Entrapment and Escape from Metal Mines: A Case Study

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SUMMARY

The nature of underground metal mining has changed dramatically over the past 30 years. Major investments in new plant and equipment and new mining methods has lifted productivity and lowered costs. Australian miners have often led the way in these areas. However, many mines have failed to keep their entrapment and escape (egress) procedures and technology as modern and effective as other areas of their operations. A risk-based assessment at MIM's new Enterprise mine came to the conclusion that the prospective risk from a mine fire would exceed acceptable standards. A satisfactory entrapment and escape system was developed which has six components. These are: early detection and warning of personnel, personal belt-worn oxygen-generating self-rescuers, high integrity escape routes and self-contained refuge stations, simple procedures, reliable personnel "tagging" systems and sufficient, trained, search and rescue and fire fighting personnel and equipment. Implementation of these principles has resulted in a dramatic improvement in the ability of the mine to get its workers to safety as soon as a mine fire or other emergency is reported.

INTRODUCTION

The *nature of underground metal mining* in Australia is changing. Consider these points:

- Many mines are becoming deeper and hotter. This has a major impact on entrapment and escape.
- The number of items of diesel equipment in use and their engine size has expanded exponentially.
- Sources of combustion have changed from mainly timber, to mainly fuels and oils, conveyors, plastics and electrical cable insulation.
- Mining methods have moved towards more productive practices with fewer workers for the same output. More workers are now working alone and in isolation.
- Many workers now work from inside air-conditioned cabins.
- Few miners now "walk" to their job. Most drive and will be unfamiliar with the traditional escape routes, many of which require walking or climbing up ladders.
- Some mines no longer reticulate compressed air, or use polyethylene piping to do so.
- The aerobic fitness levels of miners has fallen. Many mine workers are now involved in largely sedentary jobs.
- Organisations are "flatter"; there is now less experience in most mines at all levels and in total. This lack of organisation experience and memory particularly manifests itself when "rare" events such as emergencies occur.
- Many mines have changed to "fly in, fly out" arrangements. Key staff are not always on site.
- The out-sourcing and centralising of many functions means that many planning, technical and sometimes even operating staff may be in a head office, or in a consultant's office, and are no longer on site.
- Real prices of metals has fallen and continues to fall. The pressure to reduce costs is relentless.

Escape and rescue technology has also changed dramatically due in part to the demands of the NASA space program and the more sophisticated needs of the defence industry. Radios are in common use underground. Through-the-rock communication systems are also becoming more common. Smoke and POC detectors are freely available. Personnel tagging systems have become more sophisticated and self-contained (oxygen-generating) self-rescuers are now at a size where they can be belt-worn during ordinary duties.

Community tolerance of mine fatalities has also changed. What was, sadly, once considered to be almost inevitable in the mining industry is now not acceptable. Moreover, the attitude towards mine rescue is also changing, from the view that heroic measures which endanger the lives of rescue brigadesmen is acceptable, to one where no further lives should be placed at risk.

Finally, the *legislative and statutory framework* in which mines operate has also changed dramatically from the highly prescriptive and "backward looking" nature of detailed regulations to the more "forward looking" and risk based "duty of care". The risk of harm is now required to be "as low as reasonable practicable" and the risk of death or permanent injury to be "not substantially greater than zero....or extremely rare".

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Mining engineers tend to be familiar and well trained and experienced in the areas of production methods and cost control. However, most lack an understanding or appreciation of the need for the same sort of diligence and disciplined approach to the area of entrapment and escape. Most have little understanding of human physiology and its limitations. They certainly have failed to notice the changes outlined above and the impacts these can and should have on escape systems. Many are still relying on entrapment and escape strategies that date from the last century.

ENTERPRISE MINE CASE STUDY

The Enterprise mine project (EMP) is located at Mount Isa, Australia, and is wholly owned by Mount Isa Mines Limited. It is being developed, at a cost of $330 million, from about 1 000 m below surface to 1 700 m below surface and over the next 15 years, will extend to 2 000 m below surface. The project is designed to upgrade the existing 1.5 Mtpa operation to 3.5 Mtpa. Expected completion for the development and construction program is late calender 1999. During construction, the underground workforce will peak at 700 persons, with a workforce of 400 required during on-going production.

The Fire Hazard

Early in the study, it was recognised that a major fire was the most credible emergency egress situation in the EMP. This is because humans can only survive a few minutes with insufficient oxygen, and can only survive for as little as seconds when some poisonous products of combustion (POC) enter the lungs. Underground mine fires consume large quantities of oxygen (potentially producing oxygen deficient atmospheres) and produce large volumes of carbon dioxide[1] and carbon monoxide, plus many other toxic gases. Any other credible disaster scenario at EMP provides a longer safe response time than a fire. Moreover, because the ventilating air enters all the workings, a fire is the only credible hazard with the potential to affect a large number of persons.

This conclusion is consistent with experience in the USA which shows that, despite underground mining contributing only a very small percentage of industrial output, of the 98 industrial fires from 1900 to 1990 which resulted in 50 or more deaths, 51 of these fires occurred in mines (Hartman et al, 1997).

It must be emphasised that if a serious fire breaks out underground, lives are immediately in danger and the risk to life and health is very high, even with the best of emergency plans. Therefore preventing fires is remains the highest priority in terms of egress strategy. However, the Isa mines have a good record in preventing serious fires underground and, while it was recognised that these existing measures also need to be reviewed, the most urgent issue was identified as being the contingency plan in the event of a major underground fire.

Overall Philosophy

There were some guiding principles required in the design of any emergency system at EMP. These were based on the fact that a disaster scenario, almost by definition, has a very low probability of ever happening, and will therefore be outside the experience of most mine workers and managers. These principles include:

- The acceptable level of risk. At EMP, it was decided to start from the presumption that “there should be negligible risk of any *further* harm to anyone as a result of the disaster”. In other words, people may have been injured in the initial incident which gave rise to the disaster (e.g. burns) but there should be no further harm to themselves or others resulting from the POCs from the fire. The very fact that a major disaster has occurred underground means “we have failed once”, the egress protocol is to ensure “we do not fail again”.
- The overall system used must have a minimum of complexity for the operators: the “keep it simple” principle. It must be able to handle the likely level of panic and confusion in an emergency, and therefore rely to the least possible extent on the mine worker’s memory or compliance with procedures for effectiveness.
- The equipment within the system must be able to be used almost intuitively (e.g. opening and donning of self-rescuers and use of breathable air equipment inside refuge stations).
- The system and equipment in it must be fail-safe, or have effective backup.
- Equipment must be easy and inexpensive to maintain. Where practical, equipment should be “dual-purpose”, i.e. used for both daily operations and emergencies, as experience shows that equipment which is used for routine operations tends to be better maintained than equipment which will only ever be used in a “disaster” scenario.
- The systems must provide a high degree of on-going operational readiness.

[1] Carbon dioxide is twenty times more soluble in blood than is oxygen. Haemoglobin has an affinity for carbon <u>mon</u>oxide about 300 times that of its affinity for oxygen, plus haemoglobin is <u>un</u>stable - therefore releases oxygen readily - whereas carboxyhaemoglobin is stable and therefore accumulates in the blood.

- The systems (e.g. escapeways) must be capable of being traversed by mine workers who meet the minimum physical fitness requirements for the mine. Much of the work in modern mining is now fairly sedentary and the fitness levels of many miners is poor. They would be unable to "self-escape" up any significant vertical distance using a ladder, or even a significant distance of ramp.

Issues to be Considered

An early question asked in the review was "what are the fundamental differences between a large *underground* industrial facility (i.e. a mine) and a large *surface* industrial facility (e.g. a skyscraper)".

Because above-ground facilities are more numerous than underground mines, fires in above-ground facilities are also more common, in absolute numbers, than in underground mines. Vast experience has been gathered as to the precautions that are required in above-ground facilities to prevent a serious fire resulting in loss of life. These precautions include:

- Early detection of the fire through smoke and other detectors.
- Activation (automatic) of an alarm system that immediately notifies all potentially affected persons.
- A "fail-safe" non-mechanical second means of egress which provides quick and/or secure access to safety.
- Sprinkler systems or other fire suppression systems.
- Regular fire drills to ensure all persons know what to do, where to go, etc.

To some extend these measures have not been adopted in underground mines because the technology (e.g. reliable, instantaneous communications) has not been available in the past; however, this is generally no longer true.

It should also be noted that the fire detection, alarming and suppression systems in most large commercial above-ground buildings constitutes between 2% and 5% of the total capital cost. Very few underground mines would spend anywhere between 2% to 5% of the total project cost on fire prevention and control systems. This is one indication that the fire hazard in underground mines is not yet fully considered at the feasibility or operational stage.

As discussed earlier, it is rare for anyone underground in a metal mine to be in danger from the fire itself. It is the products of combustion (POC) that present the danger[2]. In many respects the safest thing a person could do in the event of a serious fire producing lots of POC would be to don a self-rescuer and wait until the fire went out or was put out. This is because of the hazard posed by trying to travel through smoke. The underground environment is generally unlit. Floors are often rough. Drives are sometimes cluttered with equipment or conveyors. Visibility in smoke is poor and sometimes nil. If anyone is in doubt about the visibility problem when in smoke, a simple test is to turn one's cap lamp off when underground and notice the immediate disorientation and anxiety that occurs. There is the hazard of falling down or driving down vertical openings, such as stopes or passes, even with barricades installed. In nil visibility situations, persons very rapidly become disoriented and lose direction. Experience at Isa is that workers can even be mistaken about such basic things as whether they are travelling *up* or *down* a 1 in 7 ramp.

Problems with Current Approaches

Because of this, a foundation upon which the egress strategy at Isa in the past has been based is the maxim "Do not enter smoke". This presumes there are credible other alternatives, such as escapeways and entrapment procedures. The "fail safe" entrapment procedure at Isa has previously been to tie one's shirt to a compressed air outlet, or to cut a hole in a vent duct and breath fresh air from the duct. However, these have serious problems at EMP:

- The standard development size is 5 m x 5 m or larger, so mine air outlets and vent ducts are normally too high to be reached without a tall vehicle.
- It is not practical to put air droppers from the compressed air line to ground level frequently enough to provide for entrapment[3].

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[2] In coal mines, there is also the danger of an explosion or of the coal seam catching on fire. Therefore getting workers out of the mine is critical. Plus, there is now more reluctance to allow mine rescue teams to enter a coal mine where an explosive mixture of gases is known to exist. In such circumstances, mine workers must effect their own "self-rescue" (Anon, 1998)

[3] However, the 'entrapped' procedure using compressed air line and one's shirt is still taught as development ends often do have accessible compressed air.

- With the size of diesel equipment now in operation in modern mines, a fire could easily have sufficient heat to burn out the connections in the mine air lines, to burn the vent duct or even to reverse the ventilation flow.
- Working places are supplied with refrigerated air directly from fresh air raises using flexible plastic ventilation ducts. The fresh air raises operate under *negative* pressure so a fire in a vent duct which trips out one of the many fans connected directly to the raise, will result in polluted air re-entering the raise, which would compromise the air in the raise and any other working places fed from the raise.
- With the high temperatures in EMP during summer, persons need to drink water to maximise their probability of survival. Water may not be available in either of the above entrapped procedures.

The issue of "second means of egress" (a statutory requirement) was also given considerable thought during the review. The EMP has three main means of egress, these being a 1 in 10 gradient production ramp, a second 1 in 7 service ramp and an inclined ladderway in a fresh air raise. Each of these connects most of the main working levels. However, the reality for EMP, as for all mines, is that the mining operation itself requires development of new sources of ore and therefore new working places, many of which are, at least initially, "dead ends". In fact, the high activity areas of the mine are often the areas currently being developed and these will rarely have two separate and independent means of egress with separate ventilation. Moreover, most modern mine workers are not especially fit, and never use ladders in their ordinary course of work. The necessary work rate and unfamiliarity of miners with climbing ladders resulted in the EMP review coming to the following conclusions:

- a second means of egress is required from all main working areas, *but*
- the second means of egress is *not* primarily for workers to escape; rather it is for access by mine rescue teams to workers who have taken refuge in safe areas or to search for and rescue lost or trapped workers, including retrieval of the injured using stretchers.

This conclusion is endorsed by the South African Mineral Act Regulation 24.20.2[4] which states:

> *The manager shall see to it that there is a refuge bay or other safe area in a mine or works within easy reach of workmen and within the limits of protection afforded by a rescuing device, in the event of an explosion, fire or other emergency.*

In a metal mine, the most probable cause of a major fire is either mobile diesel equipment or a conveyor. It was agreed that the *shortest* time to detect the fire and communicate the problem to Mine Control[5] is ten minutes[6] from the start of the fire. Isa mine has between six and eight fully trained, volunteer mine rescue crews available (on call) at any given time plus two full-time mine rescue co-ordinators. The minimum time required to assemble a mine rescue crew on the surface is 20 minutes from notification. The best response of Mine Rescue is to be underground and at the fire within another 20 minutes. By this time, a *minimum* of 50 minutes has elapsed from the start of the fire. At this point, any fire on a conveyor or diesel equipment would be a raging inferno. The best Mine Rescue could hope to achieve, in terms of putting the fire out, is a further two hours; the worst is up to four hours[7].

Therefore, there are several critical reasons to get people to safety quickly:

- To have a truly credible "entrapped" procedure would require a person to have a fail-safe supply of breathable air for at least five hours. This rules out even the largest of belt-worn, self-contained self-rescuers (SCSRs).
- It is difficult, if not impossible for relatively untrained miners to drink water safely without contaminating their self-rescuer. If "trapped" in very hot conditions without water, survival time could be limited by maximum dehydration to 5 to 6 hours (about 10-12% of body weight (Adolf, 1995)). However, acute thirst will be felt at 4% dehydration, which could be reached within 2 hours, and even earlier if the worker is already mildly dehydrated before the emergency occurs, as would often be the case.
- The EMP operation is geographically large, and mine rescue crews need to know who is unaccounted for, before starting an effective search and rescue operation. If there are numerous miners using an "entrapped"

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4 This 1956 Act was replaced with Duty of Care style legislation in 1991, but the basic principle remains.

5 Mine Control is a surface control and emergency centre which is manned continuously.

6 If the fire starts when someone is present, then the first response is to try to put the fire out, usually with two fire extinguishers on larger items of equipment, in addition to engine fire suppression equipment, where fitted. Hence at least ten minutes would occur before any phone call could be made.

7 After two hours, most of the fuel and oil on a large piece of mobile equipment would have burnt out and the fire could be contained. The four hour scenario assumes the fire is upwind or at a higher elevation than the fire fighters; both of these situations make the fire very difficult to approach or to fight with foam.

procedure and unable to communicate with the surface, then resources and time will be wasted and lives could be lost.

- Most miners would experience distress and panic if trapped in smoke for several hours. It is common for persons who wear face masks for several hours to become quite agitated. There is a high probability that personal judgement would be impaired, especially if the individual is also dehydrated, which could result in increased risk of injury or death. This is reinforced by the history of self-rescuers, which shows that hundreds of miners have died "sucking on the ends of self-rescuers"[8]. However, few if any, have died after reaching an emergency refuge station.

A New Approach

These observations led to the following conclusions:

- There is no entirely reliable, credible, "personal" entrapment procedure for EMP for the duration of a serious fire.
- Emergency refuge stations are required and need to be located to ensure all persons can access the station; the stations need to be designed to keep the occupants safe for up to 8 hours before rescue. The design of emergency refuge stations must be based on sound physiological and other criteria (Brake and Bates, in prep).
- Second means of egress are not primarily for workers to escape, but for mine rescue teams to access workers who have taken refuge in emergency refuge stations.
- Miners at EMP may need to travel through smoke to get to an emergency refuge station. To maximise the likelihood that this could be done safely, the evacuation order must be given as early as possible, and the message must reach the miners as early as possible, while smoke levels are still light.
- Previous tests of stench gas at EMP showed that it could take up to two hours to evacuate the mine using stench gas and even this did not achieve 100% reliability. The radio system, even though it is extensive, relies on a leaky feeder antenna, and cannot guarantee reliable communication to all areas, plus the antenna could be damaged in the fire and most radios are vehicle mounted and therefore would not reach persons who are distant to a vehicle. Furthermore, most mobile equipment at EMP are air-conditioned to reduce the heat and this compromises the stench gas warning. The increased usage of respiratory protection can also result in people not smelling weak stench gas signals. In addition, stench gas cannot communicate anything more than an evacuation order. It cannot, for example, indicate where the fire is, or ask an unaccounted person to call in. Therefore a faster and more effective system is required. This led to adoption of a "through-the-rock" radio communication system[9], which provides more effective, though not fail-safe, one-way communication to personnel.
- To ensure travel through smoke is possible, self-contained self-rescuers are required. Experience at other operations shows that these must be worn to ensure they will be available when required; at EMP, this has led to the adoption of a 30 minute SCSR as standard requirement, based on weight and size considerations.
- SCSRs are primarily for travelling through smoke to an emergency refuge station; they are *not* primarily intended for entrapment.
- It was also at this point that the decision was made to go to oxygen-generating self-contained self-rescuers and not to adopt filter-type self-rescuers[10]. The products of combustion in an underground mine fire on electrical

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8 For example, in the 1972 Sunshine Mine (USA) fire in which 91 miners died, many died wearing their filter-type self-rescuer. This problem is not confined to filter self-rescuers, as records from South Africa show that from 1987 to 1994, 48 fatalities (17% fatality rate) occurred in spite of activation of self-contained self-rescuers (Anon, 1995). In the 1994 Moura coal mine disaster, two coal miners drove out of the mine, after the initial explosions, without donning their self-rescuer. They were in such a hurry to get out, it never occurred to them to don their SCSR.

9 Such a system is the PED™ or Personal Emergency Device, which relies on the fact that high-wattage, ultra low frequency radio waves can travel through rock, similar to the way communication is achieved to deeply submersed submarines. The receiver is retro-fitted to the standard cap lamp battery, and buzzes and flashes the cap lamp when a message is received. The message is displayed on a back-lit LCD display and the memory stores up to three messages. When no message is being received the received displays the time signal from the transmitter.

10 Even though at EMP, SCSRs are primarily to travel through smoke and not for entrapment, it is recognised that if a person was truly "trapped", for example, in a development end, then the SCSR should protect them from POCs for at least the duration of the SCSR. For a nominal 30 minute SCSR, this could be 100 minutes for a person at rest.

cables and other plastics[11], diesel plant, hydraulic power packs, conveyor belts, diesel fuel stores, explosives, ventilation bag and a myriad of other sources are so varied and so toxic that filter-type self-rescuers were excluded from further consideration. A further factor was that the Western Australian Government guidelines are strongly encouraging oxygen-generating self-rescuers, and in Queensland from 1 January 1998, only oxygen-generating self-rescuers can be provided as new issues into coal mines.

- To ensure the evacuation order can be given as quickly as possible, emergency procedures needed to be changed to give the mine control officer the authority to issue this order. Previously, a very formal process of entering "yellow alert", "red alert" and "double red alert" was required before an evacuation order could be issued at EMP.

With these key conclusions in place, the spacing of Emergency refuge stations could be calculated.

Australian self-rescuers are generally rated under the European standard, EN401, which provides for a breathing rate of 35 litres per minute for a 70 kg worker. This is a moderately hard work rate, and the duration of the rescuer will be significantly longer (up to three times as long) at rest. Nevertheless, it is good practice (Anon 1997) to de-rate the SCSR to 60% of its nominal duration to allow for heavier persons (the 95th percentile). For a 30 minute unit, this means it is de-rated to 18 minutes.

A good practice design speed for escape under good conditions is 4.5 kph (Anon 1997). Under adverse conditions (e.g. dense smoke), escape speeds are reduced by 40% (Anon 1997). Therefore, assuming adverse conditions, no person should be further than 18 mins x 4.5 kph x (1-40%) or 750 (say) metres from an emergency refuge station at any time. Full consideration must be given to the location of these emergency refuge stations during routine mine planning and operational planning activities.

For mines or regions within mines where workers or visitors are not required to wear SCSRs, the maximum distance from an ERS was recommended to be 5 minutes at 4.5 kph or 375 m.

Note that these distances are towards the lower range of other figures quoted which vary from 750 m to 1.5 km. However, if a mine worker is *not* downwind of the fire, then "any" distance to refuge is safe. It is only the workers who are downwind of the fire who are at risk (at least initially) and 750 m is a long way to be travelling through smoke. Even with early warning systems, these workers are more likely to smell or see the smoke before receiving any warning. Fires on underground vehicles produce large volumes of black, toxic fumes within minutes of the fire starting.

Providing the evacuation order is given early, most workers will be able to access an emergency refuge station within 750 meters / 4.5 kph or about 10 minutes. In fact, most workers will be less than 750 m away and will be at the Emergency refuge station within about 5 minutes. This is exactly what a good egress strategy needs: most affected persons being able to escape to safety in very short time. In fact, at EMP most workers will be at safety before the first-response Mine Rescue team can be assembled, and even before the mine management can reach the command centre (assuming an out-of-work hours fire).

In the EMP, this requirement for no person to be more than 750 m from an emergency refuge station resulted in the requirement for 22 relocatable Emergency refuge stations, each designed to accommodate 8 persons (but in an emergency, more could be accommodated). Moreover, the three existing cribrooms (lunch rooms) have been converted into emergency refuge stations each capable of accommodating 40 to 100 persons. These precautions are necessary because of the highly mobile nature of the workforce and the very real possibility that a fire could occur during shift change or meal breaks.

To ensure mine rescue resources can be targeted to "unaccounted" persons, it is important that workers do not travel past the nearest Emergency refuge station, e.g. to travel to the cribroom. At EMP, it could take 20 minutes for persons to reach the main cribroom, even in a vehicle, and much longer on foot. Moreover, if people do travel to the nearest Emergency refuge station but do not reach it, then the search area can be greatly reduced; the mine rescue team will be able to start at the nearest station to the lost person's workplace and work backwards.

All persons in EMP will need to know where the nearest Emergency refuge station is at all times. This is difficult with a highly mobile workforce, contractors and visitors. Induction and annual refresher training is not effective in this sort of role; instead it is planned to have workers use their daily safety sheet, which is carried on their person,

[11] The plastics of main concern are polyurethanes, nylon, and PVC. All plastics give off copious quantities of carbon dioxide and carbon monoxide when heated. However, dangerous concentrations of hydrogen cyanide are given off from polyurethane, nylon and some other polymers when heated above 200^0 C. This happens whether the plastic is on fire or not, and even when there is no oxygen present. PVC also releases hydrochloric and hydrofluoric acids. Polyethylene and polypropylene give rise to only CO and CO_2 when heated, provided other materials such as plasticisers or fillers are not present. (Greig, 1989).

to note where the nearest Emergency refuge station is. Moreover, as mentioned earlier, the three cribrooms in EMP are all being designed to function as large capacity Emergency refuge stations to cover the situation where workers do come back to these well-known facilities.

For persons who are working in remote areas out of reach of an emergency refuge station, an egress permit to work will be required, which will ensure special precautions are in place in the event of a fire. Special barricades and signs will delineate these areas.

There are two other key items required in this overall strategy. The first is an effective personnel disk board (tagging system), to ensure speed and reliability in accounting for persons in the event of an egress being triggered. The effectiveness of the overall program is reduced if persons rapidly get to safety, but confusion and delays then occur in accounting for those safe versus those unaccounted.

The second is a fire detection system (where practical) to provide early warning of a fire. Metal mines typically have much more intense use of diesel powered equipment and of blasting fumes than in coal mines, and this must be taken into account in any choice of sensors and the gas protocol to ensure there is not an unrealistic number of nuisance trips.

Feasibility, Pre-Production and Construction Issues and Formal Risk Assessments and Audits

As with many projects, the highest workforce numbers and least familiar workforce often occur during the construction phase of the project. Activities in this phase are "one offs" compared to the more routine nature of activities once production is established. Fire hazards are high. Special effort needs to be made to ensure emergency egress capability is as good during construction as during production. In effect, EMP was faced with considering two phases of emergency egress: one for the construction phase where the workforce would be large and inexperienced in the underground environment, and the second for the on-going operation.

It is also crucial that the separate issues of emergency egress at both the final production stage and during construction be given proper consideration during the feasibility study. This should not have to be done "on the run" once the construction program has started. Critical issues are the integrity of the primary air intakes. What happens if various combinations of surface or underground fans go off-line? If there is a total surface and underground power failure, what happens to the primary ventilation? What effect does natural ventilation energy have? Will the direction of airflow reverse and how long will this take to occur? What environmental conditions will be experienced?

There is a tendency for the key design concepts of even the most carefully crafted egress system to be "lost in time", particularly with turnover in mine planning and operations personnel. Any critical aspect of the egress system cannot just be recorded in some notes or a report. Mine design working drawings and check-lists must be annotated to ensure key egress design criteria are not forgotten in the future.

Formal Concept, Design and Construction Risk Assessments (at each stage of plant engineering) have proved invaluable at EMP in assessing the sufficiency of emergency egress procedures prior to commencing particular design or construction activities underground. "Boilerplate" solutions to egress problems, blindly applied for token compliance, do not provide real answers to these problems. There is no substitute for formal, "first principles" risk assessments which involve the operators and designers in the process.

Finally, there is a need to ensure, after the egress measures are implemented, that the original "residual risk rating" has in fact been reduced to the desired level, and to ensure, by auditing, that operational readiness is achieved and maintained.

Triggers for Egress

Whilst there are many valid reasons to evacuate a mine, the following are some of the critical triggers with respect to risk to personnel from fire:

- confirmed or suspected underground fire irrespective of size (unless already extinguished),
- compromised primary ventilation system (fans and/or intakes, ventilation controls) which impacts on the integrity or readiness of the egress system,
- failure of mine fire fighting systems (e.g. loss of water supply if the mine partly relies on sprinkler systems),
- compromised primary ventilation intake air (an example could be a surface fire or chemical spill which could affect the fresh air intakes. For this reason, great care should be taken in allowing combustible or toxic material (diesel fuel storage, heavy vegetation, ammonia refrigeration plants, etc) near fresh air intakes,
- seriously compromised egress system equipment (communication equipment, breathable air systems, recall of self-rescuers, etc).

The Operational Emergency

Methods of directing fire fighting in mines have been described elsewhere (De Klerk, 1998). However, EMP experience is that key points include:

Early alarm and evacuation. It is critical to ensure that as soon as a fire is suspected, someone *on site* has the authority and is required to order an evacuation. Some "false alarms" will inevitably disrupt production but better this than time being lost in a real emergency. The mine manager or another off-site or off-duty executive should *not* be the only person empowered to order an evacuation. Two examples tragically illustrate this point:

- The Sunshine mine disaster of 1972 started with a small fire while the senior mine management were 45 miles away attending a stockholders meeting. With insufficient experienced staff on site, the fire became much larger and claimed 91 mine workers.
- In the Wilberg mine fire in 1984, senior mine management had gone underground to witness an attempt to break a production record. They were trapped behind the fire and 8 senior mine managers along with 19 other mine workers ultimately lost their lives.

Keeping the ventilation system intact. Large metal mines tend to have very complex, three-dimensional ventilation circuits. It is highly desirable for the primary ventilation system to remain intact and functioning normally during the fire (explosions have occurred through carbon monoxide, a POC, being drawn back over the fire because of reversals in the ventilation system). This improves the security of the remaining circuits and therefore enhances the probability of successful egress for those underground. Some exceptions to this rule exist, but these usually relate to situations where the security of the primary intake itself is threatened. The on-going integrity of the primary intakes to unaffected working areas is paramount in a mine fire.

Does the fire need to be fought? Fighting an underground fire is a hazardous activity. Generally, the safest course of action is to let the fire burn itself out (or at least reduce in intensity), providing it has been contained and no personnel are at risk.

Buying time. Enormous confusion and often conflicting reports occur in the early stages of a mine fire. A critical objective of the fire director is to buy as much time as possible without putting lives at further risk. This reinforces the point that a good strategy is to get people to safety quickly so that there is time to consider further options and to resolve the confusion and conflicting reports.

Targeting search and rescue resources. Simultaneously fighting a fire and searching for and rescuing lost workers requires a large number of highly trained personnel. It is crucial that search and rescue resources can be targeted and not sent off looking for workers in the wrong place, or workers who are already safe. If personnel tagging systems are used in the mine, these tags must be able to be interrogated during the mine fire. By implication, the location of these tags needs itself to be secure and accessible.

Mechanistic approach. Mine officials are rarely experienced in fighting fires or in managing emergency egress situations. Training is of some value. However, it is imperative that a control room exist which has "boards" for all the relevant information on its walls. Even the inexperienced fire director who is under great pressure and not necessarily thinking clearly can then see visual "memory prompts" reminding him of the sorts of activities he should be doing or monitoring during the course of the emergency. The key issues the fire director needs to know to safely manage the fire must *not* be available only via a lengthy, difficult to find and usually outdated written report.

One Final Point: Leadership

There is one almost overriding additional requirement for a sound emergency strategy in any mine: this is the support of line and senior management. Unless senior management believes mine workers need a fair chance of survival in the remote likelihood of a fire or other emergency, resources will not be made available for the strategy to be developed and implemented. Just as it costs serious money to equip a hotel building or factory with fire escapes, smoke detectors and remote alarms, so too, providing a credible escape strategy for an underground mine will cost serious money.

Then there is the issue of support from the line: line management must also positively support the arrangements, otherwise they will be poorly implemented or not maintained and when required, they will not perform.

At its most basic level, this resolves down to leadership: committed, enthusiastic, consistent leadership is required for any mine to develop and maintain a credible escape strategy with a high on-going degree of operational readiness.

Summary

After attaining full production, Enterprise Mine will be the primary source of copper production for Mount Isa for at least the next 15 years. It has some unique features that have led to the development of leading-edge technologies and practices in a number of areas. A comprehensive emergency egress plan has been adopted by EMP which will result in acceptably low levels of residual risk for the workforce, even in the event of a remote probability catastrophe such as a major fire underground. This strategy will also significantly enhance the ability of Mine Rescue to rapidly complete search and rescue operations at greatly reduced risk to the mine rescue teams themselves.

This strategy is built around the following key principles, which are listed in decreasing priority according to their individual impact on reduction in overall residual risk at EMP:

- The earliest possible notification of the fire from mine control to the workforce using a through-the-rock communication system.
- Emergency Refuge Stations to ensure all persons can reach safety within 30 minutes of the alarm and 95% of persons can reach safety within about 5 minutes
- Revised Emergency Procedures to ensure the early warning technology and the close proximity of Emergency refuge stations can be used to full advantage to target search and rescue operations
- The use of belt-worn self-contained self-rescuers to ensure all persons can get to an emergency refuge station
- An effective Tagging System to ensure reliability and speed in accounting for all persons in the mine
- Fire Detection and gas protocols to provide the earliest possible warning of the occurrence of fire

It is important to recognise that this egress strategy is dependent on the risks at the individual mine. The conclusions in this paper should not be copied into other operations without a full risk assessment being carried out.

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