

Egress and entrapment in hardrock mines (revisited)

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There has been a substantial change in attitude towards egress and entrapment, along with the role and deploy-ability of mine rescue in hardrock mines in Australia over the past decade. Regulators as well as internal risk assessments are deeming situations that would have been acceptable not that long ago no longer acceptable. The rapid development of technology for remote and tele-remote loaders, the size of equipment (and hence development headings) and the introduction of rigorous ground support standards has also led to significant changes in mine stoping methods, all of which have impacts on egress planning. Other enabling factors include the rapid development of fully standalone refuge chambers including highly mobile 4-person chambers. The compulsory use of personal, belt-worn self-contained self-rescuers in hardrock mines (unlike in the USA) has also led to a change in thinking regarding the role of 2nd egresses and in particular ladderways as well as the acceptability of ladderways now being in return air. This paper summarizes what is currently considered to be good practice in Australia in all these areas as well as the reasons why the industry has reached this point, and reviews where egress and entrapment strategies may develop over the next decade.

Changes in technology impacting on operating practices

Developments in technology have had a profound impact on hardrock mines and their associated ventilation systems over the past 30 years. For example:

- Sub-levels can be further apart due to the ability to accurately collar and drill much straighter blastholes. Precision electronic detonators and blasting techniques mean stopes can be blasted in only a couple of firings, reducing or eliminating the need for supplementary access points and therefore reducing the option to use these supplementary accesses for ventilation (e.g. as stope top or side exhausts);
- Remote LHD operation has eliminated the need for “trough” undercuts; the use of flat stope bottoms means the stope is often “open” at its drawpoints which provides a potential short-circuit path for ventilation;
- The size of machinery means that development is much larger so that ventilation controls (walls, doors, etc.) are much more expensive and time-consuming to erect; there is now resistance to install ventilation controls unless absolutely “justified”; the mere blending of used and clean air often does not necessarily meet that threshold. Where controls are installed, the size and construction of them means they are generally much leakier than in the past (including due to their reduced ability to resist many cycles of blasting overpressures);
- Air-conditioned cabins mean operators are no longer exposed to one of the most stressful of airborne contaminants: heat. Good cabin and filter design, combined with cleaner fuel and engines, has also reduced gas and respirable dust and DPM exposures;
- For ease of access as well as operating and maintenance reasons, most mines now have surface ramps; in turn, this means ore can be trucked to surface creating significant ventilation complications and constraints in the ramp;
- The high engine power of individual production units (trucks, LHDs) means a lot of air is required where the machine is working, making one-pass or parallel ventilation difficult and expensive to achieve;
- Auxiliary fans and ducts are much larger. To keep back heights as low as possible and provide safe locations for fans and their electrical starter cabinets, the location for auxiliary fans must often be *pre-planned* and the back and side stripped in this area; once the development is past that point, the ability to move a fan to an unplanned location where the back or sidewall has not been pre-stripped is very poor, significantly constraining auxiliary ventilation options;

- The time value of money and stakeholder requirements for quarterly reporting of improvements has frequently pushed the economic balance of the mining business towards higher operating costs and lower capital costs. It is very difficult to now justify “dedicated” development (vertical or horizontal) for ventilation purposes, except (perhaps) for dedicated surface ventilation shafts and even the role of these is being questioned requiring rigorous defense. Where practical mines will, for example, want to use ducted ventilation systems to ventilate levels (in series with other levels), rather than put in the required horizontal and vertical development to provide ventilation connections between levels for parallel ventilation;
- The very high productivity equipment allows for a much higher production rate for many orebodies than in the past which in turn means the orebody is extracted in a shorter time. The working life of many mine levels is much shorter than previously when productivity was much lower;
- Self-contained self-rescuers are sufficiently small and lightweight to be belt-worn and refuge chambers can be fully self-sufficient for many hours. Communication systems (including the ability to provide warnings of emergencies) have improved substantially;
- There are much higher risks from combustible materials underground (mostly the big diesel equipment with large fuel loads and tires), but these raw risks are increasingly offset by much more sophisticated fire prevention and control technologies and practices.

At least three important ventilation factors result from these changes:

- There is an overwhelming trend towards series ventilation with reuse of air, rather than traditional one-pass parallel ventilation. The main connecting backbone in most mines is now a ramp from surface rather than a shaft and this ramp is also frequently the major ventilation “intake” for the mine or at least the main intake “distributor” (if the ramp flows are supplemented by a surface intake shaft). This, in turn, is having major impacts as follows:
 - It is changing the entire concept of “fresh” air in a mine. Fresh air no longer means what a non-mining layman might assume (i.e. equivalent quality to surface air) but rather, that the air does not exceed the various TWA and STEL values, however these are defined;
 - The use of the ramp to supply fresh air throughout the mine not only means there are major fire risks constantly in the mine intake, but the toxic products of combustion from a fire (in the ramp) will reach workers far more quickly than the ability of older warning technologies such as stench gas. In mines with whole-of-mine series ventilation, it is doubtful if the surface deployment of stench gas in the event of a fire will achieve much practical purpose at all;
 - The elimination of dedicated surface intakes has meant many mines no longer have any secure fresh air bases;
 - This means that, in the event of a fire, workers must usually or frequently travel through smoke to get to a place of safety, unlike earlier times when a fire in a mine using parallel circuits meant the POCs only affected that portion of the mine downwind of that portion of the parallel circuit.
- Ventilation controls are either not present or much less effective than in the past, resulting in frequent leakage, short-circuiting between levels and, in some cases, recirculation. For example, auxiliary fans on a lower level might recirculate when a stope connecting that level to a higher level is open. This also means reliably predicting the potential spread of POCs through a mine is very difficult, as on a particular day, some stopes (or some ventilation controls) may be open or closed or leaking substantially;
- There is an overwhelming trend towards using ducted ventilation rather than undertaking the expense and time required to provide flowthrough ventilation on working levels. Modern mining is far more dependent on ducted ventilation than in the past. [1]

There are also many external factors impacting on egress and entrapment including at least the following:

- Societies (communities), governments and the media all now have very low tolerance of death or serious injury due to workers being entrapped underground due to fire or falls of ground etc. Combined with globalization of the mining industry, general suspicion of the motives of “transnational big corporations”

and the 24-hour news cycle and unregulated social media, disasters can have a devastating and long-lasting impact on corporate reputation, share price and legal and financial liabilities;

- The sometimes nebulous concept of “duty of care” (compared to mere legal compliance with regulations) is either written specifically into legislation, or considered by the public and regulators are being the de facto benchmark standard for mine operators;
- Duty of care now also extends to emergency mine rescue or firefighting crews; these persons cannot be deployed unless their health and lives are not unreasonably at risk. In practice, this is pushing the philosophy of hardrock mine rescue towards self-rescue and away from aided-rescue;
- Risks need to be properly assessed and managed at all times. No lapses in vigilance are considered to be acceptable and management discretion is reduced.

Principles for egress and entrapment

In this author’s opinion, the current principles for egress and entrapment are that:

- No person should be able to be permanently harmed by an egress-triggering event in a mine due to having no credible means of survival except for those caught at the location of the event that actually triggers the egress. For example, if an LHD collides with a wall and the LHD catches fire and the driver is trapped in the cabin, this is not an “mine egress” situation. However, the mine egress principle is that no uninvolved persons (i.e. persons other than the driver (and passengers, if any) in the vehicle that catches fire) should be permanently injured or killed as a result of this incident;
- Disaster scenarios (somewhat arbitrarily defined in this paper as five or more fatalities from the same incident) in particular must be avoided. For example, in a blind (single access) heading situation, if there are two people working in the heading and there is a rockfall between them and the (only) way out, then in a worst case, it may not be possible to reach them before they perish. However, exposure to five or more persons in this situation should be avoided. This goes to the heart of the issue regarding the practicality of providing 2nd means of egress for all persons underground—if it is not practical in all circumstances, then in what circumstances *do* we need to make it “practical”?

Historical context of the principal of a second egress

The principal of a mine being legally required to have a second means of egress originated from the Hartley mine disaster in the UK in 1862 in which 204 men and boys died from an underground fire, including sons cradled in the arms of their fathers. [2] The immediate community grief and outrage led to an immediate judicial inquiry which was quickly concluded and stated, in part:

“The Jury cannot close this painful inquiry without expressing their strong opinion of the imperative necessity that all working collieries should have at least a second shaft or outlet, to afford the workmen the means of escape should any obstruction take place.”

The resulting legislation to force collieries to have two independent means of egress spread rapidly throughout the British colonies and Commonwealth including into hardrock mines.

As noted above, it is not possible to have a 2nd means of egress from *every* heading or workplace in the mine at *all* times. Firstly, it is simply not practical unless underground mining as we currently know it were to cease; secondly, it takes time to establish a second egress. The issue of egress and entrapment is therefore one of risk (and in particular, achieving the ALARA standard of “as low as reasonably achievable”), as well as conforming to legislation and generally accepted good practice standards.

Given these changes and trends—many of which are likely to prevail well into the future—the following are the author’s conclusions and recommendations based on many operational reviews of good practice in egress and entrapment in hardrock mines.

Current good practice standards for egress and entrapment in Australian hardrock mines

In the context of hardrock mines, the two principal (but by no means exclusive) situations that could lead to an egress or entrapment requirement would be fire and major fall of ground. In controlling these risks, the following are the standards now generally in use in Australia:

- 1) Both legislation and “good practice” require a second means of egress to be operational on each new level of any mine before production blasting commences on that level. [3] The ramp can extend downwards and a level be *developed* without a 2nd egress from that level, but the level must have an independent 2nd egress to surface before *production* starts from that level;
- 2) For example, a “decline” mine (one with a surface ramp connection as its primary egress) could have a ladderway (the 2nd egress) located in the access from the decline to each level (rather than being closer to the extremities of the level) provided the ladderway can be travelled to surface independently of the principal egress (in this case, the ramp);
- 3) “Emergency exit” signs to the nearest egress or refuge should be located at all critical intersections in the mine. For example, if entering a ramp from a level, there should be a sign indicating the direction of the nearest egress or refuge;
- 4) Large levels with extensive workings should have more than one 2nd egress. This should be risk-based (taking into account ground stability issues and numbers of persons in different locations on that level, etc.) but a reasonable rule of thumb could be to put in a 2nd egress every 250 m to 350 m of strike length depending on the risks and the duration of the risk in that part of the level;
- 5) Very small production levels or those with very short life might potentially not have a 2nd egress providing they comply with the other requirements (discussed below such as 750 m to a refuge and, not working behind an LHD or truck);
- 6) Even if a mine is being developed solely “for exploration purposes” (i.e. no commitment to production) or “has not started production”, there should be a maximum delay of 12 months before it should have a second means of egress (excluding on-going shaft sinking, if applicable). [4] This prevents the situation developing where a mine of limited extent “drags on” for years with only a single egress because it is not classified as being “in production”;
- 7) All persons underground should have at least 30-minute belt-worn self-contained self-rescuers (SCSRs) at all times. SCSRs are generally rated for 70 kg persons, so the effective operating time for the “95th percentile” person (the design standard) walking up a ramp is about 18 minutes. [5] The duration of an SCSR for a person at rest is 2 to 3 times its nominal rating, so 60 to 90 minutes for a 70 kg person or 36 to 54 minutes for the 95th percentile person design standard. Note that SCSRs are not the same as “filter” type self-rescuers which can only filter out carbon monoxide not the other toxic gases created in a modern mine fire on (say) a truck or LHD.
- 8) No person should be more than 750 m from a 36-hour rated fully self-contained, standalone and independent refuge chamber (RC) or secure fresh air base (FAB) (assuming all persons are wearing 30-minute SCSRs). The logic behind these numbers and the definition of a “rated” standalone refuge chamber is described in the WA Guideline. [6] A suitable fresh air base is one which is located on a secure connection to a surface intake and which will always, even in the event of any sort of underground fire (including resulting in total or partial underground power failure), remain in fresh air from surface. It should be equipped as per the rated refuge chambers;
- 9) In most cases, this means that rated RCs or FABs should be spaced at intervals not exceeding 750 m walking distance (horizontal or ramp) through the mine. For example, in a fire evacuation situation if a person enters the ramp off a level and the refuge chamber located on the ramp “just above” that level is blocked by a truck on fire, they still need to be able to get to the alternative refuge chamber “below” them (down ramp). Hence refuge chambers should not be spaced 1500 m apart. It is important to understand that the 750 m is the *maximum* distance not the minimum! In some cases, refuge chambers may need to be much closer than 750 m as discussed below;
- 10) Areas of the mine that are barricaded off as “no entry” or “restricted entry” do not need to meet this 750 m requirement;

- 11) It is useful to provide long-sections or other plans of the mine showing the “catchment area” (coverage zone) for each RC or FAB, to demonstrate that no working or travelling area is more than 750 m from one;
- 12) It is not reasonable to expect persons to report to a refuge chamber, find it is fully occupied and then be turned away to find another refuge chamber. There must be sufficient refuge chamber capacity within the catchment zone of each working area, including for surveyors, geologists, visitors etc. For this reason, some operations require a total refuge chamber capacity equal to double the typical “dayshift” peak number of persons underground (based on surface “tag board” data analyzed over multiple days). An alternative strategy is to use a local underground tag board at the entrance to a particular region of the mine to avoid more persons being in that area than there is refuge chamber capacity;
- 13) Modern miners are frequently quite aerobically unfit or may be aged or suffering various health problems. It is not reasonable to require them to climb up or down more than 60 m (vertically) of ladders. This is equivalent to climbing a ladder up a 20 story building;
- 14) Based on Naismith’s rule, [7] it is recommended that 8 m of horizontal walking (including ramp) is counted as equivalent to 1 vertical m of climbing a ladder. Hence climbing 60 vertical m of ladders would be equivalent to about 480 m of horizontal (or ramp, see also [6]). Whilst climbing down ladders is easier than climbing up, in many cases it will be difficult to predict whether the required escape direction would be up or down the ladder, so the assumption to climb up is more conservative.
- 15) It is unsatisfactory to have people trying to escape by themselves to surface in a major fire in a hardrock mine for all sorts of reasons; rather they should go to the nearest refuge chamber because (for example):
 - a) They could fall down a ladder or into a vertical opening;
 - b) They could encounter heavy smoke due to change in ventilation en route and run out of SCSR time;
 - c) They may not be sufficiently fit and have a heart attack trying to climb perhaps hundreds of meters to surface;
 - d) They could get lost using unfamiliar routes;
 - e) There is the need to avoid sending mine rescue brigadesmen into a hazardous situation (e.g. major firefighting) unless there is no credible alternative and even then, it must be acceptably safe. If everyone is safely accounted for, this reduces the risk and the urgent imperative for management to “do something”.
- 16) In effect, this is saying that the 2nd egress is *not* principally for a worker to escape to surface, but for:
 - a) The worker to be able to get to the nearest safe refuge, and/or
 - b) For mine rescue brigadesmen to be able to bypass a problem area in the principal egress (e.g. a fire in the ramp) to provide help for entrapped workers, or to conduct search and rescue operations, if it is safe to do so
- 17) There must be a reliable personal warning system rapidly and reliably triggered in the event of an actual or suspected underground fire. It is important that a warning is given as soon as possible to allow each person to reach a safe place of refuge with the least risk of encountering POCs etc. The traditional and absolutely minimum requirement is an effective stench gas system on every intake and the compressed air supply. As noted above, in the case of a decline operation, if a truck catches fire on the ramp, then the POCs from the truck will reach the workers far sooner than the stench gas (which has to travel via the same ramp, but is released much later from surface). This can hardly be described as a “warning system”. Equipping all personnel with radios or the use of “through the rock” type communications technology should be investigated and pass the ALARA test. Some operations are putting remotely activated stench gas discharges further *inbye* the mine workings to be in advance of the POCs from a fire that may occur further *outbye*.
- 18) There must be effective, realistic and regular fire drills in the mine. All persons should experience one fire drill per year. For 7-day week operations, this usually means at least 4 fire drills per year. These should all be documented and learning outcomes incorporated in future procedures.
- 19) No person should be trapped behind (or inbye) any diesel vehicle (except low fire-risk vehicles such as development jumbos or light personnel vehicles) without a second means of egress or without access on the inbye side to a rated refuge chamber or fresh air base. [8] This applies to both development and production

activities. This has led to the growing adoption of 4-person 36-hour rated standalone refuge chambers that can be moved by forklift or even mounted on the back of a flat-top truck and driven around as part of the “PPE” of small crews.

- 20) The second means of egress should not be able to be compromised by the same event that compromises the first means of egress. This is especially the case with a rock fall, flood, mud-rush or other event that physically prevents safe access through the egresses. Ideally, it should also apply to fires, i.e. no single fire event should contaminate both the primary and secondary means of egress. Note that there is no requirement in the WA Regulations [3] for ladderways (or 2nd egresses in general) to be in fresh air (refer specifically to regulation 10.10 and 10.11); however, the WA Regulations do make use of the concept of what is “reasonably practicable”. So in this author’s opinion, *if* it is reasonably practicable to do so, and if the risk is substantially lower by doing so, then putting the 2nd egress in fresh air should be done.
- 21) And of course, for most mines with whole-of-mine series ventilation, there may be no truly “fresh” air in any event so any argument about the siting of a ladderway is a moot point.
- 22) As an example:
 - a) A worker is on a level and a fire occurs on that level physically blocking his escape back to the ramp. He can access a ladderway, which also functions as an exhaust from the level. He reaches the ladderway and the smoke is going up. He should, wherever possible, choose to use an escape route that is in fresh(er) air so if the smoke is going up, he would go down (and vice versa). If the smoke is going both ways, then he will need to make a choice. If he is on the bottom level of the mine and there is no “down” to the ladderway, then he must go up *or* there must be a refuge chamber located on that level for him to enter.
 - b) A worker is on a level and a fire breaks out on the ramp above the level, sending smoke onto the level he is on. On the basis of “not entering smoke” (on the ramp) the worker retreats in light smoke to the nearby ladderway which also functions as an exhaust. However, the smoke from the fire is also travelling down the ramp and then entering the same ladderway/exhaust from below and travelling up past his level. In this case, the worker must also choose (probably without knowing where the fire actually is) which direction to go (up or down) on the ladder or whether to attempt to escape via the ramp.
- 23) In both these cases:
 - a) A PED-style of warning system that could tell him where the fire is would be of great benefit.
 - b) It is clear that the worker will be in a safer situation if the ladderway is in fresh air; however, even if the ladder is in fresh air, he must still “leave” the ladder at some point before his SCSR expires, which means either a FAB or RC must be within 750 m.
- 24) In terms of whether a ladderway (or other 2nd egress) in return air is acceptable, the ALARA test that management needs to ask itself is along these lines:

Whether the ladder is in intake or return, both egress systems are safe (due to our policies on personal belt-worn SCSRs, spacing and rating of refuge chambers, fresh air bases, and other controls, etc.). We recognize that the ladder being in intake air is safer. If the cost of putting the ladder in intake is small, then we should put it in intake. However, if the cost is substantial, and particularly if the “intake air” is not secure from POCs anyhow, then the improved safety of putting it in intake may not be justified given both systems are already safe. Of course, there needs to be clear justification for this latter position and it should be documented.
- 25) Both egresses must be capable of passage by rescue teams, rescue equipment and stretchers. Where ladderways are small (e.g. 1.2 m Φ or smaller), then mine rescue training using stretchers in the ladderway must be in place.
- 26) Both egresses must be “maintained in a safe, accessible and usable condition” and “adequately marked or signposted, taking into account reduced visibility during some types of egress events”. [4] At the very least, this means both means of egress need regular inspections, probably not exceeding one month intervals. It also effectively bans the use of ladderways as an exhaust *if* the steelwork is going to become so slippery with diesel grime or corroded that using the ladderway becomes a hazard. In other words, even ignoring the issues of using the ladderway in an exhaust in a fire, if the ladderway in an exhaust cannot be safely *maintained*, then it needs to be placed in an “intake” anyhow.

- 27) Ladderways used for egress need wind speeds under about 8 m/s (this needs individual assessment by the mine ventilation department as it will depend on the length of that section of egress, the type of ladderway in use, the size, airflow and life of the ventilation raise, etc.). Wind speeds higher than this impact on the ability to safely use the ladderway especially in an egress situation. In some cases, this constraint may push the decision towards having separate ventilation raise and ladderway, i.e. to achieve 8 m/s in a combined exhaust raise/ladderway may require such a large raise that it is cheaper to use a smaller dedicated exhaust raise operating at (say) 20 m/s, and a small dedicated ladderway on intake (perhaps 1.2 m Φ).
- 28) Horizontal or ramp development used for egress should have wind speeds under about 12 m/s (again this needs individual assessment by mine ventilation department for similar reasons as above).
- 29) Of course, a 2nd egress does not need to be a ladderway; it could be a second ramp, or even just the same ramp that connects to a portal on surface and to a hoisting or emergency shaft at its bottom allowing two independent means to surface from every producing level in the mine.
- 30) In general, no producing stope should be lower than the depth of the primary ventilation system (i.e. no production region should be ventilated via ducted air from a higher elevation in the mine). There may be rare and very limited extent and duration situations where this is not the case, but the other controls would still apply.
- 31) In general, blind stopes or headings where there is any credible risk of major fall of ground or other hazard blocking the egress should have a second entry at intervals not exceeding about 250 m. [8][9] This would apply, for example, to wide cut and fill stopes, longitudinal stopes, tail ends of permanent haulages, or headings in poor ground where there is a significant residual risk of rockfall or mudrush, etc. Again, there may be rare exceptions to this, such as where a level or stope has very limited tonnes and limited life, but in this case, other supplementary controls may be required such as a refuge chamber complemented by a borehole to the refuge chamber that can carry air, water, food and communications if required.
- 32) Mines with issues such as oxidation, strata gases, radiation, high elevation above sea level, high virgin rock temperatures etc., must ensure the implications of these are properly risk-assessed and incorporated into egress and entrapment plans, procedures, equipment, training and standards.
- 33) Special fire precautions should be installed on underground diesels. At the very least, this includes AFFF on diesel vehicles with turbochargers. [10][11]
- 34) All mines should have an emergency plan covering at least: fire, accidental explosion (including sulfide dust), failure of the primary ventilation system, flooding, inrush of mud or tailings, inrush or outburst of gas and extensive collapse of workings, especially in the primary egress. [3] All mines should also have a Fire Control Plan.

Summary and Conclusions

As with all other areas of mine design and operations, the standard for “good practice” in egress and entrapment is never static. Changing community expectations as well as significant improvements in enabling technology are moving the goalposts (the standards) that mines need to achieve, and then consistently sustain, with regard to protection from underground disasters by way of good egress and entrapment design. Careful consideration of these issues *before* development and production design is finalized reduces the capital and operating costs of the systems, compared to retrofitting. This paper provides a summary of the current approach to egress and entrapment in hardrock mines along with detailed specifications.

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