ASSESSING WORKER SAFETY ON LONGWALL OPERATIONS DURING COAL MINE FIRES

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ABSTRACT

The Bureau of Mines has been actively involved in a study of worker safety on longwall operations during an underground mine fire. The results of this investigation were twofold. First, those factors affecting worker survival during a mine fire were defined and second, any relationships between these factors were identified. Although the individual factors affecting worker safety had been studied before, little information was available on their interdependence.

Fault tree analysis was used to evaluate the miner escape scenario. A fault tree was constructed to analyze the occurrence of fatalities during an escape from an underground mine fire. The completed fault tree contained 24 initiating events. After constructing the fault tree, both qualitative and quantitative analyses of the tree were conducted. These evaluations revealed that reduced evacuation delays were most important in successfully evacuating from an underground mine fire. These analyses further showed that improved escapeway knowledge combined with improved self-rescuer training was also important.

A brief evaluation was conducted to assess the importance of human versus engineered factors in the miner escape process. Several recommendations were given regarding human reliability under mine fire conditions.

INTRODUCTION

Longwall mining has always been associated with high productivity and increased resource recovery. Recently, there have been expectations that longwall operation could represent the future of the domestic underground mining industry. However, there are concerns regarding the risk of a mine fire, resulting in a catastrophic loss of life and property.

For many years, the Bureau of Mines has emphasized mine fire safety through the use of improved worker training and enhanced equipment design. One aspect of fire safety that is now receiving more attention is the identification of factors influencing the success or failure of an escape from a coal mine fire. This interest has increased after reviews of recent mine fires revealed that certain events contributed to the success or failure of the escape attempts.

To evaluate the miner escape scenario, the Bureau has used fault tree analysis. A fault tree is simply a logic diagram representing various combinations of failure events leading to a major catastrophic or undesired occurrence (Caceres and Henley, 1976).

Fault tree analysis is very useful as a tool for identifying various failure combinations in a system. It is also very useful as a means for evaluating the probability of this undesired event and all plausible failure combinations leading to this event (Crosetti, 1982).

There are several benefits to using fault tree analysis in evaluating the miner escape scenario. One is the considerable detail provided by this technique compared with other analytic methods. Because fault tree analysis requires a thorough examination of the miner escape scenario, it is possible to identify both single events and multiple-event combinations contributing to the failure of an escape attempt. Fault tree analysis can also provide a relative ranking of these events and event combinations. This ranking reveals those events and event groupings that are most likely to result in an unsuccessful escape. Hence, this method can be very useful when evaluating the effectiveness of certain remedial actions for improving the chances of escape.

FAULT TREE CONSTRUCTION

Construction of the fault tree begins by selecting a catastrophic event for analysis. In many cases, this choice is based upon the criticality of this event. Using deductive or "top-down" logic, all immediate causes of this event are noted along with their logical relationships. These intermediate events are then subdivided to identify their causes and logical relationships, and so on. This process continues until the events can no longer be subdivided or until failure data are no longer available.

A fault tree is always developed for a specific catastrophic event. In the Bureau fault tree, this event was defined as the occurrence of fatalities during an escape from an outby coal mine fire. In developing this tree, a number of factors were incorporated. Some of these are listed below:

- delays in evacuating the fire area
- stopping integrity
- escapeway knowledge
- self-rescuer training
- mine communications
- sensor reliability

The completed fault tree was composed of 24 initiating events. The structure is detailed in Goodman (1988).

ANALYSIS OF THE FAULT TREE

Several analyses of the fault tree have been conducted. The purpose of these evaluations has been to both qualitatively and quantitatively assess the influence of various initiating events on the chance of fatalities during the escape from the fire. The first analysis was qualitative in nature and involved the identification of the minimal cutsets.

In a fault tree, a cutset is a group of events such that if each event occurs, the catastrophic event will occur. A cutset is minimal if removing one event does not produce a cutset. In this study, minimal cutsets represented the smallest sequence of events resulting in fatalities during the mine fire.

Using commercially available software, 98 minimal cutsets were identified in the Bureau fault tree. In other words, there existed 98 different scenarios resulting in fatalities during the escape attempt. A typical cutset first involved a delay in evacuation. This delay was sufficient to allow the fire to grow in size and thus produce greater quantities of smoke and gas. Fatalities occur when the escaping workers encounter dense smoke in the escapeway and get turned around.

Another qualitative assessment of the fault tree involved noting which initiating event appeared most frequently in each minimal cutset. This gave an estimate of the influence of certain events on the likelihood of a successful or unsuccessful escape. In looking at the minimal cutsets, evacuation delays from the headgate area were most often represented. Specifically, of 98 distinct minimal cutsets, 96 involved a delay in evacuating the fire area. Other events found to be important included knowledge of the escapeways from the headgate, self-rescuer training, and stopping quality along the longwall panel. A complete listing of the minimal cutsets and a description of the software is found in Goodman (1988).

Following the qualitative or cutset analysis, a quantitative assessment of the fault tree was conducted. This involved using actual probability data for the initiating events to obtain the likelihood that fatalities would occur. Perhaps more useful information, however, would be the effects of various actions on improving the chance for a successful escape. For example, what are the effects of reduced evacuation delays or improved worker training on successfully escaping?

To begin these analyses, the probability values for each initiating event in the fault tree were established. To obtain these data, a panel of experts was formed. The main criterion for selecting an individual was technical knowledge in the area of mine fire safety. A simple questionnaire was then used to obtain the input for the fault tree. The questionnaire is described in greater detail with the event values listed in Goodman and Kissell (1990).

This quantitative analysis provided several interesting results. Delays in evacuation again stood out as being most important. In Figure 1, "baseline" represents emergency preparedness resulting in average evacuation delays. Mine X and mine Y refer to operations where the preparedness of the crew is twice as good and twice as poor as the baseline operation, respectively. Figure 1 shows that reductions in evacuation delays result in considerable reductions in likelihood of fatalities. This is not surprising considering that every minute an escape is delayed allows the fire to grow in size and strength. This increases the chance that the escape consequently will be made in great haste and possibly in the presence of dense smoke.

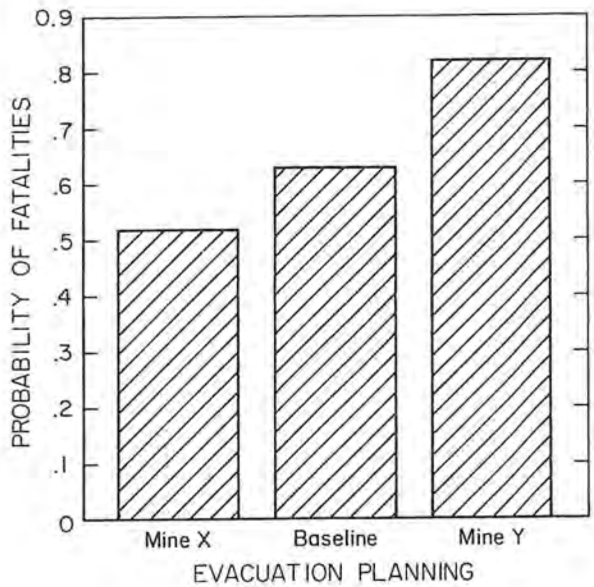

Figure 1. Improved evacuation planning at Mine X improves the chance of a successful escape.

This evaluation also revealed that the chance for a successful escape is influenced by the combination of good escapeway knowledge and good self-rescuer training. Table I illustrates these results, where self-rescuer training is characterized as either poor, fair, good, or excellent. Probabilities of not using the device correctly with these training levels have been derived from previous Bureau work and are given as 0.93, 0.44, 0.40, and 0.10, respectively. The trends shown in Table I make intuitive sense because self-rescuer training alone would be inadequate without knowledge of the proper escape route. Conversely, escapeway knowledge alone would certainly be inadequate without good self-rescuer training.

Probability of Finding Correct Escapeway	Probability of Incorrect SCSR Use			
	Poor Training (0.93)	Fair Training (0.44)	Good Training (0.40)	Excellent Training (0.10)
0.10	0.63	0.63	0.63	0.63
0.50	0.63	0.61	0.61	0.60
0.90	0.63	0.60	0.60	0.57

Table I. Probability of fire fatalities with changes in SCSR training and escapeway knowledge.

The previous group of analyses dealt with the effects of event probability changes on the likelihood of fatalities during the mine fire. Although such changes reduced this likelihood significantly in some cases, the value was still much greater than zero. This suggested that additional improvements might be made to further reduce the chance of fatalities.

The evaluation showed that several actions were necessary to dramatically reduce the chance of an unsuccessful escape. First, delays in recognizing the fire danger, gathering the workers together, and beginning the escape were significantly reduced. Second, the likelihood was very high that the workers picked the correct escape route from the headgate area and that they were able to follow it to a point outby the fire. Third, the workers were well trained in the use of the self-contained self-rescuer (SCSR). Finally, the panel stoppings were well constructed to minimize the effects of dense smoke on the escape attempt. Given all these factors, there was a 95% chance that the workers would make a successful escape from the mine fire.

It is interesting to note that the chance of fatalities was reduced by improving certain areas such as evacuation training, SCSR training, and stopping quality. In these cases, however, the improvements were somewhat limited in that the chance of fatalities still remained high. The fault tree showed that a dramatic reduction in the likelihood of fatalities was possible with simultaneous improvements in several areas. The required areas and the amount of improvement was determined only by a thorough assessment of the miner escape scenario using rigorous risk analysis techniques.

HUMAN VERSUS ENGINEERED ELEMENTS

In this study, fault tree analysis has been used to analyze the scenario of workers escaping from a mine fire. The results have shown that a number of factors influence the success or failure of the escape attempt. As a means of further evaluating these factors, they are categorized as human elements or engineered elements.

Human elements are those affected by human interaction and the success or failure of which can be influenced by human reaction. The majority of events comprising the miner escape scenario deal with such human-oriented factors. Examples of these include evacuation delays, knowledge of the proper escapeway and escape procedures, and self-rescuer training.

Engineered elements, on the other hand, are characterized by a physical design. Their reliability during the fire is dictated by the success or failure of that particular design. In this study, engineered elements include the failure of the remote sensing system, the failure of the mine communication system, and the ability of the stoppings to resist smoke leakage and fire damage.

In general, the human element represents the weak link in any system involving both human and engineered elements. This is not surprising, considering that engineered elements can be redesigned to improve durability or reliability. The improvement in safety can be calculated and proven using accepted engineering relationships. The human element, on the other hand, cannot be categorized so completely. The area of human engineering and human reliability is far less precise, and until recently, many safety analyses ignored the effects of human performance (Swain and Guttman, 1980).

Many industries have now recognized the need for human reliability analyses. Their findings clearly revealed that humans have acted not only as accident initiators and propagators, but also as accident mitigators during several industrial accidents.

Given the increased prominence of human reliability analyses in these industries, the importance of such analyses in the coal industry cannot be ignored. From the evaluations of the fault tree, it is clear that a majority of fatal event sequences involve the human element. It therefore seems appropriate that major improvements in mine fire safety can be achieved by placing more emphasis on the human elements of miner escape.

The first of these elements concerns delays in evacuation. The delay is the time that it takes the miners to recognize the fire danger and make the decision to evacuate from the headgate area. Again, the importance of prompt recognition and reaction to the fire danger cannot be overemphasized. Quick response reduces the chance that the stoppings will be breached by the fire or that critical escapeways will be choked with dense smoke.

Many operations formulate contingency plans to help management and workers in case of an underground emergency, such as a mine fire. These plans are used to establish communications between management and those workers who may have up-to-date knowledge of the fire. In this way, timely and accurate information on fire strength and location can be relayed to those workers inby the blaze so that they can quickly begin their evacuation.

The second human element deals with knowledge of the available escape routes from the headgate. In a mine fire, dense smoke could fill the escapeways and reduce visibility to less than a foot. In this case, the workers' evacuation would be slowed considerably due to the low visibility. Because of the slow progress, it would take much more time to get outby the fire. Because the fire would burn longer, the risk would greatly increase that the workers would find outby escape routes blocked by the effects of the blaze.

Knowledge of the available escape routes not only means choosing the correct escapeway, but also being able to navigate that entry when needed. This is very important in two- and three- entry gate road designs where increased airflow leads to increased pressure differentials across isolation stoppings. This may result in increased leakage and hence an increased chance of smoke in lower-pressure belt and return escapeways.

As longwall panel lengths continue to grow, the reliance on good escapeway knowledge will also grow. Future "super longwalls" will mine panels exceeding 1,000 feet in width and 10,000 feet in length. The problem of miner escape will then be compounded by increased stopping leakage resulting from increased ventilation requirements at the headgate. During a mine fire, the risk to evacuating workers would increase due to the longer distances that they would have to travel to get outby the fire and due to the increased amounts of smoke leaking into lower-pressure escapeways.

To improve the chance of a quick withdrawal in the smoke, many companies use "dense smoke" or safety lines in return escapeways. These are nylon or plastic covered wires hung along the rib or along the center row of bolts, if rib sloughing is a problem. Cones are often strung along the line with the apex pointed inby. During evacuations when visibility is a problem, the miners can hold on to the safety line and feel their way outby.

Some companies also add extra lines running from the main line into crosscuts where mandoors are located. This allows the workers to move from the return into a crosscut, feel the mandoor to see if they are outby the fire, then move back into the return without getting turned around.

The final human element is self-rescuer training. Although this is primarily concerned with hands-on training using the self-contained self-rescuer, many companies are progressing beyond this stage. These operations typically augment conventional SCSR training with training in smoke-filled chambers. One company has the workers first gather outside the chamber and don their W-65 filter self-rescuers. They enter the chamber into dense smoke and must first put on the SCSR devices. While still in the dense smoke, the workers must then walk through an obstacle course before exiting into fresh air. The aim of these exercises is to prevent the workers from just "going through the motions" during training class, while adding a touch of realism and urgency to the donning process.

PROMPT RESPONSE TO MINE FIRES

The importance of minimal delays in a successful escape is similar to the findings of others regarding the importance of time in fighting a mine fire. A quick response by knowledgeable firefighting personnel could mean the difference between an extinguished fire and one that burns out of control. It should come as no surprise that time is one of the most important factors in controlling a fire. In fact, many solid fuel fires (coal included) are very feeble when ignition first occurs. It is only after an appreciable amount of time that the combustion process accelerates (Browning, 1980). Thus, prompt reaction to the fire danger can improve the chance that the blaze is successfully contained and extinguished.

To reduce delays in fighting the blaze, an increasing number of operations are providing their workers with intensive fire fighting training. This training often goes beyond the conventional miner instruction and includes hands-on training with fire hoses and nozzles and even foam generators. These people, drawn from on-shift workers, are trained to quickly confront and control the fire in its early stages before its growth accelerates. The importance of time in successfully extinguishing a mine fire is consistent with its importance in successfully escaping the blaze and its toxic gases.

CONCLUSIONS

The Bureau of Mines used fault tree analysis to study those factors influencing escape from an underground coal mine fire. Using both qualitative and quantitative assessments, it revealed that avoidance of evacuation delays was the most important factor in successfully escaping from a mine fire. Other factors included a combination of escapeway knowledge, self-rescuer training and stopping construction.

It was also possible to dramatically reduce the probability of mine fire fatalities. This required minimal delays in detecting the fire and evacuating the area, excellent knowledge of the escape routes, improved stopping resistance to smoke leakage and fire damage, and good SCSR training.

The results of this study also revealed that the human element plays a significant role in the successful evacuation of workers. This suggested that several courses of action might be taken to improve mine fire safety. These include improved contingency planning to effectively deal with mine fire emergencies, enhanced worker training in using available escapeways and safety lines, and augmented self-rescuer training in smoke-filled chambers.

It was also shown that delays are important when fighting a mine fire. To minimize delays in fighting a fire, an increasing number of operations are training their workers to quickly and effectively confront the mine fire.

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