Criteria For The Design Of Emergency Refuge Stations For An Underground Metal Mine

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Introduction

The rationale for the design of the Emergency Egress (escape and entrapment) strategy for one underground metal mine has been previously described (Brake, 1999). Two of the key conclusions for this mine, which is equipped with 30 minute oxygen-generating self-contained self-rescuers (SCSR), were the need to ensure no person is ever more than 750 m from an emergency refuge station (ERS) and that it could take up to 8 hours to rescue workers from underground[1]. These conclusions were based on a number of considerations including the non-availability of a credible, "personal" entrapment procedure at the workplace, the duration of self-contained self-rescuers when used for travel, the need for rapid "clearing" of mine personnel to effectively and safely target mine search and rescue resources and the maximum time to either put a fire out, or to rescue affected personnel. As there is no Australian standard for refuge stations[2] (or for self-rescuers), this paper follows with guidelines for the location and specification of both fixed (permanent) and relocatable Emergency refuge stations (ERS) that may be applicable to other underground Australian metal mines.

Concept of fixed emergency refuge stations and relocatable emergency refuge stations

Whilst it was deemed essential to have sufficient relocatable ERSs to meet the distance requirement above, it was also recognised that it was essential to ensure the underground "cribrooms" (lunch rooms) were also set up as ERSs. This is for three reasons:

- A fire could credibly occur while workers are on meal break, e.g. brakes and tyres catch fire on a hot, parked, diesel LHD unit,
- In an emergency situation, workers may travel past a relocatable ERS to the cribroom, either because of panic, or because it is already "full" or because there is no smoke around and they want to go to a familiar assembly point,
- Newly "inducted" workers in the mine will not be familiar with the location of and travel routes to *all* ERSs from their first day; however, there is a much higher likelihood that they will know where the lunch room is.

Therefore it was considered essential, in effect, to have relocatable ERSs in the working areas, backed up by cribrooms which were also set up as refuge stations. Under these location criteria, there will obviously be multiple options for any person needing to escape from a fire and "redundant" egress and entrapment capacity.

Location of relocatable ERSs

The *minimum* number and placement of Emergency refuge stations is based on the higher of two criteria:

- the number to meet the requirement that no mine worker be more than 750 m from an ERS at any time, or
- the numbers of mine workers that could reasonably be expected to be in an area at any time divided by the nominal capacity rating (in persons) of the ERSs.

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[1] This distance was reduced to a maximum of 375 m for workers who are not wearing SCSRs (5 minutes travel @ 4.5 kph walking speed).

[2] There are Australian standards for breathable air systems [AS1715 and AS1716] but these do not really address the needs of a refuge station.

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Where any person is required to travel or work more than 750 m from an ERS, a special permit which details some other arrangement is required, e.g. a longer duration self-contained self-rescuer.

Other requirements for locating the ERS are given in Appendix A.

For practical reasons it was decided to standardise on a single "size" of relocatable ERS. Based on considerations of the maximum container size that can fit in the mine shaft cage (if there is no surface ramp access), and the maximum number of persons likely to be working within 750 m of ERS sites, this was determined to be 8 persons. Therefore each relocatable ERS needed to be able to keep 8 persons safe for 8 hours. Where more than 8 persons could reasonably be working at any time, an additional ERS is required.

Choice of breathable air delivery systems

There are a variety of options available for supplying persons with breathable air for 8 hours. However, the provision of compressed breathing air from cylinders using individual face masks or from cachéd self-contained self-rescuers was *not* chosen for the following reasons:

- "Therapy" masks are unsuitable for refuge; proper breathable air delivery masks are required
- If more than 8 persons came to a relocatable ERS, there would be insufficient masks or cachéd SCSRs. If "spare" masks or SCSRs are put in each ERS, then this negates the concept of a nominal capacity
- The logistics, practicality, cost and maintenance checks required to store the large number of masks/SCSRs which would be needed for the fixed ERSs (cribrooms)
- The distress caused to mine workers when required to sit for many hours with a face mask/SCSR on
- The problems of positive pressure (supply) masks: if one of these is turned on with no one wearing it, the supply of air to the remaining masks will be rapidly expended
- The problems of negative pressure (demand) masks with sealing around facial hair
- Mask/SCSRs assume the refuge station has become or could become contaminated with fumes (i.e. is not gas tight). To be consistent, this means goggles must also be worn.
- Masks/SCSRs make it difficult or impossible to drink water, an essential requirement for long, healthy entrapment in summer
- Masks/SCSRs make it difficult or impossible to communicate with other workers,
- Masks/SCSRs make any first aid treatment of injured workers difficult, and make administering expired air resuscitation impossible if a worker were to collapse

These factors reduced the number of breathable air delivery systems to:

- Compressed mine air
- Compressed bottled medical air (with no masks)
- Oxygen supply and carbon dioxide scrubbing devices.
- Use of "dead air" space, i.e. relying on the initial uncontaminated atmosphere within the refuge station itself.

The problem of keeping toxic fumes out of the ERSs means the ideal system puts the ERS under positive pressure (ideally 200 to 300 Pa) with respect to the external environment. This is true because mine workers will not all arrive at once, which means any door must be opened and closed several times, each time potentially resulting in some contamination of the inside air if not under positive pressure, and some doors are unlikely to be absolutely gas-tight even when closed[3]. New designs must be tested with a tracer gas technique such as SF_6 to check for gas-tightness and contamination potential.

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[3] Note however, that in tests conducted by Venter, in which the door was opened for five seconds each of 12 times, minimal contamination of the refuge station occurred. Venter found that sealing of the refuge station when the door was *closed* was much more significant that the small ingress of contaminants when the door was briefly opened (Venter, 1998b). Kielblock et al (1998) simulated an ERS door being opened 30 times for 5 seconds per time (simulating 30 people entering a (larger) ERS at various times) and found that the ingress of contaminants during door-opening was negligible compared to the contamination by

All breathable air systems must be able to be started and stopped from inside the ERS, must be reliable, and in the case of the relocatable ERSs, mechanically robust and easily connected to services to assist in the relocation process.

Breathable air

Normal dry air, at standard temperature and pressure (STP of 101.325 kPa and 0^0 C), consists of 20.95% oxygen, 78.08% nitrogen, 0.0314% carbon dioxide, 0.93% argon and trace amounts of 14 other gases. It may be noted that these are expressed by *volume*; the proportions are different if expressed by *mass*.

For humans, there are two principal metabolic fuels. Glycogen (carbohydrate) is the primary fuel used by muscle as workload increases. It has an RQ (respiratory quotient) of 1.0. RQ is the steady state ratio of the volume of carbon dioxide produced to the volume of oxygen consumed. Fatty acids, the other metabolic fuel, are used more at rest and have an RQ of 0.7. The average RQ that results from constant low levels of activity, as expected in entrapped conditions, is about 0.80. This RQ can then be used to then calculate the amount of CO_2 produced as O_2 is consumed. The metabolism of 1 litre of oxygen produces 20 kJ of metabolic heat.

At complete rest and in a non-stressed state, a 70 kg person will breath in air at a rate of about 7.5 litres per minute and expire air at 17% oxygen and 3.2% CO_2. This results in a “resting” oxygen uptake of 0.3 litres of oxygen per minute and a resting carbon dioxide discharge of 0.24 litres per minute. However, the rate of breathing is primarily triggered by the carbon dioxide content of inspired air with higher CO_2 levels triggering faster respiration rates[4]. Moreover, it does not take a significant increase in activity levels, or body weight, to make a substantial increase in metabolic rates and thus O_2 consumption and CO_2 production. Venter et al (1998a) found an average oxygen consumption for 12 entrapped individuals of 0.44 litres per minute, at STP, over 24 hours (including sleeping). A figure of 0.5 litres per minute over a non-sleeping entrapment period of 12 hours is a prudent, conservative design value. This corresponds to a metabolic rate of about 160 W or 80 W/m^2 for a typical miner with a body skin area of about 2 m^2, which is equivalent to a breathing rate of about 12.5 litres per minute of fresh air.

Carbon Dioxide

CO_2 is twenty times more soluble in blood than is O_2 (McPherson, 1993). As the CO_2 content of the inspired air rises, the breathing rate becomes faster. Normal air is 0.03% CO_2 or 300 ppm. The TLV-TWA (time-weighted threshold limit value) for CO_2 is 5000 ppm (0.5%)[5], headache and an increased rate of breathing occur at 10 000 ppm, the TLV-STEL (short term exposure limit) is 30 000 ppm (resulting in a doubling of normal breathing rate), panting and intoxication occur above 50 000 ppm with unconsciousness occurring at about 100 000 ppm.

These figures apply where the oxygen content of the air is *normal*. Note that the *maximum* CO_2 content in self-contained self-rescuer operation, under the European standard EN401, is limited to a maximum of 3% or 30 000 ppm (and to an average of 1.5%).

Oxygen

Perhaps surprisingly, a declining oxygen content triggers only a minor increase in breathing rate; this being governed by the CO_2 content of inspired air as discussed above.

The normal lower working limit for oxygen is 19%. At 18% there is a slight increase in breathing effort. At 16%, a flame lamp will go out, but this still continues to trigger only a slight increase in heart and breathing rates. At 14%, emotional upset, impaired judgement and faulty coordination occur. At 12%, cardiac

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leakage over the subsequent hours. This assumes the ERS has not been contaminated with POCs before the occupants arrive.

4 Care should be taken with all these numbers as they are only true at standard pressure. For mines which are well above or below sea level, or where temperatures will be above 0^0 C (which is usually the case), these numbers will change significantly and specialist advice must be sought.

5 Which is also the limit prescribed by Worksafe Australia, except for “coal mines” where the limit somewhat curiously is 12 500 ppm.

damage can occur along with vomiting. At 10%, a person would lapse into unconsciousness and death (Hartman et al, 1997).

Again, these figures apply where the carbon dioxide content of the air is *normal*. Note that the *minimum* oxygen content in self-contained self-rescuer operation, under the European standard EN401, is limited to 21% with an excursion to 17% for up to 2 minutes at the start of SCSR operation. The minimum oxygen content under the *Guidelines for Safe Mining* (Anon, 1996) is 17% whilst the minimum allowed under Worksafe Australia Standard is 18% (Anon, 1990).

Oxygen and Carbon Dioxide Limits

There are no known hard and fast rules for establishing *simultaneous* limits to low oxygen and high carbon dioxide concentrations for emergency situations (Schroder, 1989). However, based on EN401 guidelines for self-rescuers, the analysis given above, and the fact that the combined physiological cost to the body of simultaneous low oxygen and high carbon dioxide levels will be greater than that if only one or the other were to occur, suitable "emergency" working limits for the design of ERSs would be:

- for "open" systems such as compressed air: 19% oxygen and 0.5% (5000 ppm) carbon dioxide
- for "closed" systems, 18% oxygen and 1.25% (12 500 ppm) carbon dioxide, which is also in accordance with other guidelines (Anon, undated).

It can be shown that for a person breathing at a rate of 12.5 litres per minute within a "dead air" space of 1 cubic metre, an oxygen level of 18% will be reached at 58 minutes, whereas carbon dioxide levels will reach the TLV of 0.5% at only 12 minutes, and the "upper" working limit of 1.25% at 30 minutes. *This indicates that the air supply to an ERS is governed by the rate of build up of carbon dioxide, and not the drop in oxygen*. It is clear that the old adage to "crack the air line until you can hear the airflow" is unlikely to be a satisfactory arrangement when using compressed air in an emergency refuge station. This has been confirmed in 24 hour tests done by Venter (1998a), which showed unsustainable CO_2 build-up where the adage of "cracking open the compressed air line" was followed.

Furthermore, in these same tests Venter observed that participants noticed and commented when CO_2 levels reached 1%, whereas there was barely any comment when O_2 levels had fallen by as much as 6% in the same tests.

High Oxygen Limits

Some of the chemical devices for providing oxygen result in very high levels of oxygen in the chamber. Those that rely on oxygen being released from compressed oxygen bottles can obviously be regulated. However, those that rely on the decomposition of sodium chlorate (i.e. oxygen candles) typically release the entire volume of the decomposition (about 2 800 litres) in 90 minutes or so. This can result in oxygen levels of over 50% in the enclosure (this is not an explosive atmosphere, but will make any naked light burn more intensely than normal). Oxygen levels of 100% can be tolerated by healthy persons, without adverse effects, for at least 12 hours. Oxygen levels of 50% are acceptable indefinitely. In fact, the standard treatment for carbon monoxide poisoning involves oxygen therapy. Therefore, high oxygen levels in the chamber when miners arrive is probably a useful benefit, given the possibility of miners having had to travel through products of combustion en route.

Breathable air systems

Compressed Air

It has been previously shown that an oxygen uptake of 0.5 litres/minute is a good design figure for entrapment. To ensure the CO_2 content levels out below the TLV-TWA of 0.5%, a fresh air supply of 85 litres per minute per person is required. This flow rate will result in a "steady state" oxygen content of about 20.3%. Lower supplies of fresh air are sometimes quoted (e.g. 2.5 cfm per person which is about 70 litres/minute); however, these are based on unstressed, resting breathing rates (7.5 litres/minute) with an equivalent oxygen uptake (0.3 litres/minute) and do not allow for any additional persons (above the design figure) inside the ERS.

For 8 persons over 8 hours, this standard of 0.5 litres/minute requires delivery of 1.9 m^3 of O_2 and scrubbing of 1.54 m^3 of CO_2, or alternately, delivery of 326 m^3 of breathable air.

Unless there is a dedicated compressed air line to surface via a borehole[6] or other route where there is no significant risk to the pipeline, compressed air cannot be considered to be a fail-safe supply of breathable air. However, security can be enhanced by constructing high-risk sections of the line using screwed pipe. Furthermore, if the assumption is made that most persons will be at safety within 5 minutes, and all persons will be at safety within 18 to 30 minutes[7] of notification of the fire, then it is less likely that the compressed air system will be compromised in this space of time. For fixed ERSs, activating the compressed air supply as soon as the fire alarm is raised reduces the need to ensure that cribroom doors are always closed (not practical), that they always have a perfect seal to prevent ingress of fumes (not practical), that they have working air locks (not practical) and that these air locks are actually used properly in a panic situation when a miner enters from smoke (unlikely).

Therefore, compressed air is supplied to the fixed ERSs as the primary breathable air supply, and is automatically activated when the fire alarm is raised. Security of the airline is high (refer Appendix C). This ensures these lunch rooms are under positive pressure while all of the workers are getting to the refuge stations.

Maintaining positive pressure in an ERS which does *not* use compressed air is more problematic. However, oxygen generating systems [whether medical-grade air, sodium chlorate ($NaClO_3$) or potassium superoxide (KO_2)] all produce some positive pressure. Furthermore metabolic energy also produces some positive pressure by the conversion of food, water and oxygen into carbon dioxide and water vapour. For further details, refer to Anon (1997) “Respiratory Losses” and the metabolism example above. If the air inside the ERS heats up significantly, then this will also produce a positive pressure, according to Boyle’s law. Conversely, if the ERS has a refrigeration system which starts up after occupation begins, then the ERS may end up under negative pressure, in which case the integrity of the sealing systems is crucial.

Therefore, mine compressed air is a suitable primary means of providing breathable air for ERSs where the airline is relatively secure. However, mine air, even if generated on the surface where the compressors cannot be contaminated by the fire, is not a 100% reliable system. Even steel pipe, or the joiners between sections of pipe, can be burned out in a major fire or broken by a rock fall triggered by a major fire. This can result in loss of compressed air pressure[8], or contamination of the compressed air by the fire (i.e. as the fire burns the rubber couplings out, the venturi effect from the compressed air flowing in the pipe can suck in contaminating fumes, which was exactly the case in a major fire in Ontario in 1990). Therefore a back-up system is required. By deduction, this back-up system needs to be either bottled air, or a scrubbing device or the dead air itself.

Any mine compressed air system must include suitable and properly designed filtration and noise suppression, must also allow for manual open and closing, and must provide a manual “purge” to allow the routine bleeding of water from the line and bleeding of stench gas from the line in certain circumstances. Noise levels in excess of 110 dBA have been recorded with unattenuated compressed air systems inside refuge chambers (Kielblock et al 1998). Not only is this injurious to hearing, but it will make essential person-to-person and telephonic communication virtually impossible.

Dead Air Space

Dead air space can be used as either the primary or back-up air supply, depending on the circumstances.

Calculation of the drop in oxygen content and of the increase in carbon content over time depends on the initial volume of the ERS, the number of persons inside and their metabolic rate. Charts such as those developed by NASA can be used for these calculations, but because of the high stress levels during

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[6] Boreholes are popular with some coal mines; however, this is a function of the two-dimensional nature of coal mines and their normally relatively shallow depths of operation.

[7] 30 minutes being the rated, nominal capacity of the SCSRs in use at many underground mines, and 18 minutes being an accepted design (de-rated to 60%) capacity. Longer-duration SCSRs will require recalculation of travel times and distances. With a 750 m maximum travel distance, an “average” travel distance of 375 m would take 5 minutes at 4.5 kph.

[8] Calculations, based on the assumption that the compressed air line was broken at any one of a number of locations need to establish if pressure and volume at the main ERSs will remain acceptable. However, an ERS fed by the broken line would obviously be affected.

emergency entrapment, a better approach is to use equations developed from first principles. These use the starting volumes of O_2 and CO_2 in normal air and the rates of consumption and production of these gases given off at various metabolic rates.

In many mines, calculations will show that dead air space is a viable supply of breathable air for the cribroom-sized, fixed ERSs, but is not a viable supply of breathable air for the relocatable ERSs.

Chemical oxygen supply and carbon dioxide scrubbing

There are only two options remaining for supply of breathable air for ERSs. This is compressed medical air (or medical-grade oxygen in cylinders) or technology which produces oxygen by the decomposition of a chemical substance and absorbs carbon dioxide using another substance. Commercial devices such as the oxygen candle technology in the Rescueair-E™[9] or compressed oxygen technology such as Refuge One™[10] are available. Both devices rely on scrubbing of carbon dioxide using soda lime[11]. Each technology produces different levels of heat, and also different positive pressures within the ERS. Detailed studies are required to identify the best option for the circumstance.

Medical Air Cylinders

A typical arrangement such as a "J pack" consists of 15 off G size cylinders, in total containing a nominal 175 m^3 of medical air at standard temperature and pressure, pressurised to 25.3 Mpa. The plan area size of the J pack is 1.5 x 0.9 m. Total weight of the pack is 1.6 tonnes. Two J packs would be required for 8 persons for 8 hours.

As discussed previously, it is usually unsatisfactory to use oxygen masks with bottled air and the air must be discharged directly to the atmosphere within the ERS.

Specification of ERSs

The standard specification for an ERS is given in Appendix C. It is important to recognise that all ERSs need to be regularly inspected to ensure they remain fully operational.

Temperatures in Emergency Refuge Stations

It is very common to misjudge the heat build up when a number of "resting" persons are placed inside a restricted space. In the infamous "Black Hole of Calcutta" incident, 123 of the 186 British soldiers died when imprisoned for only one night. Likewise, in the Kosti disaster in the Sudan, of 281 civilians imprisoned in one room for one night, 194 died (Leithead and Lind, 1964). The often-used shipping-type container or "steel box" placed underground will simply become a coffin, and not a refuge bay, for miners trapped for any significant length of time in many mines in Australia.

A person consuming 0.5 litres of oxygen per minute generates about 160 watts of heat. Therefore 8 persons in an ERS could generate the same heat as a 1.3 kW bar heater.

Moreover, there are other sources of heat inside an ERS, which include:

- Electrical equipment, including fans for scrubbers and DC power supplies or AC inverters,
- Emergency lighting and caplamp lighting (small quantums),
- Any heat of oxidation from CO_2 scrubbing, or decomposition from oxygen reactions,
- Any heat gains or losses from compressed air, or water flowing into/out of the ERS, and
- Radiative or convective heat gains/losses from the ERS to the surrounding air.

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[9] This is an oxygen generating (sodium chlorate) and CO_2 scrubbing device using technology similar to that used on many submarines. It decomposes exothermically to oxygen and common salt according to the reaction: $2NaClO_3 \rightarrow 3O_2 + 2NaCl$.

[10] This is a bottled oxygen and CO_2 scrubbing device using similar principles to most mine rescue breathing apparatus, except on a larger scale.

[11] Soda lime consists of 80% calcium hydroxide, 3% sodium hydroxide and 17% water. The exothermic reaction is as follows:
$CO_2 + H_20 \rightarrow H_2CO_3$; $H_2CO_3 + 2NaOH \rightarrow Na_2CO_3 + 2\ H_20$; $Na_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$ + heat.
116 gram of soda lime can adsorb one mol (22.4 litres @ STP) of CO_2.

Over time, the temperature inside an ERS will increase. Venter et al (1998a) found that even with relatively low starting temperatures of around 25 degrees, a small "shipping container" with 8 persons in it will develop very stressful temperatures (29 WB, 29 DB, i.e. fully saturated) within about 60 minutes. Kielblock et al (1988) likewise found that the temperature in an ERS climbed from 20.9 WB to 35 WB in 90 minutes after the compressed air failed. Excessive heat stress and the development of heat illness for those trapped inside is likely, even if the toxic gas concentration is satisfactory.

Note that autocompression alone (before any other heat sources such as strata heat or diesel equipment) means that average wet bulb temperatures in a 1000 m deep mine are about 4^0 above surface wet bulb temperatures and average dry bulb temperatures can be up to 10^0 above surface dry bulb temperatures (depending on moisture pick-up). The distribution of underground wet bulb temperatures in a mine with well maintained ventilation has a standard deviation of about 2^0. Thus, knowing the maximum surface design, a *rough* indication of the *minimum* expected wet and dry bulb underground temperatures surrounding an ERS can be calculated for a mine at feasibility study stage. However, a proper underground environment simulation study should be used prior to finalising any design.

Underground starting temperatures inside relocatable ERSs will typically be the ambient underground temperatures, which on a hot summer's day in many mines in Australia is about 28^0 wet bulb and 34^0 dry bulb. Starting temperatures inside fixed ERSs which have continuous refrigerated airconditioning, will be about 16^0 to 18^0 wet bulb and 24^0 dry bulb.

Humidity inside an ERS will increase with time, because:

- expired air (i.e. expired breath) is always saturated with respect to moisture vapour. With typical expired air temperatures of 35^0, moisture content will be 34 g water per cubic meter of expired "dry" air. Each miner will therefore expire about 30 ml/hr of moisture vapour.
- sweat rates between 0.5 and 2.0 litres per hour per miner are credible for unrefrigerated ERSs. However, as the human gastric emptying rate and gut absorption rate is limited to about 1.4 l/hr, progressive dehydration will occur at high sweat rates, even with unlimited access to water.

Contrary to popular belief, "compressed air" coming out of a pipe, if it does no useful work, is at the same temperature as the pipe itself, i.e. ambient conditions. Any cooling effect from compressed air is due to the high velocities at the discharge, and the low humidity levels in the compressed air, both of which assist in evaporation of sweat from the body[12] and in the reduction of the wet bulb temperature. However the compressed air will only assist in cooling to the extent that it reduces the average humidity levels in the chamber (and hence the wet bulb temperature), unless temperatures inside the chamber become greater than those outside, in which case some sensible heat transfer will also occur.

Separate calculations of dry and wet bulb temperature increases inside the ERSs need to be made, both for the primary and back-up sources of breathable air. A computer program was written to simulate the environmental and physiological state of persons inside an ERS. The cut-off point for survival times in the ERS was governed by:

- deep body core temperatures, which were restricted to a maximum of 39^0 *and*
- wet bulb temperatures inside the ERS, which were limited to 35^0 WB, based on war-time and other experiments and summarised by Leithead and Lind (1964).

It should be noted that these are very stressful limits.

It is also critical to realise that the "starting" core temperature for most workers who have been engaged in physical work under thermal stress could already be up to 1 degree above "normal" (i.e. up to 38^0 C), and persons could also start out at up to 2% dehydrated (the onset of the "thirst" response). These are therefore sensible starting conditions to assume for ERS calculations.

Under a "no airflow" scenario, core temperatures increase rapidly, which indicates the human thermoregulatory system is under great strain. In these conditions, a limit of 39^0 for core temperature is not realistic as it assumes that when this "cutoff" point is reached, persons are withdrawn to a cool

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[12] For example, assuming compressed air is coming from a pipe at 35 degrees C (ambient conditions around the pipe) and at 500 kPa and was originally saturated at its initial pressure of 700 kPa, each 5 litre/sec of compressed air generates 1.1 kWr.

environment (i.e. no "overshooting" occurs). In a rescue situation, even after a mine rescue team arrives, it could be a considerable time before trapped persons are in cool conditions. Therefore, the limit of 35^0 WB inside the ERB is the more appropriate limit. This limit is also reached much earlier than the 39^0 core temperature limit and in this sense is "conservative".

Therefore, to maintain steady state temperatures inside an ERS, a cooling system that can remove at least 8 x 160 W (=1.4 KWr) plus heat from other internal and external sources needs to be established.

Studies of various simulations led to the following conclusions:

- High rates of compressed air flow would be needed to keep the ERSs within acceptable cooling limits in mid-summer at their design capacity of 8 persons.
- Good airflow over the skin would be required.
- Miners would need to strip down to minimal clothing.
- If the compressed air system were to fail and other means of cooling are not available, survival times would be limited to an unacceptably short duration.
- If the primary ventilation system were to fail, resulting in increasing ambient air temperatures outside the ERS and increasing temperatures of the compressed air, survival times would again be limited to a short duration.

Options for cooling

There are several options for cooling an ERS:

- Split refrigerative air-conditioning systems. "Off the shelf" mains-powdered units, which are designed for installation in fixed surface buildings, will not be robust enough for relocatable, skid-mounted underground refuge stations. Moreover, being mains powered, they will cease operation if the power supply fails. A back-up power supply (diesel generator) would further complicate the arrangements and would breach the key guidelines of the egress strategy being simple and robust. However, purpose-built refrigerative air-conditioners are now available that run from an a.c. inverter fed from lead-acid batteries, which are themselves constantly "trickle charged", i.e. a system much like an uninteruptible power supply. This is a practical option for relocatable ERSs in ambient conditions up to 40 degrees. Insulation on the ERS is required, in which case a small 8-man ERS can maintain satisfactory temperatures with a 3 kWr refrigeration unit.
- "Cold guns" of the vortex tube type, which can provide refrigeration capacity of up to 1.5 kWr per unit. These are compressed air devices with no moving parts, are relatively inexpensive and require little maintenance. However, if the compressed air has not failed, refrigeration is not required, and if the compressed air fails, then the vortex tubes will not work; moreover, it would be very difficult to ensure these devices do not allow noxious gases into the ERS after the compressed air fails. These devices are also very noisy, and installation of a muffler will increase the back-pressure on the device and seriously affect its performance.
- Alternately, vortex tubes could be operated off medical air cylinders. As the vortex tubes sacrifice about 1/3rd of the air to reject the heat, this would reduce the duration of the cylinders. Again, however, the difficulty of ensuring noxious gases do not enter the ERS using the vortex tube discharge port ruled this option out. Therefore vortex tubes are not suitable as a solution.
- Use of unchilled or unchilled service water. The service water would need to be hosed over the body. Whilst there are some scenarios in which this is theoretically possible, in most mines it will not be practical. It would require water-proofing of electrical equipment and one-way (no gas return) drain holes and would be exceedingly uncomfortable. Except in site-specific circumstances, this is unlikely to be a unsatisfactory long-term, robust solution.
- Cold vests (such as those used by fire fighters). These can provide up to 1 600 kJ (about two hours per jacket for a person with a metabolic heat load of 160 watts) of cooling. A refrigerator would need to be provided in each ERS with its condenser outside the ERS. If and when the compressed air or power were to fail, the cold vests would provide the necessary cooling. Preliminary indications are that two cold vests per person could provide comfortable conditions for four hours. However, for practical reasons and because of the time limitations, this option is also unsatisfactory.

- Stored ice. This option requires a large block of ice to be frozen inside an ERS in a freezer. In the event of a power failure, the block slowly melts soaking up external heat according to the sensible and latent heat of melting. The practical difficulties in doing this would need to be resolved prior to introduction; however, it remains a possible low-cost option.

It is critical to recognise that most underground mines in Australia which rely on "shipping container" type designs for ERSs will be unable to keep occupants alive for 8 hours during summer conditions unless some form of cooling is provided. The need for a cooling strategy does not just apply for deep mines in the northern part of the continent.

The Psychology of Entrapment

Any real emergency which results in "entrapment" of underground workers will create panic and high levels of anxiety. For a trapped underground worker, especially if alone, there may be little difference between "entrapment" and "entombment". Venter (1998b), after conducting 24 hour entrapment *exercises* (i.e. low stress compared to a "real" entrapment), reports the following:

- Heart rates and oxygen consumption initially increase when the lighting was unexpectedly turned off inside an ERS (due to an increase in anxiety);
- Any concerns expressed by the leader about the effectiveness of the oxygen or carbon dioxide systems resulted in increased heart rates and oxygen consumption;
- Trapped workers heart rates and oxygen consumption decrease markedly when they commenced playing cards or other such activities;

It is crucial, if at all possible, to keep trapped persons informed about the progress of the rescue activities. "No news is good news" does *not* apply for anxious trapped workers, who will inevitably fear that rescuers may not reach them in time, etc.

Hence reliable communication (at least one way) between the rescue command centre is very highly desirable, as is a "fail safe" environmental system and the provision of such simple relaxation activities as a few packs of playing cards.

Summary

A comprehensive emergency egress plan is required for all underground mines 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. A key component of this strategy is the siting and specification of suitable Emergency Refuge Stations to contain all persons underground at the time of the incident starting, until they can be rescued.

For most mines in summer, maintaining safe temperatures within an Emergency Refuge Station is the most difficult criteria to meet, in terms of an 8 hour minimum entrapment criteria. The second most difficult criteria to meet is maintaining carbon dioxide levels. Maintaining sufficient oxygen is the easiest criteria to meet.

Whilst the guidelines identified in this paper are not cheap to implement, it should be recognised that the fire protection and fire escape systems in a large surface building cost between 2% and 5% of the total cost of the building. An underground mine is, if anything, more hazardous; is it not reasonable to expect that underground workers should have a similar chance for safe escape from a fire as surface or office workers?

It is important to recognise that these specifications are dependent on the hazards at the *individual* mine and the resulting total and residual risk profile. This must include site specific factors such as summer temperatures, underground heat loads and the depth of mining. The conclusions in this paper should not be copied into other operations without a full risk assessment being carried out to identify and assess these site specific issues.

Appendix A Location of Emergency Refuge Stations

- On main or normal routes of travel where they achieve high visibility and high workforce recognition, wherever practical
- Where more than one ERS is required on a level, they should be located so as to maximise the options workers have to access the ERSs from different directions/routes.

- At least 60 m from a magazine.
- At least 15 m from a transformer greater in size than 5 KVA.
- So that a fire in a parking area or refuelling bay will have minimal effect on the ERS.
- Sufficiently distant to any combustible material so that the ERS cannot catch on fire and so that direct access from the thoroughfare to the ERS cannot be blocked off by fire.
- Away from a place where they will be damaged by concussion in stope blasts.
- To have "stop log" or very strong barricade to ensure vehicles cannot park in front of them or back into them.
- Where practical, to be located where there is a second egress and/or access for mine rescue teams. A self-contained ERS can also be effective in acting as a "staging post" for a mine rescue team. A back-up rescue crew, or back-up equipment could be positioned at the nearest ERS upwind of a fire. Alternately, first aid to injured persons could be administered in the ERS. Because even a small ERS should be able to operate without initiating the oxygen-generating or carbon dioxide scrubbing systems for up to one hour after occupation using its "dead air" space, use of an ERS in this role (with air-conditioning) has no significant costs attached.
- Where they can be towed or carried into position with no damage to the ERS or the towing machine or forklift.
- So they ready access to utilities (telephone, power, etc).
- Where they cannot be flooded.
- Where the ground is sound and good roof support is in place.
- To be located after consultation with the relevant mine rescue leaders, who may want to examine alternative routes for retrieval/rescue of personnel if the main access to the ERS is blocked.
- Even though the "design capacity rating" of a ERS should not be placed on the ERS (this could imply that once this number is reached, people are then to be turned away!), it is important to recognise a "rating" for the purposes of deciding if and where more ERSs are required because of the numbers of people working in a high-activity area.

Appendix B Specification of mine compressed air supply to Emergency Refuge Station

- Provision of a properly sized, secure (good hangers/ties) preferably-screwed compressed air line, preferably painted or signed so it is not interfered with.
- The airline should discharge to the back of the ERS, at the opposite end to the entrance door.
- The airline needs a filter, regulator and a silencer. The regulator should be pre-set to the airflow required for the number of people in the room; however, the filter, regulator and silencer must be designed to operate under both normal mine air pressures and *below normal pressures* in the event of the air line being damaged.
- Manual override is required for the regulator in the event of low compressed air pressure (e.g. the line has been damaged or contamination of the compressed air has occurred).
- The regulator should be designed so that it will not freeze up under the range of conditions that could be encountered during emergency egress.
- Airline discharge is activated on confirmation of *any sized fire or smoke detected or suspected*. This must be able to be done remotely be a responsible person (e.g. the person who gives the mine evacuation command), locally from within the ERS, and also, in the case of fixed ERSs which usually have a fan and vent duct feeding fresh air into the cribroom, operated by a smoke detector which also closes the fan feeding the cribroom, which in turn operates a self-closing damper on the duct inlet to the cribroom.
- A purge line *outside* the cribroom, which can be opened and closed from a simple mechanical valve *inside* the cribroom, would allow someone in the cribroom to purge the first few minutes of air from the line for maintenance or other reasons.
- A pressure relief valve at the opposite end to the airline discharge to ensure pressures do not become excessive within the ERS.

Appendix C General Specification of Emergency Refuge Station

- Fail-safe breathable air supply, or primary supply with backup.
- Brick walls used in the external construction of the ERS to be painted to avoid gas leakage. Two coats of oil-based paint are required.
- For the fixed ERSs, a dedicated screwed water line, clearly marked, which is also used for day-to-day water supply to the cribroom to avoid problems with bacterial growth in the water.
- For the relocatable ERSs, a store of cachéd water, replaced at appropriate intervals, along with drinking cups.
- Telephone and AutoPED[13]. Essential telephone numbers must be on a sign near the telephone.
- A sign with the unique name of the ERS must be inside the ERS to ensure that all persons, even those unfamiliar with their location, can identify exactly where they are.
- No smoking signs outside and inside the ERS.
- Provision of a very basic emergency toilet, toilet paper, note books and pens (for taking names of persons, instructions, measurements etc), stretcher(s) [site specific] and trauma kit, playing cards (1 pack per four persons) and masking tape (for emergency sealing of cracks) all housed in a locked wooden cabinet, with "in case of emergency, break glass".
- Note that a 3 mm crack around a door leaks 5 litres/s of air per metre of crack when under 120 pascals. Therefore sealing is important to avoid possible contamination of the station, even when under positive pressure from the compressed air.
- The door to the ERS should be single, steel clad and should be outward opening with a good seal.
- The ERS should be clearly marked as "Emergency Refuge Station" and optionally painted in the Australian standard green and white for emergency facilities.
- The turnoff from the main thoroughfare to the ERB should be whitewashed to ensure prominence and high recognition for the ERB.
- Siren and flashing light outside the ERS (visible and audible indicators) activated automatically on issue of the mine evacuation order with manual override (so they can be turned off after a suitable time) and battery (UPS) backup. Orange lights have been shown in South African studies to be most visible colour in smoke.
- Optionally, an ERS which is less accessible or visible from the main thoroughfare should have guide cones installed from the main thoroughfare to the ERS.
- ERS external walls should have one hour fire rating.
- Internal emergency lighting much the same as in a surface building. In the fixed ERSs, this also helps people find caplamps etc if there is a power failure during other circumstances.
- If temperatures in the ERS could reach levels that result in serious health problems, a method of cooling the occupants.

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[13] AutoPED is a reliable one-way communication device, based on similar technology to that used to contact deeply submersed nuclear submarines, installed as a fixed installation.

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