular shape to that of an ellipse. In order to avoid issues related to deformation in the refuge chamber door under dynamic loading conditions, the authors recommend that the shape of the door structure should be converted from a circular shape to that of an arc and that stiffening elements, especially vertical stiffeners, be welded between the door panel and cabin, a cost-effective measure to greatly increase the strength of the zone.

The only study that compares the static and dynamic analysis on the fully assembled geometry of the refuge chamber is established by Zhang and Gu. [92]. Although there is no detailed information about the analysis such as loading methodology, the authors exhibit the maximum stress and displacement values of both dynamic and static analyses for each member of the chamber structure, including the entry door, emergency escape door, cabin, and stiffeners. According to the given results, the static analysis shows greater deformations than the dynamic analysis, and the other remarkable point is that the highest maximum stresses and displacements are observed on stiffeners.

Gong et al. [93] examined the full-scale geometry of the chamfer-type refuge chamber by explosion analysis. Five external sides of the refuge chamber, excluding the bottom, were loaded simultaneously to conduct numerical simulations and ensure that the cabin's anti-knock impact performance met a set of regulatory requirements of China. The connection between the front door and the cabin shows the highest stress in the results of this study as well. While there is no displacement result shared, the effect of plate thickness is pointed out for the performance of the explosion resistance. Gong et al. [94] compared three different models of refuge chambers with various emergency escape hatch positions using a nonlinear dynamic simulation. The highest maximum stresses are observed at the junctions of the door and cabin for all sides and the central region of the front sides of the chambers in this study as well. A comparison of the effect of different stiffeners on refuge chambers has been conducted by Gong et al. [95]. In a divergence from previous research studies, the authors utilized a TNT equivalent method to simulate the explosion, as opposed to the previously conducted triangular simplification. In addition, the explosion was simulated within a tunnel model, which is a closer approximation to the conditions in which refuge chambers are found. The main difference of this study is that the explosion is generated by an FSI rather than a triangular simplification as done by previous researchers. During the course of the analysis, no elements in the refuge chamber structure were plastically deformed, whereas the inference of this work is external stiffeners are better than interior stiffeners with a square shape for the explosion resistance.

Zhang et al. [96] used a solid–fluid interaction with a mixture of air and methane to simulate the explosion shock wave on a full-scale refuge chamber geometry in a 100-m-long tunnel (Fig. 9a). While the analysis results show that no plastic deformation has occurred in the refuge chamber structure, as did the previously mentioned studies, the maximum stress during dynamic loading is observed at the junction of stiffeners and the front plate of the chamber. Similar to other studies conducted, the largest displacement values are seen on the central zone of the door in the refuge chamber (Fig. 9b). The stress concentrations of all sides of the chamber are also given, and it can clearly be seen that the stresses mainly occur in the connection area of the structures such as the junction of door and door frame, the connection of the observation window, and the bulkhead. According to the results obtained, the researchers claim that the FSI can simulate the methane explosion and the propagation of shock waves, having good agreement with the experimental data. Based on the results, the authors state that the ability of a refuge chamber to withstand blasting pressure relies on a set of critical components, such as the cabin door and the front plate. Due to the reflection effect of the tunnel wall during the late stage of the blast process, the connecting flange at the cabin back, as well as the stiffeners on both sides, may experience higher pressures. These components may become the "weakest link" in the refuge chamber structure; hence, flexural rigidity must be enhanced in future designs to improve impact resistance.

Zhou et al. [97] conducted an explosion simulation on full assembly with the simplifying omission of small components such as the cabin door's doorknob. However, there are no other inferences shared apart from similar results to the previous studies.

Guo et al. [98] analyzed a refuge chamber model consisting of 10 cabins, connected by flanges, which has an entry door at the front end and an emergency escape hatch at the rear end. A 100-m laneway is used as a medium where propagation of explosion is simulated by an FSI using AUTODYN code to get pressure curves. The deformation analysis is simulated by LS-DYNA code with respect to the pressures acquired by AUTODYN. The spectrum analysis is also investigated to observe the effect of resonance in this study apart from the other research efforts. While no severe damage was noted on the refuge chamber, the recommendations pointed out that an appropriate boundary condition should be chosen to avoid resonance. The flange has to be strengthened and a topological optimization should be performed to reduce the stiffener's weight.

Zhang et al. [99] designed a model in which the bulkhead of the refuge chamber model is built of conventional Q235-B steel, while the front door and stiffeners are constructed of Q345-B steel. Different failure mechanisms were produced when distinct design elements of the refuge chamber model were changed and subjected to dynamic loads. The researchers implemented the FSI approach to simulate the explosion and observed two different failure modes with several parameters involving different stiffeners and thicknesses of the plate and door. The first failure mode is an unrecoverable massive deformation of the front door, and the second is the front door detaching from the bulkhead. The first component

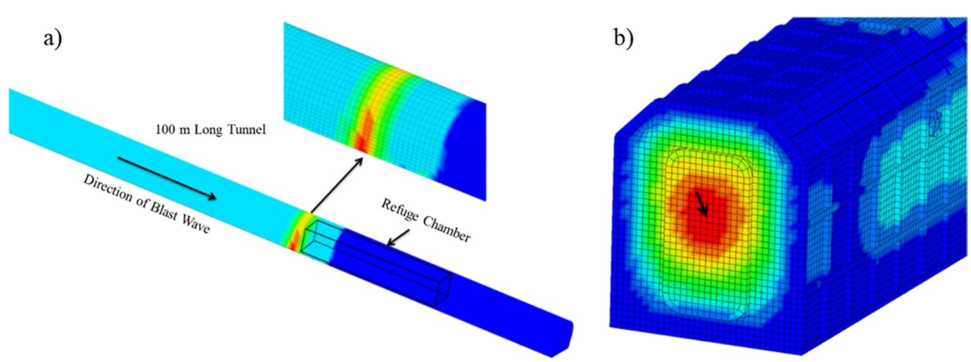

Fig. 9 **a** Explosion simulation through a tunnel with an FSI approach. **b** Deformation contour plot of refuge door [96]

to encounter the shockwave is the front door, which is also the most easily destroyed (Fig. 10). By increasing the thickness of the door and stiffeners, the deformation can be efficiently controlled. The upper portion of the front door may detach from the bulkhead if the welding is poor, making the refuge room useless. As a result, several steps such as increasing the thickness of the door and stiffeners, as well as reinforcing the welding between the door and the bulkhead, are advised to ensure the safety of the refuge chamber's occupants.

One of the researches focusing only on a component of the refuge chamber rather than a whole structure was established by Meng et al. [100]. In this study, a triangular shock wave is only applied to the door of the refuge chamber. The small components of the door are not included in the geometry of the model; however, they are simulated by various numerical method applications; for instance, the rotational element in the model is used to mimic the door hinge, and the welding is represented by overlapping nodes in the model. The handwheel is not included in the model since it is considered that there is no effect on the explosion resistance. After the initial simulation results, stiffeners are included in the design of the door so that the weight of the structure could be reduced with increasing resistance. Similar to this study, Li et al. [101] investigated the response of airtight blast doors under shockwave. However, the smooth particle hydrodynamics algorithm is used to simulate the FSI in this study rather than the Lagrange and the arbitrary Lagrange-Eulerian approaches used by other studies. The static and dynamic responses are also examined, and it is found that the results of the dynamic analysis show larger deformations than the ones of static for that analysis in contrast to the results presented by Zhang and Gu [81].

Wang et al. [102] describe the difference between direct and indirect coupling methods of the FSI before implementing the indirect coupling method in the analyses. The indirect coupling method is the separate simulation of gas explosion and deformation of the refuge chamber whereas in the direct coupling model, the explosion, air, roadway, and refuge chamber models are all merged into a single model. Both Wang et al. [102] and Zhao et al. [103] prefer using the indirect method so that finer mesh-sized elements could be created to model the 3D geometry of the refuge chamber for deformation analysis. They recommend that a large-scale physical experiment should be conducted to evaluate the explosion response of the refuge chamber further.

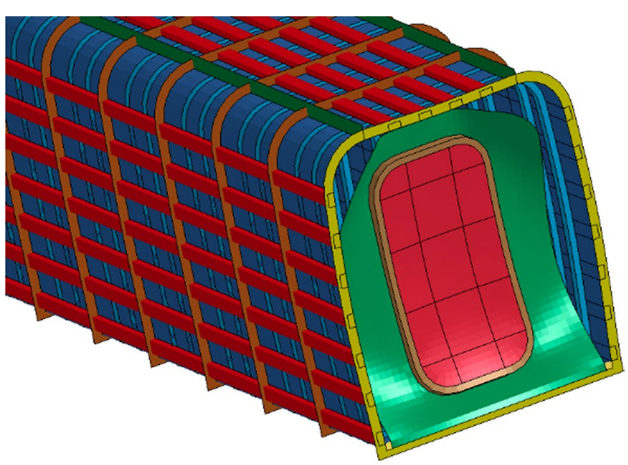

Fig. 10 A deformed view of a front door of 3D model [99]

In many circumstances, in a finite element simulation, the explosive loading is simplified into the equivalent triangle wave loading. The flaws in this method include an overly idealized interpretation of explosive loading and a failure to account for the complex fluid–structure interaction between the gas explosion shockwave and the refuge chamber structure. The concerns of expansion, reflection, and diffraction induced by the air blast wave, according to Zhang et al. [99], cannot be ignored. The current simplified equivalent triangle computation approach ignores the impact of these variables. While such a basic idealization decreases processing cost [104], it fails to reflect the consequences of complicated fluid–structure interactions. Several studies have shown that the expansion reflection and diffraction induced by air blast waves must be taken into consideration; otherwise, the damage to the refuge chamber may not be effectively measured, which will be the focus of the current study Zhang et al. [96]. Impact loads operating on chambers are achieved in fluid–structure interaction models by simulating a realistic explosion source in roadway models using the ALE. Li et al. [105] carried out a physical explosion experiment in a refuge chamber and compared the experimental displacements to the findings calculated using fluid–structure interaction simulation methods. It was shown that the calculated results using the fluid–structure interaction technique were similar to the experimental results, whereas the calculated results using the triangular wave method were higher than the experimental results. As a result, this method is currently more commonly used to simulate impact loads on the surfaces of refuge chamber models Wang et al. [102].

In the literature, the full assembly and/or components of refuge chambers were loaded by varying levels between 0.3 and 1.5 MPa with various pulse widths. The researchers utilized different codes for the explicit time integration analysis such as LS-DYNA, AUTODYN, ANSYS, ABAQUS, and SOLIDWORKS with three main steel material models (Q235, 345, and 460). A summary of the researches conducted with the dynamic analysis approach for deformation analysis of refuge chamber is presented in Table 2.

8 Discussion and Recommendations

Based on the findings of this review, the authors acknowledge that regulations pertaining to the construction and utilization of refuge chambers differ considerably from country to country. This high degree of regulatory variation may be due, in part, to a lack of quantitative information on the performance of RAs. To form such requirements, the design, performance, and response of RAs to various emergency situations should be evaluated in a manner that provides useful quantitative information, such as through the use of numerical and experimental studies.

In the light of this research, significant research gaps have been noticed and recommendations for further studies are given. The numerical studies clearly prove that the most affected parts of the refuge chamber structure during the explosion are the front end, where the door is placed, and the junction of the connected components. The door is the first barrier for a refuge chamber, and its performance directly determines the dependability and stability of the capsules or chambers. It can withstand a specific strength of shock waves and prevent the entry of toxic gasses. To withstand the shock wave created by a gas explosion, an airtight blast door must be robust and flexible. The small components of the refuge chambers, such as the observation window, hinges, locks, handles, knobs, latches, and sealings, are critical to the overall structural resilience of refuge chambers to static and dynamic loading conditions and should be extensively analyzed by experimental and numerical methods. In addition to this, it is obvious that the contribution of stiffeners is clear with the existing research outcomes; however, a more comprehensive study should be established considering the location, type, and alignments using topology optimization. The effect of the temperature is not taken into account in any numerical analysis study such as using thermo-couple solution yet but could play a large role in the variation of refuge chamber deformation. On the other hand, although BIP RAs play crucial importance as a refuge option, which has several advantages over portable RAs, the structural response of BIP RAs for a possible emergency event must be conducted. It is obvious that even though the numerical studies related RAs focuses on refuge chambers, these efforts are still very limited, and the studies on the evaluation of BIP RAs are the areas that should be addressed more. As discussed in MSHA Final Rule, the distance has a significant effect on deciding whether escape or shelter and an RA shall be provided for the nearest distance greater than 2000 feet between the working face and surface. Further numerical studies can be focused on this parameter to enhance or verify that quantitative parameter. Consequently, since the primary and secondary explosions are very serious issues, the possible injury effect of these accidents on the human body is also a real concern that the researchers should work on.

9 Conclusion

Underground mine emergency events might be severe situations that leave mine workers with limited options for escape. RAs are designed to provide a safe haven for miners during emergency events in which escape is impractical or impossible. The selection of RA utilization mainly depends on the following factors: (i) the type of mines, (ii) mining conditions, and (iii) the type of potential emergency events.

Events and significant parameters to be considered to improve the utility and reliability of the RAs were pointed out in this review. The underground mine explosions, one of the pioneer events that cause very severe problems and even fatalities, especially for underground coal mines have been discussed. Basic human requirements, waiting for a rescue team, and the required physical specifications of RAs during the events have been analyzed in detail for various countries with their regulations.

The required study areas to enhance the safe use of RAs were also evaluated, and the factors were released; essentially, the ability to endure overpressure, breathable air and temperature control, product adaptability and investment cost, and the factors related to the general survivability and utilization are the most important ones and should be given more consideration in technology design.

In this paper, the explosion performance of the refuge chambers has been handled. As indicated, the experimental efforts have some limitations such as cost, repetitions, and observation during the explosion test. This is why numerical analyses might be a more helpful tool to understand the complex response of these structures against explosions. For this purpose, different approaches and methods have been done in the literature to investigate the occasions. These different approaches can be either static or, dynamic analysis; also the differences of those analyses within the dynamic simulation of explosions like the fluid–solid interaction (FSI) or simplified triangle-trapezoidal pressure–time curve with the Lagrangian algorithm, or the arbitrary Lagrangian–Eulerian algorithm (ALE). Numerical modeling of RAs also differs in modeling geometry (such as full assembly) and the modeling of the specific components (such as a door or chamber cabins with different material types). It is concluded that the front door section in the zone having the highest deformation, and comparing the abovementioned approaches, the ALE is the most suitable solution technique for this kind of deformation analysis.

Funding The authors would like to thank the National Institute for Occupational Safety and Health (NIOSH), CDC-NIOSH BAA 75D301-20-R-67922, for financial support.

Declarations

Competing Interests The authors declare no competing interests.

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