14th United States/North American Mine Ventilation Symposium, 2012 – Calizaya & Nelson
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Series ventilation circuits in hardrock mines - Can they be designed and operated safely?

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ABSTRACT: With hardrock mines using mobile equipment with ever larger diesel engines in ever larger development dimensions, the use of traditional parallel ventilation circuits has become increasingly difficult as it requires large total airflow volumes and is therefore capital cost and energy intensive. The response by mine operators has seen the increasing use of series circuits which re-use the air and therefore lower the total mine airflow volume. However, series ventilation circuits can result in poorer working conditions for downwind operations and can increase the risks in the event of fire or other emergencies such as falls of ground due to loss of egress and entrapment options. This paper explores the factors driving the trend towards series ventilation circuits, the problems this is introducing in terms of both ventilation design and operation, and proposes some design and operating guidelines that could set a good practice standard for the use of series ventilation circuits.

1 Introduction

A series ventilation circuit is one in which the air is first used in one workplace, then directed to another workplace and then potentially reused in many other workplaces. It has also been variously described as "cascade" ventilation or "daisy-chaining". *Re-use* of air via series circuit design should not be confused with *recirculation*, which is where the same air is used twice in the same workplace.

The other major style of ventilation circuit design is parallel circuits, also known as "one pass" or "single pass" ventilation. In parallel designs, air is used in one workplace and then directed to a return.

Series ventilation circuits have become very popular in many if not the majority of hardrock mining operations in Australia over the past 15 years. Many smaller operations now rely solely on a single series circuit for their entire mine, typically using their surface ramp as the intake and an exhaust system taken down as short lengths of raise as the mine is deepened. This rising dominance of series ventilation circuits is being driven by a number of factors most of which are likely to remain in place or accelerate over the years to come. Many, including this author (Brake, 2009) have questioned the reliance on series circuit design especially with regard to safety. It is therefore timely to review just how safe and effective series ventilation circuits are, under what circumstances are they applicable, and what additional controls are required for their safe design and operation.

2 Advantages of Series Circuits

The trend towards series circuits is being driven by the following factors:

- Series circuits use air more efficiently as the air is more thoroughly vitiated before being discharged; parallel circuits frequently result in substantially "fresh" air being discharged into the returns without doing any real "work"
- The demand for higher mine productivity has meant larger equipment; this in turn has meant much larger development sizes. The standard development size has increased from about 3 m x 3 m in the late 1970s to closer to 6 m x 6 m, a four-fold increase in area. It is very difficult to maintain the normal design requirement of 0.5 m/s minimum wind speed in such large development if airways are ventilated in a one-pass, parallel circuit design.
- A corollary is that large, productive equipment is powered by large, powerful diesel engines which need substantial airflow at a typical airflow allowance of about 0.6 m^3/s per kW. However, this high airflow is only required where the machine is actually working at any time, but for practical purposes, is often provided at all locations where the machine will need to work at some point in its cycle. For example, a development crew may need six or more faces to be efficient (drilling, mucking, ground support, extending services, etc), all of which need to be ventilated but only one of which will have the LHD in it at any time. However, a full allocation of airflow for the LHD is provided in each heading all the time irrespective of which activity is in the heading.
- Therefore operating workplaces in series requires a lower total airflow if the volume is based on engine kW¸ e.g. 0.06 m^3/s per kW in the *aggregate* rather than in *each* potential work area
- Series circuits have lower ventilation operating costs especially power due to lower airflow. The mine resistance may be higher, but is more than offset in most cases by the lower airflow
- Series circuits are simpler than parallel circuits and operate by mixing fresh and used air together, leading to the following:
    - There may be a lower need for ventilation

control devices (VCDs) and in particular for regulators
  - Series circuits are easier to understand and operate: there are no or many fewer air splits
  - In fact, in many mines with series circuits there is hardly any need for a ventilation officer at all which is particularly important in fly-in, fly-out operations where staffing an operation with "back to back" coverage on technical positions is seen as wasteful
- Series circuits provide and preserve strong airflows throughout the operation (no air is being deliberately "lost" into the exhaust at any intermediate points) so there may be less risk of dead spots, regions of low wind speed or local flow reversals. In some cases, a series circuit is also arguably less susceptible than a parallel circuit to leakage or recirculation (e.g. through an open stope) or leaky VCDs.
- The potential reduction in total mine airflow arising from series ventilation also is very important in simple mines where the surface ramp is the only intake, as total mine airflow is restricted to (say) 30 m^2 x 6 m/s = 180 m^3/s
- Where extra vertical development is required for ventilation, the airways' size and therefore capital cost are minimised when airflows are minimised. This is particularly important given both the high cost and growing safety concerns about "entry" systems of vertical development, such as shaft sinking and Alimak-raising.
- Series ventilation is better suited to the modern "top-down" system of mine development since production can start on the level "just behind" the ramp face using the same (limited) exhaust as the ramp development. These results in faster start-up of production, faster and earlier cash flows, and less working capital tied up.
- "Mixing" of air will happen anyway due to modern mining methods which have stope brows open much of the time (due to the advent of remote mucking and more sophisticated blasting practices including programmable detonators) so the mine often already has many short-circuits. If the air will end up as a "blend" of fresh and exhaust to many jobs, why bother trying to keep the circuits separate?
- Even the best designed mine with extensive use of parallel circuits will still operate some working places or travelways in series with others; therefore the debate cannot be put as baldly as "series versus parallel" but rather the degree of series ventilation within the mine
- Recirculation is theoretically not a major concern with series ventilation providing the net fresh air inflow to the recirculating section is sufficient
- Perhaps perversely, the continued reduction in TLVs is also driving mines towards series circuits as unless air is fully used before discharge, the required volume of air escalates as TLVs are reduced.

3 Advantages of Parallel Circuits

By contrast, the advantages of parallel circuits are generally seen as follows:

- Parallel circuits offer a safer system in the event of a fire as a smaller region of the mine is affected
- Parallel circuits are more effective, more flexible and safer in terms of clearing fumes after blasting
- Parallel circuits provide fresh air at (most) working places; however, this will not necessarily mean better quality air, as the discharge of a fixed flow of contaminants into a smaller quantity of fresh air may result in higher contaminant concentrations than the same flow into a larger volume of partially vitiated air
- Parallel circuits are more flexible since a ventilation "problem" in one area (e.g. a stope outcasting dust from drawpoints) won't usually affect other areas
- Parallel circuits are more amenable to having the second egress in fresh air
- In most cases, parallel circuits make more extensive use of "flow through" ventilation than do series designs. This often results in shorter ventilation ducts and operations that are less dependent on well installed and well maintained ventilation duct. Shorter ventilation ducts are more efficient distributors of air as they are less subject to leakage between fan and outlet. It should be noted that airflow allowances for diesel operations should be based on net airflow to the face area (duct outlet), not fan inlet air flow.
- The mine resistance, at least through the workings, is usually lower in parallel circuits. Usually this means the pressure across district ventilation controls is lower. Due to nearby activity and also blasting, it is usually these more local VCDs that become damaged and start to leak (or are poorly constructed in the first place). Furthermore, any leakage is generally only within a district and other districts are unaffected. Therefore, if controls do leak in a parallel circuit, the impact is not as serious on the mine as a whole compared to a series circuit where a leaking control may dramatically reduce flows near the mine bottom, which is often the area of most intense activity and worst environmental conditions. This problem is aggravated by the "top-down" approach to extending the primary ventilation system (which often accompanies series circuit design), as this results in many very short lengths of primary exhaust raise, with a large number of controls (all potential leakage paths) and large number of shock losses due to the bends and offsets.

4 Other Factors Impacting on Hardrock Ventilation Circuit Design

There are also other factors that are, or will, become important contributing factors to hardrock ventilation circuit design in the future:

- Diesel engine technology (including cleaner fuels) is resulting in much lower diesel engine emissions (except heat). This has not been reflected to date in lower airflow design requirements for diesels (i.e. 0.06 m^3/s per kW) but may in the future.

- Diesel engines continue to become more powerful resulting in much higher heat output and potentially higher absolute levels of contaminants. Even if a diesel engine produced no gaseous or particulate contaminants, it requires a substantial airflow to keep temperatures within acceptable limits. Furthermore, in practice, even if emissions per kW are reducing, because engine kW are increasing the absolute level of contaminants that need to be diluted is not falling as quickly as emissions per kW would suggest.
- The growth in the number and kW of light vehicles. Few workers or supervisors walk around mines today; this has resulted in a dramatic increase in the size of the light vehicle fleet. The engines in these vehicles are typically less clean (on a kW basis) than the heavier fleet vehicles.
- TLVs have reduced and are likely to continue to reduce over the years to come (e.g. NO_2, quartz). Such reductions will demand more airflow to dilute concentrations to acceptable levels.
- Ventilation on demand (VOD) in one of its various forms may offer power savings as well as reducing total mine airflow, whilst still allowing for parallel circuit operation, or even more dramatic reductions in airflow and power if combined with series circuit design
- Egress and entrapment technology has greatly improved over the past 30 years, particularly with respect to self-contained self-rescuers and refuge chambers. More and better controls are available in this area and this has removed or reduced some of the major constraints on mine ventilation system design.
- The approach to mine rescue is changing, from one of aided rescue to one of self-rescue. This is driven, in part, by the Duty of Care towards mine rescue brigadesmen

5 Defining Satisfactory Ventilation Design

Satisfactory ventilation circuit design and operation means more than just designing safe circuits; it must achieve at least the following four outcomes:

- Safe: the design must be safe, which is discussed further below
- Legal: the design must meet all applicable laws, and in most cases, any applicable Codes of Practice or Approved Guidelines. It must also meet any 'internal' company standards including a Safety Case, if applicable. With the trend towards global mining businesses, there is also a noticeable move towards safety standards (including ventilation) meeting the higher of the local laws or the laws applicable in the country of origin of the mining house.
- Contingency: the design needs the robustness and flexibility to be able to handle the normal range of changes in schedule etc in an operating mine, i.e. needs to have some contingency in it
- Economics: the design must add the greatest possible value to the operation but this is (or should be) subordinate to the other design objectives.

Looking at the first of the criteria above (safety), it should be noted that the ventilation system in hardrock mines has perhaps four key deliverables that impact on safety:

- Providing safe air to breath, in respect of airborne contaminants: gases, dusts, radiation hazards etc
- Providing safe and productive thermal conditions (heat and cold stress, but principally heat stress)
- Providing suitably rapid re-entry after blasting (by clearing blasting fumes)
- Providing for safe egress and/or entrapment in the event of toxic air and blocked egress (due to fire, sulphide dust explosion, spontaneous combustion, fall of ground or other events), and subsequent safe egress or rescue.

Each of these will be considered in turn, but consider first the issue of what is a "safe" design.

6 Safe Ventilation Design

In general, legislation around the world is moving towards defining "safe" in two senses:

Firstly, "safe design" is defined in an absolute sense.

For example, the national OH&S regulator in Australia, Safe Work Australia (Safe Work Australia, 2006) defines "safe design" as:

> *"Safe Design is a design process that eliminates work health and safety hazards, or minimises potential work health and safety risk, by involving decision makers and considering the life cycle of the designed-product.*
>
> *"A Safe Design approach will generate a design option that eliminates work health and safety hazards and minimises the risks to those who make the product, and to those who use it."*

Many would argue that this is an impossibly high or impractical standard for safe design. Nevertheless, it is consistent with most of the large mining houses, mining professional societies and mining representative groups which typically state that "All accidents and incidents are preventable" (AusIMM, 2002) or target "Zero harm" as being a required corporate outcome (Qld Mining Council, 2009).

Perhaps more reasonably, the Queensland hardrock mining legislation (Qld Govt, 1999) defines an 'acceptable' level of risk in this way:

> *What is an acceptable level of risk*
>
> *26.(1) For risk to a person from operations to be at an "acceptable level", the operations must be carried out so that the level of risk from the operations is—*

(a) within acceptable limits; and

(b) as low as reasonably achievable.

(2) To decide whether risk is within acceptable limits and as low as reasonably achievable regard must be had to—

(a) the likelihood of injury or illness to a person arising out of the risk; and

(b) the severity of the injury or illness.

The important things to note here are that:

- Whilst there is an absolute level of safety that must be achieved (including, by inference, in ventilation circuit design and operation), it is acceptable to take into account both the likelihood (probability) and severity (consequences) of injury or illness that may occur.
- Achieving ALARA is a specific and mandatory deliverable for all mining operations.
- Both of these requirements must be achieved simultaneously, i.e. the absolute level of safety as specified PLUS achievement of ALARA. It is not a matter of achieving one OR the other in a ventilation design, but BOTH.

7 Example of Using Carbon Monoxide as a Design Criterion

As an example, consider carbon monoxide as a design criterion for a ventilation engineer. The TWA for carbon monoxide varies around the world and in Australia, at present, is 30 ppm for a roster involving five 8 hour shifts per week (25 ppm in USA). However, no responsible ventilation engineer would consider a ventilation circuit to be "satisfactory" if it were to result in workers being exposed to a CO concentration of 30 ppm averaged over their full shift of 8 hours. Why is this?

Firstly, responsible mine operators already achieve ambient CO concentrations well below this level. A rule of thumb this author has used for many years has been:

- CO < 5 ppm: ventilation is adequate
- 5 ppm < CO < 10 ppm: local ventilation is stressed and should be rectified as a matter of priority (within one or two shifts)
- CO > 10 ppm: work should cease immediately until ventilation is rectified

Secondly, the value of 30 ppm is for five 8 hour shifts per week. Where persons are working the more typical 12 hour shifts, this value is effectively halved, i.e. to 15 (or 12.5) ppm. In this regard, it is very important to note that this is the case even if the total number of hours worked per week remains the same as on an 8-hour shift roster. Some incompetent persons have advised that these "time weighted average" values can be weighted over longer periods than 8 hours; this is not the case and has been specifically barred by the ACGIH. Quoting from Hewett (2007):

"The ACGIH expressly forbids redefining the TLVs: "it is not appropriate for individuals or organizations to impose on the TLVs ... their concepts of what the TLVs ... should be or how they should be applied ...". While it is abundantly clear to most practicing industrial hygienists that the TWA TLVs are defined as limits for each TWA exposure, there is a tendency among a minority to insist that the TWA TLVs represent long-term, even lifetime average exposures. Such a view basically redefines the TWA TLVs, extending the averaging time from a single shift to months or years or, in the view of some, the employee's working lifetime. Because the long-term average exposures permitted by this practice can be double or more over those that result when the TLV is properly interpreted as an upper control limit for each TWA (see the previous discussion on models of compliance), the level of protection provided by such a modified TLV cannot possibly equal the level of protection provided by the original TLV. Since OSHA's TWA PELs and NIOSH's TWA RELs are clearly defined as upper limits for each single shift average exposure (TWA) it is clearly inappropriate to manage exposures as if they represented limits on long-term, average exposures."

This comment is not inconsistent with the exposure adjustments for non-standard working hours, as these roster adjustments only ever adjust exposure standards "downwards" not "upwards", i.e. they act to decrease the allowable limit on any given shift, not increase it.[1]

Thirdly, the TWA values do not represent a "no effects" value. The Guidance Note "Exposure Standards in Australia" (National Occupational Health and Safety Commission, 2001), states:

"1.4 The exposure standards do not represent `no-effect' levels which guarantee protection to every worker. Given the nature of biological variation and the range of individual susceptibility, it is inevitable that a very small proportion of workers who are exposed to concentrations around or below the exposure standard may suffer mild and transitory discomfort. An even smaller number may exhibit symptoms of illness."

Similarly, the Australian Institute of Occupational Hygienists (AIOH, 2009) makes this statement:

"The AIOH supports the current ASCC (Australian Safety and Compensation Council) occupational exposure standard of 0.1 mg/m^3 for respirable crystalline silica. The principal reason for this position is the declining reported incidence of silicosis in Australia. However it is becoming evident that there is not a substantiated "no observable adverse effects level" (NOAEL) at which it can be categorically stated that exposure to crystalline silica has no adverse health effects. The literature is demonstrating risks to health at levels previously considered as being acceptable. The determination of such a level may also be hampered by limitations in measurement technology which do not allow the measurement of very low level exposure. There is an emerging trend within the

1 There are rare exceptions to this, principally in radiation protection.

occupational hygiene community to take a pragmatic approach to the measurement and control of exposures to toxic substances without attempting to define a dose response based exposure standard. Thus the AIOH acknowledges the importance of adhering to good control strategies so as to reduce exposures to "as low as reasonably practicable (ALARP)".

In summary, merely meeting the TWA value for carbon monoxide is a necessary but not sufficient condition for safe circuit design. CO values must be reduced to ALARA via ventilation circuit design and operation.

8 Demonstrating ALARA: How to Comply?

So how does an operation demonstrate that it is meeting the ALARA standard?

- It must show that a range of designs (options) have been considered and risk assessed, and the chosen design is not only safe in the absolute (legal) sense, but the cost to reduce the risk further to a lower-risk design, cannot be justified, *and*
- It must demonstrate via benchmarking that its design standards and practices meet "industry good practice" compared to its peers, *and*
- It must show that adverse outcomes are continuing to reduce, i.e. a powerful way to demonstrate ALARA is to show (for example) that respirable crystalline silica dust doses to various similarly exposed groups of workers at the operation are showing a consistent downwards trend with time. In effect, that the operation is achieving a continuous improvement in all key deliverables from the ventilation system design and operation.

9 Best Practicable Technology

With respect to benchmarking, an important concept only erratically taken up by hardrock miners to date (and generally only in the context of radiation controls in uranium mines) is that of "Best Practicable Technology". Particularly prior to making important design or investment decisions, it is highly advisable to not only benchmark against similar operations (peers) but also to check more widely, including in other industries, that technology from other industries cannot be adapted to this operation allowing better or lower-risk management of a particular hazard. Such a review should also identify emerging technologies that may be of relevance, or even key success factors, to the operation in the future.

10 Variations on Series Circuit Design

Just as there are a variety of configurations for parallel circuit design, so there are also a variety of configurations for series circuit design. Perhaps the most common style of series circuit in the primary ventilation system is where the ramp is the 'intake' (a dirty intake, as it is progressively blended with return air from the active levels), and the exhaust is a single connection at the bottom of the ramp which is progressively extended with the ramp. This system puts the ramp in dirty 'fresh' air, but has the disadvantage that a fire on the ramp will contaminate the entire mine, including all the active levels as these are ventilated off the ramp. It also results in the worst conditions being at the mine bottom, which is usually a high activity and high priority area. One alternative is to reverse the system so that the vertical 'exhaust' becomes the mine intake and the ramp the return, with the ramp portal becoming the surface exhaust (Brake, 2011). This may allow some truly fresh air to be bled onto some levels, but in any event, means that any person on a level can access a secure fresh air base by passing through a simple pedestrian door into the fresh air raise on that level. It also pushes the best air in the mine to the ramp bottom.

11 Types of operations not amenable to series ventilation

Some types of hazards are not amenable to series ventilation. This would include: uranium mining, mines with serious spontaneous combustion issues, mines where leakage could result in a serious hazard (e.g. ingress of toxic gases), or regions within a mine affected by sulphide dust explosion potential.

Similarly, some operations will simply be more economic or practical using parallel circuits. This would particularly be the case for mines with high tonnes per vertical meter, which means extensive lateral spread of workings; in this case, parallel circuits are needed to provide sufficient air to feed the number of simultaneous activities on a level, and to provide the flexibility needed to maintain a high production rate. However, any operation where the service ramp cannot carry the required total mine airflow are also likely to require a parallel configuration.

Specific areas in a mine that also generally cannot have downwind activities include refueling facilities, crushing circuits, shaft loading areas, ore/fill/mullock pass ventilation and dedicated stope exhausts.

12 Series Ventilation in respect of Airborne Contaminant Levels

Based on the above analysis, it is this author's opinion that in terms of contaminant levels, for series ventilation circuits to be acceptable:

- The design must meet the required TLVs correctly adjusted for non-standard rosters as required
- Contaminant doses should be lower than for parallel circuit designs. Adoption of series ventilation circuits must be justified on more than just being "lower cost"; there needs to be an improvement in aggregate health and safety outcomes at the same time, i.e. a "win-win" must be targeted.
- Multiple designs must have been examined and it is

documented that achieving lower contaminant doses by revised circuit design (whether it be parallel or hybrid techniques) cannot be justified by the cost or social impacts involved

- Benchmarking of peers, as well as a review of Best Practicable Technology in non-related industries, confirms the design is sound and at the level of lowest reasonably practicable risk
- The operation must be able to demonstrate that contaminant doses are continuing to trend downwards with time

13 Series Ventilation in Respect of Re-entry after Blasting

Series ventilation circuits create some special design issues with respect to clearance times and re-entry procedures after underground blasting

- Longer travel route for fumes. The path for the air to travel from the blast site to the exhaust is generally longer in distance (and usually, but not always, also longer in time)
- Blast fumes are not kept localised on the level. In most cases, series circuits return the blasting fumes to major travelways such as the ramp rather than isolating them within the local ventilation district. This can restrict travel through these arterial travelways even to jobs that are otherwise "fresh", resulting in long re-entry times particularly if the ventilation on the level that was blasted is not very effective, as blasting fumes will be exiting via the ramp for a considerable time.
- Blast fumes are pushed into other areas. Blast fumes are pushed throughout the mine following the series circuit path. This frequently introduces blast fumes into areas that were not, in fact, blasted, creating additional hazards and additional areas that need to be checked for fumes.
- Fewer escape paths resulting in migration of fumes through small openings. Adoption of series circuits often also means fewer areas with flow through ventilation. This often means stopes that have fewer paths for blasting fumes to exit. This, combined with modern blasting practices, is resulting in situations where fumes are pushed under considerable pressure (via the blast overpressures) through small holes (even blast holes) into other areas of the mine.
- Difficulty firing from a place of safety. Unless blasting is initiated from surface, series circuits may complicate or reduce the range of locations from which the blast can be initiated safely
- Difficulty re-establishing ventilation after firing if the auxiliary fan won't start or the duct is blown off. If there is no flow-through ventilation on a level and the blast fumes are to be cleared via a forcing fan on the ramp, or on the level (e.g. bolted into a fresh air raise), then if the fan does not come on after the blast, or if the duct has been blown off the fan or badly damaged, the level may not "clear" at all, or only very slowly via natural ventilation or diffusion. In this case, the fan may need to be re-started, or duct repaired, by workers under breathing apparatus.

Additional controls for blasting gases that may be required when operating series circuits include the following:

- Modelling. Whereas rules of thumb or some simple hand calculations may have been sufficient for understanding blasting fumes behaviour with respect to clearance times for parallel circuits, the more convoluted paths for blasting fumes in series circuits, especially if combined with multiple blasting involving both development and production sized blasts, means that more detailed modelling is required under a "Duty of Care" to understand the implications of blasting fumes on series circuit design
- Real-time monitoring. Since the ramp or main travelways will become contaminated by blasting fumes, in some cases it is desirable, or even essential, for real-time monitors with telemetered data back to surface to be used to assess safe conditions
- Electronic gas monitors. Re-entry cannot be based solely on "time delays" (e.g. re-entry 30 minutes after blasting); actual gas tests using electronic gas monitors are required prior to allowing persons back into potentially affected areas. This requires higher skill levels and training of personnel and regular maintenance and calibration of gas monitors.
- Trained clearance crews. Due to the potential additional hazards of blasting fumes in series circuits, re-entry (clearance) crews need to be well-trained. They should also do their re-entry inspections in pairs, and have reliable communications with surface at all times.
- More workplaces affected by delays. Delays in re-entry with parallel circuits usually only affect a smaller area of the mine and therefore limited number of workplaces. Delays with re-entry in series circuits may result in no one being allowed underground and therefore no work re-starting after a blast. This has particular implications for mines that may be subject to sulphide dust explosions. These are usually triggered during blasting and can produce very large volumes of SO_2 and other toxic gases. Such operations are probably not amenable to series circuit design at all.
- Workers with personal gas monitors. Some operations with series circuits and "marginal" ventilation designs have issued personal gas monitors to all workers, e.g. the MSA "cricket".
- More comprehensive and rigorous re-entry procedures. At the very least, more comprehensive and rigorous, carefully risk-assessed, re-entry procedures are required in series operations. In most cases in Australia, "re-entry plans" or checklists are required for every blast design, i.e. the ventilation officer is required to endorse the proposed re-entry procedure for every single blast in the mine.

14 Series Ventilation in respect of Egress, Entrapment and Rescue-ability.

It is perhaps in respect of safe egress, entrapment and rescue-ability that series ventilation design is most vulnerable. The principal concerns are:

- A greater area of the mine (and hence higher proportion of persons underground) will be affected by a fire where there is extensive (or exclusive) use of series circuits
- It is more likely that persons underground will need to travel through products of combustion (POCs or "smoke") to reach a safe place of entrapment. This is an issue not only of the toxic nature of the products of combustion, but also the difficulties of seeing in smoke and/or becoming disoriented and lost
- It may be more difficult to fight the fire either because there are no "parallel" airways (and therefore ways to travel around the fire to attack it from a more suitable direction), or because the fire is well supplied with oxygen due to the very strong airflows in a series circuit or because there are no reliable forward fresh air bases for mine rescue crews, increasing the potential delay period (and risk) for those entrapped before being rescued to surface
- It may be more difficult to undertake search and rescue operations (for similar reasons as above), putting more reliance on individuals underground to "self-escape" and more reliance on the need for close access to refuge chambers or secure fresh air bases.

There is no doubt that any unbiased and competent risk assessment will find that series circuits have a much higher *absolute* risk than parallel circuits with respect to serious fires. However, it can be argued that, providing sufficiently strong controls are used, series ventilation has a similar or lower *residual* risk in terms of fire than a parallel circuit design (that does not employ the same controls).

In this respect, this author's view is that the following standards should be used for all underground hardrock mines. Some of these standards are not specific to series ventilation circuits but in most cases, the greater absolute risk involved in series circuits presents an even stronger case for these controls than in parallel circuit design:

- A second means of egress should be operational on each new level of any mine before production commences (ore winning) from that level
- 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 shaft sinking, if applicable). This prevents the situation developing where a mine of limited extent "drags on" for years with only a single egress.
- All persons underground should have at least 30 minute belt-worn SCSRs at all times
- No person should be more than 750 m from a 36-hour rated fully self-contained, standalone and independent refuge bay or secure fresh air base (assuming all persons are wearing 30-minute SCSRs)
- There must be a reliable personal warning system rapidly and reliably triggered in the event of an actual or suspected underground fire. It is vitally important that an early warning is given to allow the fastest and easiest possible escape to a safe place of refuge.
- There must be effective, realistic and regular fire drills in the mine. These should be documented and learning outcomes incorporated in future procedures.
- There should be sufficient rated refuge chambers or rated fresh air bases for whoever might reasonably need to use that facility at any time. Note that this can be a considerable cost to the operation with a single rated refuge chamber for 12 persons costing up to $100 000.
- No person should be "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
- 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. In most cases, it should also apply to fires, i.e. no single fire event should contaminate both the primary and secondary means of egress.
- Both egresses must be capable of passage by rescue teams, rescue equipment and stretchers.
- 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" (Qld Govt, 2001). 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 general, no producing stope should be lower than the depth of the primary ventilation system (i.e. no production to 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.
- In general, "blind" (single access) 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 250 m. This would apply, for example, to wide cut and fill stopes or headings in poor ground where there is any significant residual risk of rockfall or mudrush, etc.
- Special fire precautions should be installed on underground diesels. At the very least, this includes AFFF or similar technology on diesels other than light vehicles but there are a wide range of other measures

that, in most cases, would be considered to be "reasonably achievable" and therefore required under the ALARA principle (WA DOIR, 1997).

It must be emphasised again that, without these strong additional controls being in place and operating effectively, series ventilation circuits, in this author's opinion, have a much higher and unacceptable risk from a major fire, compared to parallel circuit design.

15 Conclusions

There has been a widespread trend towards the use of series ventilation circuits in underground hardrock mines. Many of the factors driving this trend will remain, and probably even accelerate, over the years ahead. The use of series ventilation circuits will become an important part of overall mine ventilation design. Series ventilation circuits should not become the default style of ventilation in hardrock mines and they are incompatible with some types of underground hazards; however, such circuits can be safely designed and operated in many circumstances, but there are important safety, operating and cost issues that must be understood and addressed before series circuits are adopted. Not only must the series circuit design be safe in an absolute sense, but it also must be able to be shown as reducing the risk to "as low as reasonably practicable". Series circuits must not only be safe during normal operations, but also with respect to "upset" conditions such as fires, dust explosions, floods, mud-rushes or other potential hazards applicable to a given mine. Series circuits also have important operational implications for re-entry procedures after blasting. Many series-ventilated mines currently operating in Australia and elsewhere would not be able to comply with the standards recommended in this paper. Operators should not adopt series ventilation circuits without proper consideration of these factors and the necessary operational constraints and other controls that are required such as personal belt-worn SCSRs, 36-hour rated refuge chambers or secure fresh air bases and special modifications to underground diesel vehicles.

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