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Underground Mining Self-Escape and Mine Rescue Practices: an Overview of Current and Historical Trends

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Abstract
This formal literature review identifies strengths and shortcomings of current literature related to mine rescue, self-rescue, and self-escape technology. Key concepts and factors that influence the decision making behind mine rescue and self-escape were identified. Historically, underground mining has been one of the most dangerous occupations due to the harsh nature of working environments. During the latter half of the twentieth century, and into the twenty-first century, mining fatalities have declined, yet large-scale mine emergencies persist. The emergence of new technologies, in combination with evidence-based mine emergency research, is resulting in new training methods, monitoring systems, and self-escape approaches being tried in operating mines. This review identifies areas in which substantial research is being conducted, such as the use of virtual reality and game-based training and areas that warrant further development such as the measurement and information gathering capabilities of unmanned ground and aerial vehicles, as well as emergency management and incident command systems. This paper summarizes the current underground mine rescue and self-escape landscape in the USA, including the breadth and depth of mine rescue and self-escape training and practices as evident in the literature.

Keywords Mine rescue · Self-escape · Mine emergency · Mining health and safety · Mine incident command system

1 Introduction

Historically, underground mining has been one of the most dangerous occupations due to the dynamic and harsh working conditions such as heat, noise, confined spaces, and the presence of toxic gasses [1]. Aside the inherent dangers, more than 726 mining disasters [2], henceforth classified as incidents involving 5 or more fatalities [3], have occurred in the past century. Moreso, from 1900 to 2006, a total of 11,606 underground coal mine workers died in a total of 513 mine disasters in the USA alone [4]. Additionally, of 1147 metal mine, 78 non-metal mine, and 152 aggregate mine workers died between 1869–1972, 1910–1979, and 1884–1952, respectively. Additional mine disasters occurred in the USA in 2007 and 2010, killing 9 and 29 miners, respectively.

Major coal mine disasters can be viewed in three main time frames. The period between 1900 and 1909, prior to the founding of the United States Bureau of Mines, is widely considered to be the deadliest period for coal mine workers [5]. The second period, between 1910 and 1969, saw a significant decrease in the number of emergencies and associated fatalities. This is most often attributed to an increase in mine safety research and fatality investigations that promoted the mitigation of mine disasters [6], anecdotally associated with the Bureau of Mines. The third period spans from 1970 to current. Within this period, the number of coal mine disasters has reduced to an average of one every 4 years [7], separate from the 3 major metal–non-metal mine disasters from 1970 to 2010.

During the twenty-first century, the mining industry in the USA has had expanded access to a century of mine disaster history, revealing several trends in rescue and self-escape practices. The mining industry has previously focused on controlling fires and explosion as a means of disaster mitigation. Gradually, mining health and safety research has expanded the scope to broader engineering solutions such

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as the use of intrinsically safe equipment that pass permissibility regulations and the use distributed electrochemical mine gas sensor networks. Within the last 25 years, human behavior has also been viewed as critical to improving survivability of mine catastrophes.

The most recent engineering solution to miner self-escape and mine rescue has been through the use of, predominantly tethered, unmanned ground vehicles. Rescue vehicles exist in two forms: manned and unmanned ground and aerial vehicles. Manned ground vehicles would include trucks or all-terrain vehicles that have been outfitted for firefighting or rescue purposes, and unmanned ground vehicles (UGV) exist primarily as rescue robots. A manned aerial vehicle would be, for example, a medical evacuation helicopter, while an unmanned aerial vehicle (UAV) would be more like a drone, that can be used for reconnaissance. The latter, UGV/UAV, is becoming more desirable in mine rescue situations, especially underground, when the environment is unknown and potentially hazardous to humans. The benefit of unmanned technology is that it eliminates the immediate need to send people into an unknown and dangerous situation, allowing the use of unmanned vehicles to size-up the environment. Unmanned vehicles are also smaller, can require less maintenance, and can be produced at a lower cost [8].

2 Methodology and Overview of Results

A review of mine disaster events for the period of 1951 to 2022 was performed. Sources included scholarly works, US Mining Safety and Health Administration (MSHA) records, and US legislature documents. Topics analyzed include the shortcomings, defined as topic areas with little research and supporting data, and advancements, defined as topics with extensive research, supporting data and/or improvement over time, in mine rescue, self-rescue, self-escape, and self-escape technology. Also included were important methodologies and factors that influence these topics and their progression over time.

The literature reviewed is comprised of 68 articles, of which 29 include topics of self-escape technologies; 16 include topics of self-escape and rescue training; 8 include topics of prevention, response, and recovery; 6 include case studies of mine disasters; 6 include current and historical legislation; and 3 include current and historical research funding programs.

Among the literature reviewed, several comparisons were made, including training techniques employed over the years (1951–2022), technology utilized in self-escape practices, and technological advancements [9]. Furthermore, this review identifies advantages and disadvantages of using technology to overcome the challenges miners face in self-escape. Advantages include increases in survival rates, reduced mortality rates, and complimentary items that enhance rescue procedures.

To identify strengths and deficiencies in the way self-escape and mine rescue practices have developed over the last 70 years, three case studies were examined: the Quecreek Mine Rescue [10], the Sunshine silver mine rescue [11, 12], and the Jefferson Island Mine inundation [13]. These case studies examine response time and decision-making in both successful and unsuccessful events which contributed to the mine evacuation.

From the data identified, a retrospective analysis is performed and presented graphically, elucidating the relationship across mortality rate, the classification of emergencies, and the type of mine within the USA.

Finally, a synopsis of post-event US federal legislative changes from the 1968 Coal Act through the 2006 MINER Act is provided, including the administrative process used by MSHA to identify mine disaster cause, effect, and related procedural changes [14, 15]. Within the legislative review, second-order count vectorization of removed 10-g was performed, by which uni- and bigrams were extracted as a measure of intentionality and causality in the editing process moving from the original bill to the final law [16].

3 Active Escape and Rescue Equipment

This section discusses active, as opposed to passive, rescue and escape equipment and methods. The main topics discussed include closed circuit respirators, unmanned ground and aerial vehicles, and virtual reality (VR) training. All of these topics were keywords when searching for mine rescue, self-escape, and escape technology. Additionally, VR and UAVs/UGVs were emerging themes in rescue training and escape technology.

3.1 Closed-Circuit Respirators

Coal mine operators in the USA were officially required to make available and accessible to each underground miner a (SCSR) on June 21, 1981. The regulation required that each miner wore or carried an emergency respiratory device with a minimum capacity rating of 1 h, certified by the appropriate agencies [17]. Commercially, there are 2 types of portable, self-worn, closed-circuit respirators available: self-contained breathing apparatus' (SCBAs), which contain compressed oxygen, and self-contained self-rescuer (SCSRs), which usually rely on chemically produced oxygen or the scrubbing of carbon monoxide. An SCBA supplies oxygen to the wearer from a high-pressure cylinder, and the CO_2 exhaled is removed from circulation by an alkali canister. Standard inspiratory temperatures while using an SCSR can reach upwards of 55 °C within 20 min of use in mine self-escape scenarios [18, 19]

Various studies [19–22] indicate that the use of SCSRs and SCBAs is sufficient means of airway protection during mine self-escape efforts. Advances in SCBA technology have resulted in reduced size and expanded capacity for oxygen-providing devices, resulting in a widespread shift from chemically produced oxygen devices (SCSRs) to compressed oxygen devices (SCBAs). This shift has resulted in increased survivability in low oxygen (below 19.5% O2) environments. However, SCSRs and SCBAs have measurable limits in effectiveness. One study on lung and diaphragm stress conducted in 1986 suggests that the maximum effective time for SCBA use ranges between 20 and 30 min under unacclimated moderate to heavy exercise [21]. Although longer-rated SCBAs have been developed, they are often extremely heavy, and most effective during rest and light exercise [22]. Both types of devices protect users from carbon monoxide inhalation during mine self-escape efforts [19] for a limited time of 10–30 min depending on the specific device and the respiratory rate of the wearer. However, SCSRs are impacted by concentration of carbon monoxide, whereas SCBAs are not, as they have a localized oxygen providing system [23].

Fit and ergonomics are also of concern with the employment of SCSRs and SCBAs. The specific biomechanical impacts of SCSR and SCBA use is still lacking in research, and most simulations fail to include considerations for changes in inspiratory temperatures associated with carbon monoxide scrubbing nor excessive environmental temperatures representative of a mine fire. Additionally, most SCSRs and SCBAs are designed to single facial dimensions, which negatively impacts device fit for all users [24]. Issues with fit and ergonomics are even more concerning for females, who report pain and extreme discomfort at a higher rate than their male counterparts [25]. A 2020 survey of women in mining positions in South Africa identified that the majority of female respondents reported pain while using the SCSRs as well as a higher rate of musculoskeletal repetitive strain injuries associated with wearing SCSRs on a mine belt than male respondents [25]. For future manufacturing and development considerations, it is key that user fit is taken into account during the design phase of new rescue equipment. If rescue team members were forced to use equipment that is not designed for them, thus causing pain and discomfort, it would be reasonable to assume that the team member would not be performing at optimum capacity, possibly hindering rescue efforts.

3.2 Unmanned Ground and Aerial Vehicles

Self-escape is widely accepted to be the initial method for the evacuation of mine personnel and is therefore highly dependent on human behavior [26]. However, should rescuers lack easy access to the mine, or face poor data reliability for mine conditions, the use of technology, especially UGVs or UAVs is advisable. This technology serves to aid rescuers in the initial assessment and access obstructed sections of the mine. Furthermore, the deployment of UGVs and UAVs allows for the identification of otherwise imperceptible hazards, such as deformation within the excavation, and air toxicity. They also offer the ability to see through adverse conditions such as smoke and dust.

Since 2000, the use of UGV and UAV robots in mine rescues has increased. Several scientific articles have been published, specifically after 2010, showcasing a variety of drones and UGVs that have been tested in laboratory and field settings [27]. Two of the currently MSHA approved robots for mine disaster rescue are the Gemini-Scout Mine Rescue Vehicle and the Sarcos Snake Robot [28]. Both vehicles were showcased by MSHA in 2017. One problem with some of the existing UGVs is that they are tethered to where they are being deployed from. Having a tethered vehicle makes the robot more prone to being caught on obstacles and rendered useless if the tether snaps. This was precisely the case during the Crandall Canyon disaster in Utah in 2007 [29].

The notion of using robotics to aid in mine rescue is a promising one, especially now that technological advancements are resolving previous challenges such as the visibility, communication, operations within a GPS-denied environment, intrinsic safety regulations, and accessibility [30]. While the number of mine disasters remains small, there are several scenarios in which the deployment of a UAV or UGV would aid in miner self-escape and mine rescue, such as when there are toxic gases present, inundation, extreme heat, unknown conditions, risk of secondary explosions, or when the mine's structural integrity is compromised. Some of the notable features of a successful robot or UGV or UAV include the ability to travel rough and uneven terrain, waterproofing, a resistance to explosions, a reliable communications system (preferably wireless), and a relatively long battery life (> 24 h) [31]. Ultimately, a successful robot should have the ability to map the underground mine system, especially given that the terrain has likely changed after a disaster event.

4 Escape and Rescue Training

In the event of an emergency, the best asset the underground miner has is themselves. For this reason, the regulatory bodies in the USA have placed a keen emphasis on improving workers' skills and competencies in preparation for an emergency. Training in the form of drills and mock disasters affords the planners with an opportunity to identify and resolve problems, examine, and evaluate the feasibility of developed procedures, and train individuals who will be responding to an emergency [32–35]. One of the more promising examples of emergency response training is the implementation of a "tactical mine rescue course" and development of a mine rescue medical kit, which was done by research at TU Bergakademie Freiberg, in Freiberg, Germany [36].

More than 70 years of research has identified that effective competency-driven, andragogical training considers design, delivery, and implementation elements. Active learning methods such as the use of serious games, have also shown to be effective for adults, enabling knowledge retention rates as high as 90% [37, 38]. Software-based training programs also motivate younger learners in ways that other activities cannot, as these learners are more likely to maintain these activities and thus gain competency [39, 40]. For this reason, more research is being conducted in the development and inclusion of serious games for rescue and escape training [41, 42].

NIOSH employees for the Office of Mine Safety and Health Research have been working on developing ways to assess the utility of virtual environments for teaching critical mine emergency response skills. This software allows mine rescue team members to gain familiarity or additional practice in assembling the Draeger closed circuit breathing apparatus. The virtual training, in turn, helps improve cognitive and motor skills of the user. Field testing amongst 30 mine rescue team members revealed that trainees found the software to be useful in teaching the breathing apparatus assembly skills and challenged them to think about new ways of apparatus assembly [43].

An emerging theme in the mine rescue and training community is the use of virtual reality (VR) training simulations. Several scholarly works [44–46] highlight the important benefits and drawbacks of VR training. As training has been identified as one of the key factors for mine rescue teams, VR technology is a good way to provide additional training time for rescue team members and non-rescue team mine personnel when live training exercises cannot be conducted or are otherwise not feasible.

VR training for mine rescue and self-escape is a promising method for development of hazard recognition and decision-making skills in workers and rescue teams. VR training systems for mine rescue have shown a measurable increase in hazard recognition skills and a reduction of decision times in high stress simulated mine rescue events. VR training platforms are anticipated to become a significant aspect of mine safety training protocols. This supplemental training has the potential to reduce the total number of mine rescue team related fatalities and injuries, as a lack of training and skill is one of the leading causes of harm to rescue teams in rescue scenarios [47].

While VR training seems promising, two studies in 2006 and 2019 address a major concern that VR training often fails to capture an appropriate level of realism that live training exercises can currently offer [44, 45]. There is a general lack of realism in most aspects of currently available VR software; range of motion is constrained and the total degree of freedom the user has over their actions is extremely limited. The 2019 study indicates that this is a large barrier that VR training for mine rescue must overcome before it will be an effective standalone tool for safety training.

As methods and philosophies for safety training change in the mining industry, it is the authors' opinion that VR training will become an increasingly important tool in task training for critical tasks. This extensive task training, especially in self-escape and self-rescue situations, has been shown to reduce feelings of dread in mine workers and increase confidence in personal capability and perceived safety in underground mining [46]. Based on the literature reviewed, the authors conclude that further development of capabilities for realism and mobility within VR systems may likewise lead to similar results of reduced emotional distress associated with discussion of mine rescue and miner self-escape.

5 Prevention, Response, and Recovery

According to MSHA, as of 2008 each mine must have an Emergency Notification Plan for notifying necessary personnel such as supervisors, administrators, and government officials when an emergency occurs. The primary function is establishing a command center manned by the most appropriate representatives. The command center oversees communication between outside entities, rescuers and responders, and miners inside the mine. It is the location where scheduling, assignments, tracking, rotations, and methods of exploration or firefighting are made. The coordination of crucial decisions determines mission success and rescue team survivability [26].

In 2006, NIOSH conducted a series of focus groups aimed at identifying what happens during the first moments of a mine disaster. All members of the focus group had experienced a mine emergency or were part of a mine rescue team during a rescue situation. The types of emergencies included fires, explosions, and inundations, mostly in underground coal mines. From this, 5 overall themes emerged: mine emergency planning, communication, training, decision making, trust and leadership, and personal issues [4].

When discussing the key issues during the initial moments of response, it was concluded that research supports self-escape as opposed to rescue as the most likely scenario for reducing fatalities. Regarding the lessons learned, subjects indicated that training should include such topics as traumatic incident stress and SCSR expectations training

[4]. In summary, after interviewing 7 mine rescue teams and 10 individuals, NIOSH released the following list of focus areas regarding the initial response during a mine emergency: preparation and planning, communication and information, leadership and trust, and training.

6 Mine Rescue Case Studies

In this review we considered three case studies, the Quecreek Mine (coal mine) where all 9 trapped miners were rescued, the Jefferson Island Mine (non-metal mine) where all 50 escaped, and the Sunshine mine (metal mine) where 91 miners died. In all three cases the mine rescue outcomes were affected by several key decisions that either made the mine emergency response successful (having survivors) or unsuccessful (having fatalities). The ability to establish and maintain communication with the command center and determining the accurate location of every worker in the mine is pivotal in achieving rescue objectives. In the case of the Quecreek and Jefferson Island mines, communication with the surface command center helped in making escape paths and devices available. However, in the Sunshine Mine, the supervisors had no aid or directives to help them on their rescue mission. Another factor that especially helped in the rescue process at the Jefferson Island mine was the availability of an evacuation procedure that was known by all the workers. The rescue procedure lasted only 50 min at the Jefferson Island mine because the evacuation signals were known by all workers, and this helped in assembling them within that brief period.

Interestingly, one commonality of all three case study events is that a primary causative factor was found to be poor geological mapping of old, inactive areas of the mine. The mapping error caused a breach in the face connecting the Quecreek mine with adjacent abandoned workings resulting in inundation, while at the Jefferson Island mine, a surface drill rig pierced the salt dome resulting in collapse, and at the Sunshine mine, a blow out of a ventilation control wall Sunshine mine resulted in explosion and fire.

6.1 Quecreek Mine Rescue Case Study

On July 24, 2002, a breach into unknown adjacent and flooded abandoned mine workings caused water to fill the active mine excavation trapping 9 miners. Based on existing mine maps, an educated guess was made as to where the 9 trapped miners would go to get to high ground and avoid flooding. Air holes were then drilled at that stop until eventually a rescue hole could be dug. After 77 h, all 9 trapped miners were rescued via a two-foot-wide hole [10]. This flooding began due to inadequate mapping of neighboring historic workings.

The Quecreek Mine incident and subsequent successful rescue revealed several important features: (1) The establishment of an incident command system (ICS) greatly aided rescue efforts, as well as allowed for quick communication and appropriate organization of supplies; (2) Improved mapping of neighboring mine workings can help mitigate similar instances in the future; and (3) It is vital for mine operators to be knowledgeable and well trained on disaster protocol.

6.2 Sunshine Silver Mine Rescue Case Study

On May 2,1972, miners complained that they smelled smoke during the night shift, but the morning shift workers ignored this because many of the miners smoked underground. Smoking at the time was not banned in hard rock mining, as it had been in coal mines. Moreso, it was also common for small electric motors that ran the fans to overheat and produce smoke [11].

In 1972, no regulations required hard rock miners to carry SCSRs or SCBAs. Due to a fire that was caused by the violent failure of the bulkhead because of smoke and gas pressure building behind it, 91 workers suffered fatal asphyxiation. An additional 80 miners were able to escape and two were rescued after eight days in the mine. This disaster laid the groundwork for the 1977 Mine Act, effectively bringing hard rock mining under the same level of safety regulations as coal mining [12].

6.3 The Jefferson Island Mine Inundation Case Study

In November 1980, the chief electrician working at the 1300-feet level noticed a stream of muddy water carrying along some of the drums and equipment he was working with. He quickly shouted a warning to the foremen and crew members he was working with a that same level. The foremen in turn started a series of well-coordinated evacuation process that led to the successful evacuation of all but 4 personnel who were working beyond the reach of all the evacuation signals that were sent out. These 4 men were later rescued by the supervisors who drive to the remote areas to pick them up. With expanded practice of evacuation protocols and excellent communications between miners and the hoist operator, all 51 individuals were able to escape the quickly flooding mine in a matter of 50 min [48].

Investigations by Crystal Diamond officials, those who owned and operated the mine, revealed that a P-20 drill rig belonging to Texaco oil and gas, operating some miles away from the mine had pierced the salt dome and the inundation was because of the lake draining into the mine. The consequence of the lake draining away included land subsidence and collapse of nearby gas wells. MSHA issued orders to halt mine operations and evacuate nearby residents. Overall,

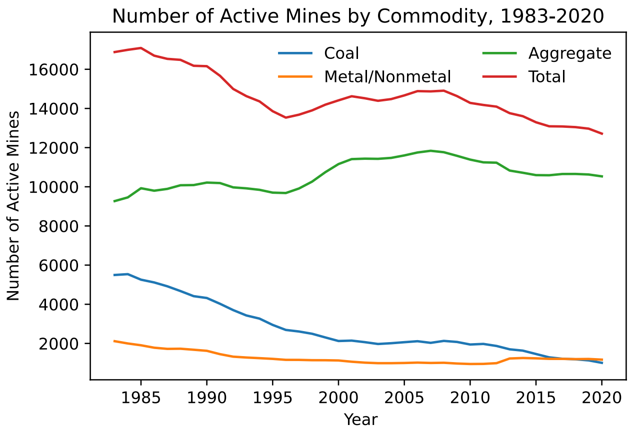

Fig. 1 Number of active mine sites based on commodity, from 1983 to 2020 [50]

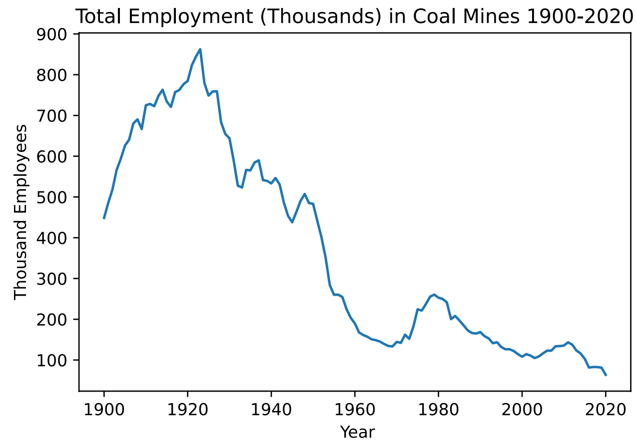

Fig. 2 Total employment in coal mines from 1900 to 2020 [52]

the inundation was because of poor geological mapping by Texaco oil and gas. Yet, the rescue process was still deemed successful [49].

7 Trends in Active Sites, Employment, Disasters, and Fatalities Over Time

This section, which includes data on active mine sites, injuries, and fatalities across coal, aggregate, and metal/non-metal mines, is included for the purpose of providing contextual evidence for the improvement in mining health and safety. In 2020, there were a total of 12,714 active mine sites in the USA, the fewest in 50 years. Comprised of 1,009 active coal mines, 278 metal mines, 895 non-metal mines, and a combined 10,532 aggregate mines (as defined by the sum of sand, gravel, and stone mines). The number of active coal mines in the country has been on a steady decline since 1983. Similarly, aggregate mines have been steadily declining since 2007. However, since 2011 the number of active non-metal mines has been increasing, except for the year 2020 [50]. Of the 12,714 active mine sites in 2020, 12,218 were surface mines and 496 were underground mines. Specific breakdowns by sector can be seen in Figure 1.

Despite consistent and decreasing employment trends of the M/NM and coal sectors, respectively, the fatality rates per 100,000 employees have stalled, as shown in Figs. 2, 3, 4, 5. In the years following major mining health and safety regulatory legislation, the fatality rates for metal/non-metal and coal miners decreased steeply, as seen in the years annotated within Figs. 4 and 5. The high number of fatalities, especially in 2006 and 2010, demanded an update of regulations to improve the development of rescue practices and training for emergency response in underground coal mines. In 2006 and part of 2007, after MSHA issued the Mine Improvement and New Emergency Response Act (MINER Act) which was signed into law,

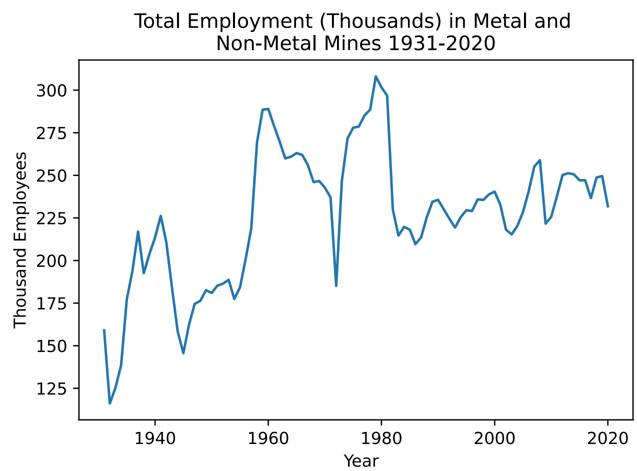

Fig. 3 Total employment in metal/non-metal mines from 1931 to 2020 [53]

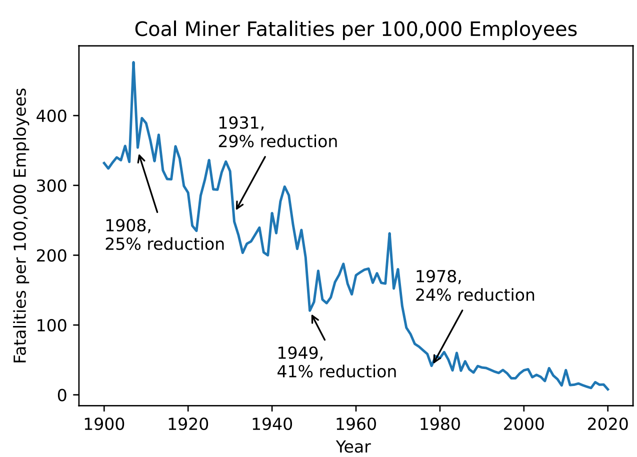

Fig. 4 Coal miner fatalities between 1900 and 2020, per 100,000 employees [52]

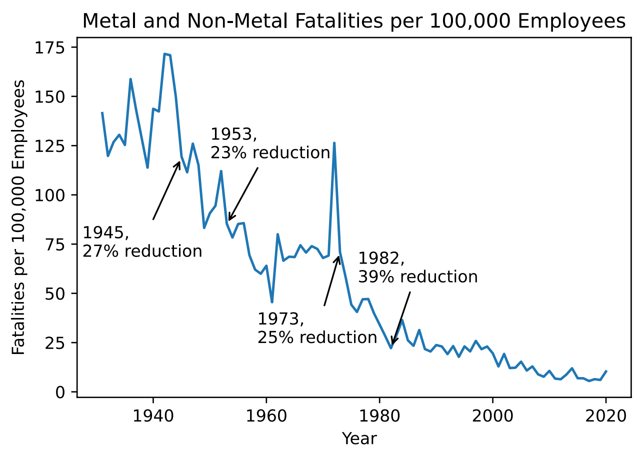

Fig. 5 Metal/non-metal miner fatalities between 1931 and 2020, per 100,000 employees [53]

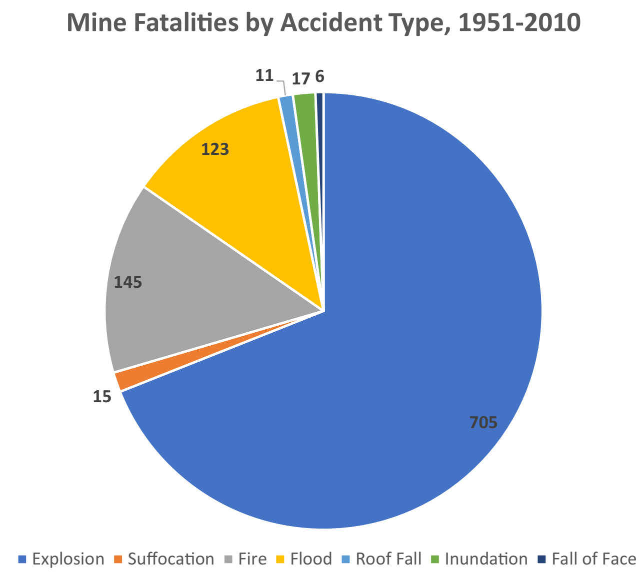

Fig. 6 Total number of mine fatalities from 1951 to 2010, by accident type [2]

fatalities decreased by 28%, 39%, and 72% in 2007, 2008, and 2009 respectively [51], compared to 2006 figures.

Although current rates of fatalities are still declining demonstrably decade-over-decade, the year-over-year reduction in rate of fatalities has largely failed to match the steep decline in fatalities seen after the passage of the 1977 Mine Act.

There has been a total of 56 disaster incidents in coal mines between 1951 and 2021, resulting in over 1000 deaths. Note this does not include annual fatalities in coal mines, just those that occurred during a disaster, as defined by MSHA. Most of these incidents and subsequent fatalities were caused by explosions, with a significant number also caused by fires (see Fig. 6).

In 2016 and 2020, the coal sector achieved single digit fatalities. A single-digit threshold has not yet been achieved in metal/non-metal mines. A year-to-year single-digit fatality threshold has never been achieved across any mining sector in the USA. While a clear decreasing trend in mining disasters and year-to-year fatalities has occurred through 2010, the past decade of year-to-year fatalities across the mining industry has remained flat. Despite progress made in disaster mitigation in the wake of the 2006 MINER act and the 2010 Upper Big Branch disaster, there has been no appreciable progress in overall fatality reduction, nor in reduction of fatality rate.

According to MSHA data there have been at least 522 coal miner deaths in the twenty-first century (see Figure 7) [52]. However, the two peaks corresponding to 2006 and 2010 show an increase in fatalities, resulting in increased public pressure on MSHA [3, 4, 6, 7] to understand causative factors and needed preventative actions resulting in updates to the mining legislation. In 2010, the drafting of a complementary law that would help ensure the conditions of workers in aspects of communication and tracking, sealing of abandoned areas, and safe points, led to a reduction in fatalities by 87% compared to the events that occurred in 2010. Following these legislative changes, the years 2010 to 2020 realized a reduction in underground coal fatalities by 25%, comparing the period from 2000 to 2009 and 2010 to 2022.

8 Legislation

Historically, legislative changes tend to follow major mine disasters or series of several smaller-scale fatality events. For example, the Coal Act of 1969 came soon after the 1968 Consol No, 9 Coal Mine disaster in Farmington, WV which

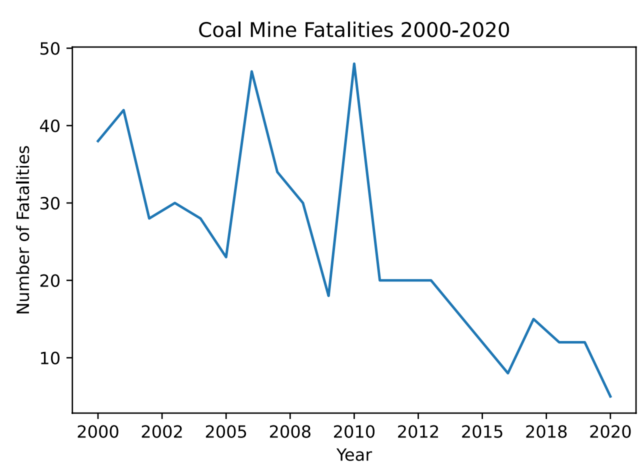

Fig. 7 Total coal miner fatalities from 2000 to 2020 [52]

killed 78. Again, the Mine Act (1977) came followed the Scotia Coal Mine disaster in Ovenfork, KY, where 26 miners died. Then, most recently with the MINER Act (2006), which followed a period of 29 years (1977–2006) with 100 fatalities that then culminated when the Sago Coal Mine disaster occurred in Buckhannon, WV where 12 miners died, [54]. Looking at major milestones in mine health and safety legislative progression, the landmark Acts occurred in 1952 (Federal Coal Mine Safety Act), 1969 (Coal Act), 1977 (Mine Act) and 2006 (MINER Act). These legislative landmarks are summarized in Table 1.

While the goal of passing these new laws was to improve health and safety, it is also important to understand that the law itself was a compromise between what mine workers and the people wanted, vs what lawmakers were willing to agree to.

For example, when reviewing the initial draft of the MINER Act vs the law itself as it is enacted today with the use of count vectorization [16], a machine learning approach to natural language processing, the phrases "emergency response" and "rescue team" were the 9th and 11th most common phrases in struck passages of 10 or more words, indicating a large degree of intentionality. In other words, phrases with the terms "emergency response" and "rescue team" were some of the most common phrases to be struck from the original bill, and likewise were the most likely semantic cause for the passage to be struck. While the overall method of natural language processing analysis is outside the scope of this paper, their respective prevalence indicate that the phrases are the driving factor for the removal of larger sections of proposed legislation.

Public law 95–164, also known as the Mine Act, was passed in 1977 to promote safety and health in the mining industry, to prevent recurring disasters in the mining industry, and for other purposes [14]. Contrary to trends seen with the MINER act of 2006 [15], the initial bill was subject to many additions that formed the framework for the modern existence of the United States Mine Safety and Health Administration. Within changes made to the original bill prior to the Mine Act becoming law, terms related to "operators," "miners," and "relief" were the most common driving factors in expanding the original bill.

Table 1 Key mining legislature from 1952 to 2006 [55]

Act name	Year enacted
Federal Coal Mine Safety Act	1952
Federal Metal and Nonmetal Mine Safety Act	1966
Federal Coal Mine Health Safety Act (Coal Act)	1969
Federal Mine Safety and Health Act (Mine Act)	1972
Mine Improvement and New Emergency Response Act (MINER Act)	2006

9 Research Funding Portfolio

Two of the main sources of funding into mine rescue and self-escape practices and technology come from the National Institute for Occupational Safety and Health (NIOSH) Mining Program and the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. founded by court directive in 2011 following the Upper Big Branch disaster of 2006 [56]. The Alpha Foundation (AF) has funded 99 different projects to 34 entities [57]. The AF invests in four main mining research sectors: safety and health interventions, mine escape, rescue and training, safety and health management and training, and injury and disease exposure and risk factors [58]. The current review was limited to the mine escape, rescue, and training category. Mine escape, rescue, and training are further divided into four subtopics, including communications and tracking, training and decision making, sheltering and escape strategies, and rescue strategies and technologies.

In 2021, no new grants were awarded yet 6% of the annual funding went towards ongoing grants from mine escape, rescue, and training [57]. By 2022, there were two completed grants in communications and tracking, no completed grants for training and decision making, one completed grant for sheltering and escape strategies, and one completed grant for rescue strategies and technologies.

In contrast, the NIOSH Mining Program, which is a US federal entity created within the CDC in 1997 as a partial replacement for the Bureau of Mines (founded 1910) [59], has awarded at least 200 contracts in support of advancing miner health and safety. In 2021, there were 39 active NIOSH funded grants including 13 and 22 contracts related to escape and rescue technologies and training, respectively [60]. In 2020, the US federal budget for "mining research" as classified by the CDC budget was \$60.5M out of a total \$342.8M (17.6%) for occupational safety and health, and in 2021, the budget was \$61.5M out of a total budget of \$345.3M (17.8%) for occupational safety and health [61]. Note the increase to mining health and safety research during the period of decreasing overall occupational safety and health research investment.

10 Discussion and Research Agenda

Our findings indicate that there is substantial research and time being invested into mine rescue practices, self-escape, and escape technology. As a result, a more comprehensive safety culture for miners has evolved. This change is evident by the reduction in fatalities in coal and metal/nonmetal mines, as seen in Figs. 4 and 5, and by the change in legislature to be more progressive towards safety, as demonstrated by the changes between the Mine Act and the Miner Act. Alternative mine rescue training practices such as virtual reality and game-based training, have been developed. However, there is concern among occupational and safety psychologists that current training methods lack critical realism for effective preparation in mine rescue and self-escape. Furthermore, within training efficacy, measuring actual rescue and escape competency, and related preparedness, has proven incredibly difficult due to the inherently unpredictable and undesirable nature of mine rescue and self-escape events.

Moreso, a series of case studies performed on the three contemporary mine rescues discussed above, found that proper planning and development of a highly functional and centralized command structure using incident command system resulted in favorable outcomes. Consequently, these case studies found that poor and inaccurate mapping of the mine was a major contributing factor which hindered rescue operations.

Furthermore, there has been a recent and much needed push towards the use of robotic technology including ground and aerial vehicles to aid in rescue and self-escape. Key characteristics such as data collection capabilities, thermal and RGB imaging, reliable wireless communication, and navigation and route planning have been identified for the use of robot-aided rescue and self-escape. Based on the current two MSHA approved rescue robot vehicles, and the research into the subject that has been done, more testing and further prototype development is needed.

The impact of personal rescue devices such as the SCSR and SCBA, along with emerging UGV and UAV technologies in an emergency, is discussed as an aid to enhance the likelihood of survival in disaster scenarios. Complementarily, emerging technologies such as UGVs and UAVs [62] can provide efficient support in rescue practices in combination with existing passive rescue technology such as strobelights [63, 64], laser pointers[65, 66], and lifelines [67].

Given the arduous nature of the role that underground miners serve, in combination with the harsh environment, it could be expected that there are significant barriers to the health and safety of miners. However, those barriers have widely been overcome through means of legislature, improvements to training and technology, and an overall safety conscious approach. Provided all the technological and training improvements in the last 20 years, there should be little reason as to why the fatality rate in mining has not been reduced to a near zero level. This margin of fatalities, while lower than ever before, can be caused by human error. It is possible to overcome this final threshold through future work into alternative training methods, rescue practice and self-escape techniques and devices.

Limitations to this paper include the data sets being bounded to what is available by MSHA, NIOSH, and other government sources, meaning that all of the figures had timespans anywhere from the last 20 years to the last almost 100 years. Additionally, while the case studies analyzed in this paper provide important and relevant information to factors of success and limitations of rescue in three different mining environments, these incidents were also specifically picked, and not reflective of most mine rescues or rescue attempts.

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Data Availability All the data for mining fatalities, including that in figures 4, 5 & 7 are openly available from MSHA at: https://www.msha.gov/data-and-reports/fatality-reports/search. All the data for mine employment, activity and disasters, including that in figures 1, 2, 3 & 6 are openly available from NIOSH at: https://www.cdc.gov/niosh/mining/statistics/default.html.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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