A Review of Good Practice Standards and re-Entry Procedures after Blasting and Gas Detection Generally in Underground Hardrock Mines

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There have been many single and multiple fatalities over generations of underground mining due to workers being gassed by toxic blasting fumes or an irrespirable atmosphere after re-entering the area that was blasted, or some area connected to it. The traditional approach to determining safe re-entry (clearance) times was to use a fixed time interval after blasting based on either experience, limited testing with chemical stain tubes, or simple dilution calculations, as well as training miners to "use their nose" to smell for fumes. With the advent of relatively inexpensive and reliable electronic gas monitors, combined with the now well-established principal of managing risks to the "as low as reasonably achievable" (ALARA) standard, re-entry procedures have been undergoing considerable changes. Gas monitors are now frequently used to test all "potentially" affected locations. However, the risks from migrating blasting fumes have also increased due to the trends to allow or even design ventilation circuits with major short-circuiting through open stopes and other leakage paths, as well as using the main ramp in some mines as a "dirty intake" with one level effectively in series with another. In all of these cases, blasting fumes from one location may be introduced into non-blasted locations. Moreover, the introduction of 12 hour shifts and "long" rosters has created some divergence in the industry with respect to the gas limit standards for "safe" gas levels for re-entry. This paper reviews modern procedures for safe re-entry after both development and production blasting, including how it is being undertaken, the target gases being used for re-entry clearance criteria, and general risk management considerations. It makes recommendations for safe standards.

Keywords: gas, monitors, blasting, re-entry, ALARA.

1. Introduction

Incidents resulting in serious injury and fatalities due to being exposed to toxic blasting gases continue in the mining industry. A key problem is that most hardrock mines blast between two and six times each day, so that it is easy to become "over-familiar" with the issue of blasting fumes and complacent so that when the unexpected or unusual happens, workers can be gassed.

This paper deals solely with the safe re-entry in terms of noxious gases; it does not discuss any of the other important safety aspects of preparing for blasting, or safety requirements at the conclusion of blasting such as disconnecting firing lines, checking for misfires, barring down, setting up water sprays, etc.

Most Australian mines now have a system of written "Authorized Firing Plans" (AFPs) or similar documentation (one AFP for every blast), that sets out the "check and clear" information for the blasting crew and the re-entry information and required checks for the re-entry crew. In effect, an AFP is a standard checklist that is customized for each particular blast and includes extracts from level plans showing where barricades are required, etc. These AFPs are issued by the mine design staff (including the ventilation engineer), completed in writing by the re-entry crew and handed back to the supervisor after each blast. Just as airline pilots, no matter how experienced, complete written checklists before take-off, so these AFPs reduce the potential for human error in blasting checks.

2. Gases produced from blasting

With modern explosives (ANFO and/or emulsion [or various mixtures of the two]), the amount of toxic gases or fumes produced from blasting varies according to the explosive mix, the degree of confinement in the hole, the amount of water in the hole and the sleep time of the explosive, among other factors.

It is always difficult to predict how much blasting fumes will be produced, and also how long it will take for the fumes to "clear". Empirical methods have been developed but these are at best an indicator of the likely clearance time and hence are more intended to provide an estimate of the impact on mine productivity, and should never be considered to be "prescriptive" or sufficient in terms of safely allowing persons back into the area.

In the following discussion, "safe" re-entry gas concentrations are taken as being the current Australian TWA values: CO (30 ppm), CO_2 (5000 ppm), NO_2 (3 ppm) and NO (25 ppm). Other gases such as NH_3 and SO_2 are unlikely to be critical. As will be seen below, SO_2 and H_2S are not strictly substantial products from explosives, but where present are usually due to the use of explosives in sulphide-containing rocks. NH_3 should

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also be minimal unless lime is present (e.g. due to cement).

Table 1 summarizes key available data in terms of the toxicity of the concentrations of blasting gases. The values in columns A to C of this table are expressed as m^3/s of fresh air required to dilute the volume of blasting fumes produced from 1 kg of explosive to the TWA values as noted above. Column D is discussed separately.

- Column A of Table 1 is from Rowland, Mainiero and Hurd [5] who also found that for fresh emulsion, an average NO_2/NO_x ratio is about 30% (see also figure 1 and 2).
- Column B of Table 1 is from Lovitt [3] who also found that emulsion ("Powergel") has a NO_2/NO_x ratio of about 30% (see also table 2).
- Column C of Table 1 relates to non-ideal detonation of ANFO and is from Lovitt [2]. See also figure 4.
- Column D of Table 1 is from Hardcastle [1]. Whilst numerical data is not available, Hardcastle found the critical gas was CO, followed in descending order by NO_2, NO and CO_2.

Effectively Table 1 shows that for emulsion, the most critical blasting gases are CO and NO_2, with NO and CO_2 much less significant. The critical gases with ANFO are much harder to predict as it suffers much greater production of toxic gases (from ideal detonation values) due to presence of water. However, the most toxic gases for ANFO and emulsions will remain CO, NO_2, CO_2 and NO in *some* order.

Table 1. "Criticality of gases from blasting" expressed as m^3/s of fresh air to dilute blasting fumes from 1 kg of explosive to the TWA as above, except for column D which is by critical order

	A	B	C	D
Explos-ive	Emul-sion	Emul-sion	ANFO (non-ideal det)	Unspecified
CO	500	583	833	1
NO_2	333	307	2500	2
NO	40	97	700	3
CO_2	30	21	35	4

Examples of actual gas concentrations from blasting (production and development) are shown in Figures 6 and 7.

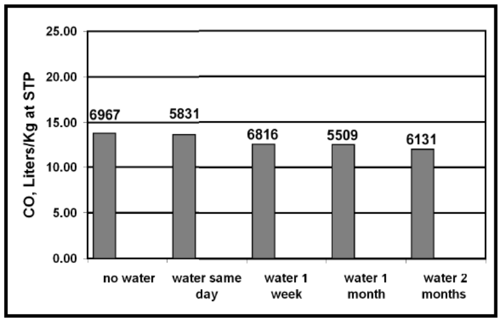

Fig. 1. Carbon monoxide production of emulsion shot in steel pipe following exposure to water for up to two months. Numbers above bars are detonation velocity in m/s (Rowland, Mainiero and Hurd [5])

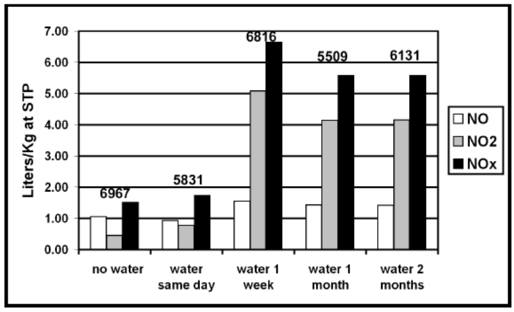

Fig. 2. Nitrogen oxides production for emulsion shot in steel pipe following exposure to water for up to two months. Numbers above bars are detonation velocity in m/s (Rowland, Mainiero and Hurd [5])

Table 2. Data from Lovitt [2] (original source 1984)

Explosive type	Computed toxic gas value (L/kg)				
	NO_x	NO	NO_2	CO	CO_2
AN60	8.53	5.93	2.60	65.95	195.38
Powergel	3.35	2.43	0.92	17.51	105.02
Molanite 115	5.70	4.66	1.04	27.84	70.15

Component	ANFO	ANFO
	litres/Kg	Percent
Methane	minor	minimal
Carbon Monoxide	5 to 44	1% to 4%
Carbon Dioxide	100 to 250	9% to 24%
Hydrogen	minor	minimal
Ammonia	0.3 to 3	0.03 to 0.3 %
Water	580 to 680	53% to 63%
Hydrogen Sulphide	minor	minor
Nitrogen	100 to 250	9% to 24%
Nitric Oxides	10 to 40	1% to 4%
Oxygen	minor	minor
Sulphur Dioxide	minor	minor

Fig. 3. Data from Lovitt [2] who states "In normal use, the following rates of production…can reasonably be expected. Water is the main cause for non-ideal nature."

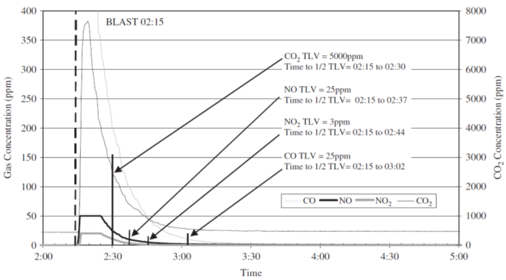

Fig. 4. Data from Hardcastle [1]

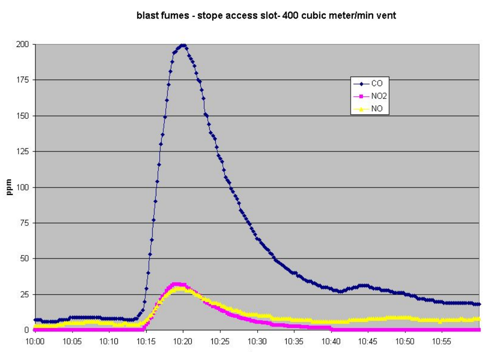

Fig. 5. Data from stope blast

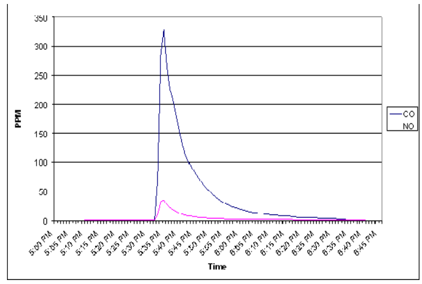

Fig. 6. Data from development blast (same mine and time period as Figure 6)

3. Blast gas measurement procedures

Whilst supervisors have often been used in the past to check the blast-affected areas for fumes, most Australian mines now use dedicated, trained re-entry crews. These crews are usually either development charge-up or production blasting personnel and usually operate as "pairs" (two persons per crew[1]). They operate to strict procedures. They usually have two persons per crew for safety, although often using only one gas monitor providing it is maintained, operated and calibrated strictly in accordance with the manufacturer's requirements.

Based on the earlier discussion, the minimum gases that need to be measured before re-entry are shown in Table 2. This table also shows other gases commonly installed on these monitors, as the monitors are often used for other purposes than re-entry after blasting.

Table 2 also shows the recommended maximum gas concentration in any part of the area before the area can be considered safe (in terms of atmosphere). Note that some mining operators use different values for these levels. Typical values/criteria across the industry would be to use the:

- STEL (short-term exposure level)
- 8-hour TWA (time-weighted average)
- Roster-adjusted TWA (for 12 hour shifts, this is usually 50% of the 8-hour TWA for most gases).

This author recommends use of the roster-adjusted TWA, as this is the "safe" level even if no further dilution of blasting fumes in that location were to occur. This is conservative but most Australian mines use this approach.

Less conservative criteria could be used if careful risk assessment finds this acceptable; however, often the extra time required for the gas concentration to fall from (say) 30 ppm to 15 ppm in well-ventilated areas is only

1. Some operations do allow single persons in this role providing they are carrying reliable, accurate gas monitors. However, the author would not recommend this practice.

Table 3. Usual minimum gases to be measured in hardrock mine (TWA and STEL values are those applicable in Australia)

Situation	Gas	Criteria (8 hr shifts, 40 hr week)	Criteria (12 hour shifts, 42 hr week)	STEL
Minimum gas checks for blasting in inert material	CO	<30 ppm[2]	<15 ppm	<50 ppm[3]
	NO_2	<3 ppm	<1.5 ppm	<5 ppm
Extra gas to be checked if sulphides present	SO_2	<2 ppm	<1 ppm	<5 ppm
Extra gases-desirable	NH_3	<25 ppm	<12.5 ppm	<25 ppm
	CO_2	<5000 ppm	<2500 ppm	<30 000 ppm
Confined spaces[4] LEL should also be measured where flammable gases may be present, e.g. strata gases or large lead-acid battery charging stations	H_2S	<10 ppm	<5 ppm	<10 ppm
	O_2	>18 %[5]	>18 %[5]	
	CH_4/H_2 LEL	>20 % LEL	>20 % LEL	

Some operations do allow the re-entry crew, who are carrying gas monitor(s) and are specially trained, to enter an area above the TWA but below the STEL, solely for purposes of making the area safe (e.g. turning fans on, or shorting-out firing lines), providing the exposure meets STEL guidelines (maximum of 15 minutes no more than 4 times per shift separated by at least one hour per exposure). Some gas monitors now have the facility to continuously monitor on a time-weighted basis for TWA and STEL values and alarm accordingly.

There is a limit to the number of sensors that can be fitted to a handheld gas monitor, and more sensors also mean higher initial purchase cost and more expensive recalibration, etc. Fitting the maximum number of sensors to a monitor is not always the best option. In some cases it may be better to have two monitors (say an "A" monitor and a "B" monitor—each with different sensors), if the mine does want to measure a number of gases.

Effectively Table 2 shows that the minimum gases to be checked in most hardrock mines (most of which have some sulfides present) would be: CO, NO_2 and SO_2, with NH_3 also desirable. A second monitor could carry: CO_2, H_2S, O_2, CH_4/LEL and NH_3 (if not on the first monitor).

In Australia, current good practice gas re-entry procedures for blasting is as follows:

1. Blast-proof barricades[6] are placed to prevent entry to any area which could be affected by the blast directly (concussion, flyrock) *or by fumes from the blast*. An AFP is essential for production blasts other than small blasts (e.g. opening up the cutoff slot, often to a limit of (say) 3000 tonnes ore) and good practice would be to have at least a "generic" AFP for development headings on various levels of the mine or in various sub-circuits of the ventilation system. As noted earlier, some operations require an AFP for all blasts.
2. With parallel ventilation circuits, barricades may not be required on the ramp and on many non-blasted levels. This should be resolved in the risk assessment used to develop the AFP.
3. All potentially affected persons are then removed to safe locations (usually the surface or a cribroom that is also a secure fresh air base). All persons are accounted for.
4. The blasts are initiated.
5. The priority for re-entry checks is usually the ramp so that most if not all persons can get back to work assuming they can get to their workplace without going past a blasting barricade. The re-entry crew will give priority to checking the ramp (if required under the AFP) and then these areas are declared 'all clear' and any barricades on the ramp removed.
6. If fans (including development fans) on fume-affected levels can be restarted immediately and automatically from a safe central location, this is done immediately after the blast. Alternately, and assuming the development fan "electrical starters" are located in a "safe" area with fresh air, the re-entry crew might be required to wait (say) 10 to 15 minutes after the blast and then, with gas monitors, proceed to turn on the fans manually. If gas levels exceed the allowable value before they reach the fan starter, they retreat to the surface or cribroom and wait a further 10 to 15 minutes. If fan starters still cannot be reached safely, then trained persons (e.g. mine rescue crew) using breathing apparatus may be required.

2. Hour TWA for CO in Australia is 30 ppm; in North America it is 25 ppm
3. There is no STEL for CO although there is a special Guidance Note in Australia. This is a typical value used for short-term re-entry.
4. The "standard" gases to be checked in Australia for confined spaces entry are O_2, CH_4/LEL (flammables) and two toxic gases which are usually H_2S and CO_2. However, confined space gas entry requirements can vary with circumstances and regulatory authority. Check first.
5. At normal barometric pressure.
6. Blast proof in the sense that the personnel barricade (e.g. chain) and sign cannot be blown away due to the blast. In some cases, sentries are posted. Some operations also use flashing blue lights at the barricade.

7. If that fan can be turned on, then the re-entry crew may proceed to the next fan allowing time for the fumes in that heading to clear.

8. A minimum of (say) 15 to 30 minutes *after the ventilation is re-established*, the re-entry crew will start from the "safe" area and proceed to each barricade and then into the firing area, checking for fumes as they go. If they encounter fumes above the re-entry criteria, they withdraw and leave the barricade up. If they check the entire potentially affected area (including blind headings) and gases are below (within) the re-entry level criteria, then they remove the barricade.

9. The gas levels at the fan inlet (for a blind heading) should be checked first to ensure no recirculation is occurring.

10. The gas monitor must be exposed to the air that potentially contains the toxic gases, i.e. if travelling by vehicle (normal practice) the re-entry crew passenger's arm is held safely out the window with the gas monitor exposed to the outside atmosphere. It is unsafe to just have the gas monitor on the seat of the vehicle, or held inside the vehicle.

11. In some mines, workers who then enter the area that was fired once it is "cleared" and declared safe *also* carry a gas monitor (in case of residual gas not detected by the re-entry crew).

12. If the mine has many areas to "clear", then more than one re-entry crew can be utilised, according to a carefully constructed and coordinated plan.

13. When considering areas that <u>may</u> be affected by blasting fumes it is essential to understand the following:

    a. Fumes are initially and instantly produced as a concentrated cloud that then starts to move through the mine towards the exhaust (for that area) as a "plug" (diluting and dispersing as it goes). It is therefore possible that the fume level may be falling, or even safe, in an area close to the blast, *but still be increasing or unsafe in another area between the blast and the exhaust*.

    b. This issue is particularly the case in mines with series ventilation of multiple levels, where the fumes from a blast on a level will return to the ramp and then move down the ramp so that a gas monitor on the ramp will show levels increasing and decreasing as the fumes from the first blast pass. However, a blast fired on a level further up in the mine may then have its "plug" move down the ramp past the same monitor *which will then show a second peak*.

    c. The fumes produced as part of the blast are "thrown back" instantly filling a substantial volume. This means they can be pushed into areas other than the region directly between the blast position and the local exhaust.

    d. Ducting may be blown off development fans or "broken" part-way along the duct meaning the fan may be on but the fresh air may not be reaching the face. Therefore as noted earlier, solely adopting a time-limit for re-entry is not acceptable.

    e. For a similar reason, it is possible that the ramp and "general" mine areas can be declared "clear" of fumes, but the re-entry crew then enters a fired area and finds a fan is off. If this fan is turned on, the plug of fumes may enter an area into which workers have already proceeded. Therefore once an all-clear has been given, fans that may disperse blasting fumes must not be turned on until workers are cleared from potential return paths for those fumes.

    f. Fumes can migrate or be pushed or pulled from the level on which the blast occurred to other areas even down blastholes or raisebore holes or through open stopes due to leakage or short-circuiting. Circuit fans that "should" be on after the blast to clear fumes may not be (due to damage) or ventilation controls may be damaged. To follow on from the example in dot point a, as fumes proceed down the ramp, any fan on the ramp that is "on" will pick up those fumes and push them into levels that may not have been fired. Therefore it is essential to take care to ensure that all potentially affected areas have been checked. As a minimum ALL levels that are open (via *any sort of vertical opening*) to a stope that is blasted (even if the blast is not on that level) should be checked, as well as any area fed by a fan that could have taken in blast fumes to its inlet.

    g. Fumes can be contained within the muck pile and only released into the air once loading operations commence, i.e. after re-entry is allowed. The conversion of NO to NO_2 in the presence of oxygen can be constrained by the low-oxygen potential in the muckpile (see Mainiero et al [4] and Sapko et al [6]).

Ventilation modelling can be useful in understanding blast fume behaviour and clearance times, especially in complex mines or mines with disseminated blasts. Some packages offer substantially better techniques for this purpose than others.

References

[1] Hardcastle S, Kocsis C & O'Connor D, 2009. Justifying ventilation-on-demand in a Canadian mine and the need for process based simulations. 11th U.S./North American Mine Ventilation Symposium 2006 – Mutmansky & Ramani (eds)

[2] Lovitt M, 2008. Explosive gases from ANFO and Powerbulk VE (pers comm).

[3] Lovitt M, 2014. Personal communication.

[4] Mainiero R, Rowland III J, Harris M and Sapko M, 2006. Behavior of Nitrogen Oxides in the Product Gases from Explosive Detonations, NIOSH.

[5] Rowland J, Mainiero R and Hurd D, 2001. Factors affecting fumes production of an emulsion and ANFO/Emulsion blends (NIOSH). Proc 27th Ann conf explos blasting Tech. Vol II (28-31 Jan 2001, Cleveland OH: Int Soc of Explos Eng, 2001:133-141)

[6] Sapko M, Rowland J, Mainiero R, and Zlochower I, 2002. Chemical and Physical Factors That Influence NOx Production During Blasting - Exploratory Study (NIOSH).