Investigating Ammonia Loading Mechanisms at an Underground Gold Mine

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Abstract

The use of ammonium nitrate based explosives is widespread in the hard rock mining industry. Nowadays, most mining operations rely on either ammonium nitrate based emulsion or ammonium nitrate fuel oil to fragment ore bodies. In both cases, it is commonly understood that a certain portion of the explosives brought to a blast zone will remain undetonated, and eventually be dissolved by mine water. Dissolution of ammonium nitrate leads to the presence of ammonia nitrogen in the water. Although several technologies are available to remove ammonia nitrogen from impacted water, reduction at the source is considered a best practice.

This paper documents the efforts aimed at reducing ammonia nitrogen loading at the Meliadine underground mine located in Nunavut, Canada. Loading mechanisms and resulting ammonia nitrogen concentrations in mine water are discussed and compared to other underground mine sites. The observed loading rates were found to be on the lower spectrum of available information found in the literature, averaging 7 g NH_3-N / kg of emulsion used in 2021. This study also revealed that tasks performed at the explosive storage facilities accounted for approximately 11% of all undetonated underground explosives, while development and production blasting operations contribute 43 and 46%, respectively.

Improvements in monitoring and interpretation of ammonia concentrations in mine water are also discussed, including the use of a key performance indicator to track monthly changes. Mitigation measures to reduce the ammonia loading rate are grouped in four categories: 1) data acquisition improvements, 2) behavioural changes, 3) engineered solutions and 4) governance. Preliminary results indicate a 19% reduction of the ammonia loading rate following the establishment of a training and awareness campaign. Upon completion of these mitigation measures, the mine is expecting a reduction of ammonia loading rate above 30%. Areas for further research, notably the quantity of undetonated explosives trucked to the surface alongside ore and waste material, are also discussed.

Introduction

Ammonium nitrate (AN) is commonly used in the hard rock mining industry as a base product for explosives. Nowadays, the most prevalent types of explosives found on mine sites are either emulsion (typically 70–80% AN, 10–20% water, 4% oil and 1–2% additives) or ammonium nitrate fuel oil (ANFO) (typically 94.5% AN and 4.5% oil) (Jermakka et al., 2015). It is commonly understood that a certain portion of the explosives brought to a blast zone will remain undetonated due to spillage or misfires. Even though emulsion is more water-resistant than ANFO, both products are eventually dissolved by mine water. Watson (1991) reported a nitrogen leaching rate of about 50% for ANFO after one minute of contact time, and 1.2% for emulsion, after 144 hours. For this reason, using a 100% emulsion approach is considered a best practice by many mining companies.

Once dissolved in water, AN dissociates into nitrate (NO_3^-), ammonium (NH_4^+) and ammonia (NH_3). The resulting proportion of NH_4^+ and NH_3 is a function of the pH and the temperature of the solution; in this paper, both species will be referred to as ammonia nitrogen (NH_3-N).

Although several technologies are available to remove ammonia nitrogen from impacted water, reduction at the source is also considered best practice.

Studied site overview

The Meliadine gold mine, operated by Agnico Eagle Mines, is located approximately 25 km north of Rankin Inlet and 80 km southwest of Chesterfield Inlet in the Kivalliq Region of Nunavut. The mine site is located on the peninsula between the East, South, and West basins of Meliadine Lake (63°01'23.8"N, 92°13'6.42"W). The area is accessible from the all-weather gravel road linking the Meliadine mine site with Rankin Inlet.

The current mine plan of Meliadine includes six gold deposits, and relies on both open pit and underground mining practices. This paper discusses activities at the underground mine targeting the Tiriganiaq zone (referred to as the Meliadine underground mine in this paper), which hosts the largest deposit to date and has a strike length of approximately 3 km and a known depth of 800 m. This mine is hosted in a magnetite-rich oxide iron formation, accessed by ramps, and relies on long-hole mining methods. At the time of writing this paper, the mine reaches a depth of 525 m.

Following best practices, the Meliadine underground mine uses bulk emulsion for both long-hole blasting operations (hereinafter referred to as production blasting), as well as blasting operations, to access the mineral deposit (development blasting). The Meliadine underground mine also relies on a combination of cemented pastefill, cemented rockfill (CRF) and dry rockfill to backfill its stopes. The pastefill is produced using filtered tailings from the Meliadine mill.

The mine is in an area of continuous permafrost, with an estimated base depth between 285 m and 430 m. Despite the presence of permafrost, underground excavations act as a sink for groundwater via the shallow flow regime located in the active layer (seasonally thawed), and most of all, the deep flow regime beneath the base of the permafrost. This deep flow regime is characterized by high levels of total dissolved solids (TDS). Groundwater samples collected beneath the permafrost since 2018 show TDS values between 40,500 and 71,000 mg/L, with an average of 55,900 mg/L.

To allow for recirculation of mine water, a water treatment system is present underground for total suspended solids (TSS) treatment. Apart from CRF operations, all underground tasks typically rely on recirculated water. A simplified diagram of the underground water balance of the mine site is presented in Figure 1. Inputs and outputs that are not captured in this figure are considered negligible. Any surplus of water pumped to the surface is stored in dedicated saline storage ponds. A water treatment plant is also present at the surface to treat this saline water for TSS and NH_3-N prior to being discharged to sea. All water discharged from Meliadine site must meet the water quality requirements set by Environment Canada and Climate Change within the Metal and Diamond Mine Effluent Regulations (MDMER). TSS treatment is performed using a high rate clarifier, while NH_3-N treatment relies on the breakpoint chlorination technology.

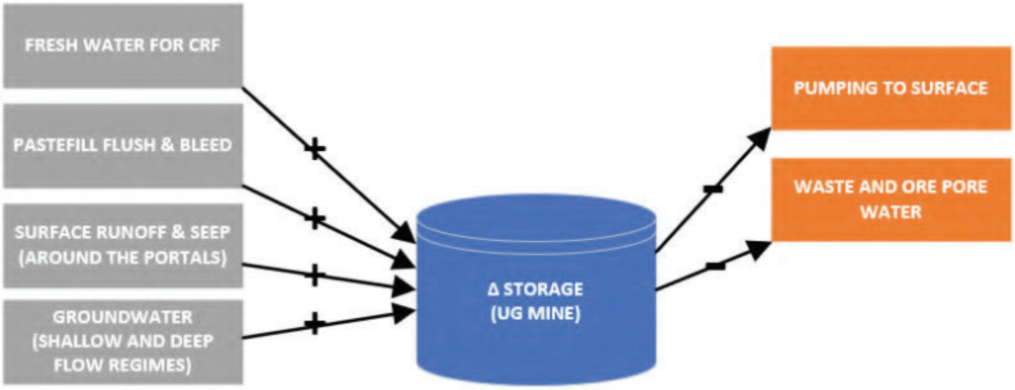

Figure 1: Simplified diagram of the underground water balance

Ammonia loading rate

The use of AN based explosives inevitably leads to leaching of NH_3-N in the water of the Meliadine underground mine. For this reason, NH_3-N is considered a key compound of interest, and is monitored for operational and compliance purposes. Part of this monitoring includes the concentration assessment of NH_3-N in the water pumped to surface, as presented in Figure 2.

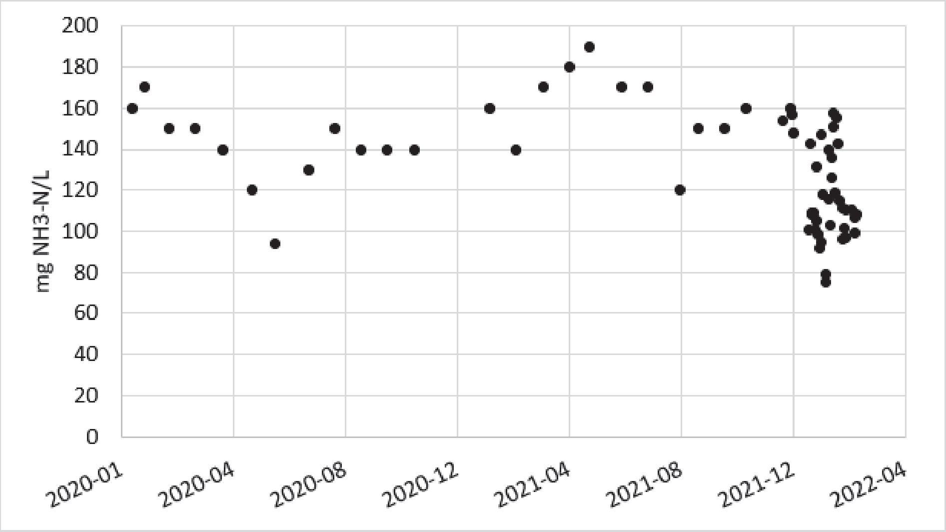

Figure 2: Ammonia concentration over time in the water pumped to surface

As shown in Figure 2, NH_3-N concentrations at this control point were measured monthly until November 2021, then more frequently afterward. Figure 2 also shows that NH_3-N concentrations range from 75 to 190 mg N/L, while most of the readings fall within the low to mid 100s. These values have, however, limited meaning by themselves. Factors such as water inflow entering the mine and the extent of blasting operation strongly influence NH_3-N concentrations in mine water. As an example, lower ammonia concentrations were reported in May 2020, which coincided with a period during which underground operations were scaled back due to the COVID-19 pandemic. A more meaningful value, referred as the ammonia loading rate in this paper, was calculated using the following formula:

$$Ammonia\ loading\ rate\ = \frac{Q_{inflow}\ x\ C_{NH3}}{M_{explosives}} \tag{1}$$

Where:

Q_{inflow} represents the calculated inflows (m^3/year).

$M_{explosives}$ represents the mass of explosives used (in kg/year).

C_{NH3} represents the ammonia concentration of the water pumped to surface (yearly average, in mg NH_3-N/L) of the following month.

This value then allows for comparison with other mine sites, as shown in Table 1.

Table 1: Comparison of measured ammonia loading rate with other underground mine sites

Mine sites	Location	Emulsion to ANFO ratio	Inflow rate (m^3/day)	Average explosive use (kg/day)	Average NH_3-N (mg/L)	g NH_3-N/ kg explosive
Meliadine underground mine (average 2020)	NU, CA	100:0	292	5200	155	8.6
Meliadine underground mine (average 2021)	NU, CA	100:0	259	5830	160	7.0
Lapa underground mine (average 2016 to Q1 2018)	QC, CA	78:22	949	706	10.7	14.4
Lapa underground mine (Q2 2018)	QC, CA	100:0	806	300	2.2	5.9
Undisclosed (Sidenko, 2018)	MB, CA	82:18	N/A	N/A	N/A	6 to 43[1]
Multiple mines (Morin and Hutt, 2009)	BC, CA	Mostly ANFO	N/A	N/A	N/A	20 to 47[1]
Multiple mines (Jermakka et al., 2015)	Finland	N/A	N/A	N/A	N/A	Up to 33[1]

[1] Assuming 70% AN in emulsion, and 94.5% AN in ANFO.

The Lapa underground mine (Quebec, Canada), which was in commercial operation between 2009 and 2018, is another Agnico Eagle property. This mine was of particular interest due to similarities with the Meliadine underground mine, such as limited supply of fresh water and recirculation of most of the process water directly underground. This mine site also gathered a high-quality dataset including NH_3-N concentrations, water inflows, and explosive consumption over the course of its operation. Notably, a transition from a mix of emulsion and ANFO to 100% emulsion can be observed in this dataset.

Averaging 8.6 and 7.0 g NH_3-N/kg explosive for 2020 and 2021 respectively, the ammonia loading rate of the Meliadine underground mine is similar to the Lapa underground mine when using 100% emulsion. This loading rate also appears to be on the lower spectrum of what is found in references such as Sidenko (2018), Morin and Hutt (2009) and Jermakka et al. (2015). However, all mine sites studied by these references relied on at least some ANFO explosives. Discrepancies with reported values in the literature could also be partially explained by underlying assumptions behind the ammonia loading rate calculation presented in this section. For one, this method fails to account for the undetonated explosives trucked outside of the mine alongside the ore and waste material.

Sources discrimination

A series of workshops and audits were performed to determine the main sources of NH_3-N in the Meliadine underground mine water. In addition to undetonated explosives, two other sources were identified:

- Natural occurrence in groundwater. Water samples collected from unimpacted groundwater since 2018 show an average of 5.3 mg NH_3-N/L.
- Nitrogen-based contaminants in pastefill bleed. The pastefill is produced using filtered tailings from the Meliadine mill. It is assumed that some of the moisture contained in the tailings becomes pastefill bleed and mixes with mine water. With an average concentration of 100 mg NH_3-N/L in the tailings water, there is little doubt that this source contributes to the ammonia loading underground. Also, cyanate (CNO-) present in the tailing water (average 290 mg-N/L) likely undergoes partial or complete hydrolysis to form NH_3-N once released underground.

Assuming complete CNO^- hydrolysis and using available information on the groundwater and pastefill bleed flowrates, the contribution of these three sources of NH_3-N in the Meliadine underground mine water was calculated, and is presented in Figure 3.

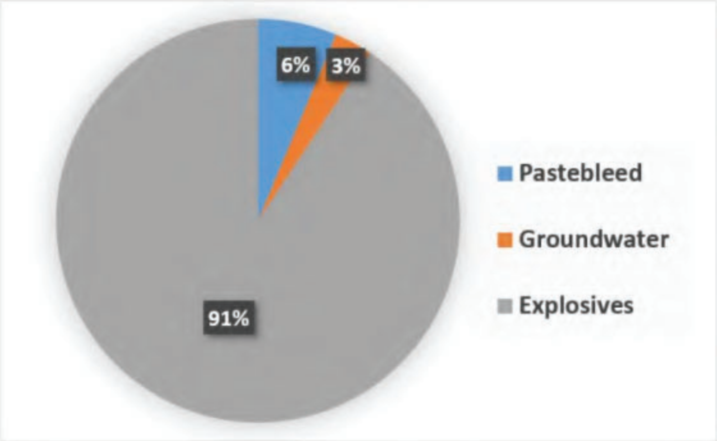

Figure 3: Suspected contributors of ammonia nitrogen in the underground mine water

Once it was determined that undetonated explosives were the main contributor to the ammonia loading rate observed at the Meliadine underground mine, further studies were performed to determine which tasks led to the most undetonated explosives.

Workshops and interviews were conducted with experienced blasters, drill and blast technicians, as well as third-party blasting experts. Following this exercise, the mining operations were subdivided into three categories: explosive storage facilities tasks, development blasting, and production blasting. For each category, the most likely events resulting in the release of undetonated explosives were identified. Assumptions were developed on the frequency of such events, as well as the likelihood and size of release. The results of this exercise are presented in Figure 4.

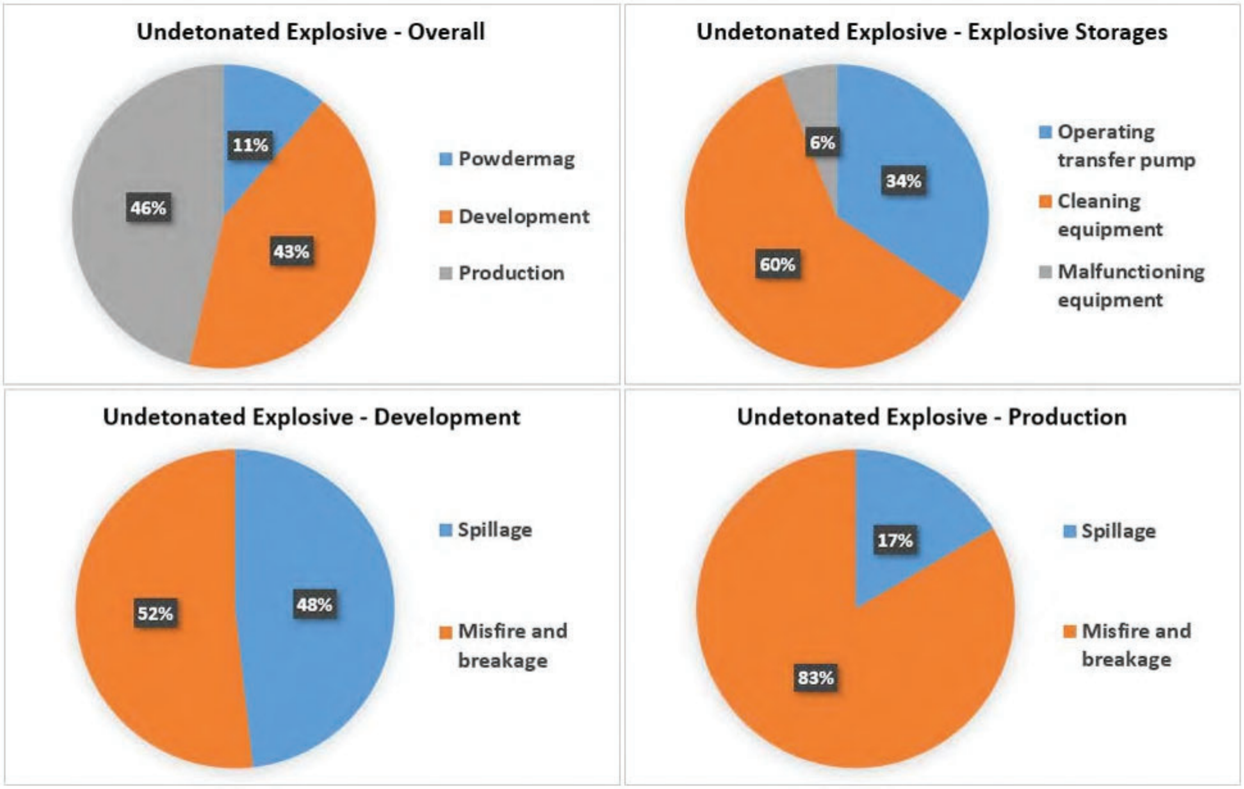

Figure 4: Breakdown of the various sources of undetonated explosives

Although a multitude of professionals were consulted while developing Figure 4, a high level of imprecision is to be expected of numerous assumptions supporting these graphs. Nevertheless, the degree of detail was deemed sufficient to guide future mitigation actions.

Figure 4 shows that tasks performed at the explosive storage facilities are suspected to generate approximately 11% of the overall release of undetonated explosives, whereas development rounds and production rounds equally share the remaining responsibility. This indicates that none of these areas should be considered insignificant. Undetonated explosives releases at the explosive storage facilities are mostly due to routine tasks, and could likely be mitigated by engineered solutions, establishment of Standard Operating Procedures (SOP), and training. About half of the suspected release from development rounds occur during routine tasks involving the handling of the emulsion hoses (i.e., spillage). Awareness campaigns, training, and SOP are the likely solutions to reduce these occurrences as well. The remaining half of the suspected release on development rounds appears to be due to breakage and misfires. Such events are suspected to represent over 80% of the overall release from production rounds. In both cases, improvement to the blasting patterns could reduce this source. These solutions are further discussed in the following sections.

Key Performance Indicator

To quantify the impact of mitigation measures on ammonia loading rates, the data presented in Table 1 were reported on a monthly basis and are used as a Key Performance Indicator (KPI) for emulsion handling underground (see Figure 5). To reach a wider audience, the units of this KPI were converted to percentage of undetonated explosive. This was done using a conversion factor of 0.81, while assuming 70% AN in the emulsion.

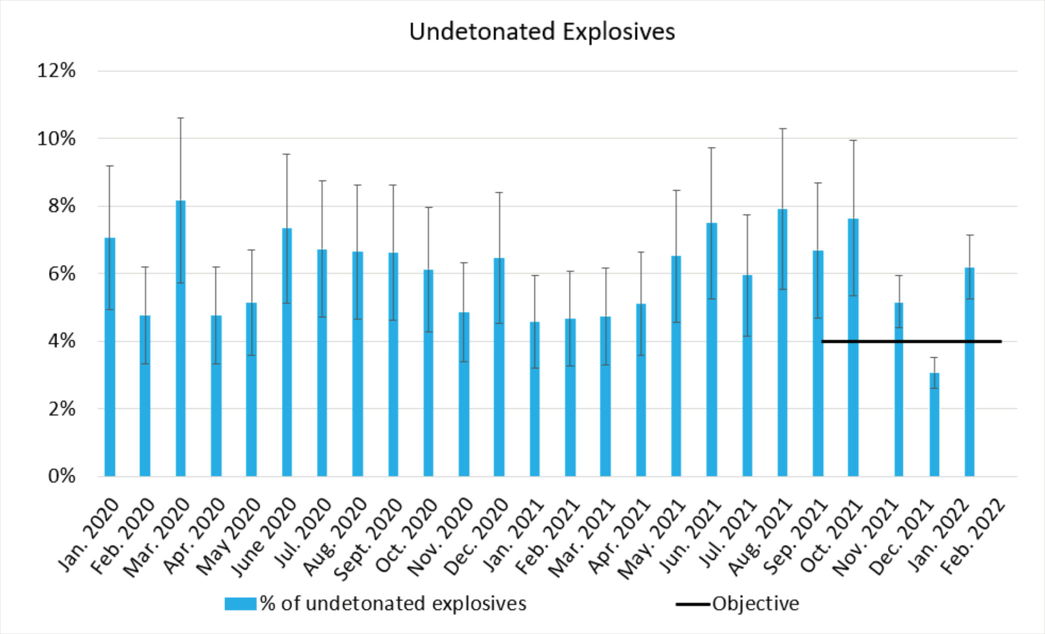

Figure 5: Key Performance Indicator to track handling of explosives underground

From January 2020 to November 2021, an accuracy of ±30% is assumed on this undetonated explosives KPI. Establishing an accuracy range was deemed important, since some of the values used to calculate this KPI have known uncertainties. For example, in February 2021, a sampling campaign performed over the course of 12 hours revealed large variations in the ammonia concentrations of the water pumped to surface. The data collected during this exercise suggests that relying on a single monthly analysis of NH_3-N to calculate the undetonated explosives introduces an inaccuracy of ±15% by itself. To mitigate this inaccuracy, the frequency of NH_3-N analysis was increased in December 2021. The remaining ±15% can be attributed to known uncertainties on the calculated inflows. The error margin on the mass of emulsion used per month is assumed to be inconsequential, based on discussions with the mining engineers responsible for reporting these values.

In September 2021, an internal objective of 4% undetonated explosives was set as an upper bound. Justified by the documented reduction of the ammonia loading rate following similar initiatives (Forsyth et al., 1995; Matts et al., 2007; Jermakka et al., 2015), this objective represents a 30% decrease compared to the 2021 average.

Mitigation measures considered

Mitigation measures to reduce NH_3-N loading are already documented by numerous authors in conference papers (Forsyth et al., 1995; Revey, 1996; Cameron et al., 2007), reports (Matts et al., 2007) and management plans (DBC, 2013; ERM, 2017; AKHM, 2019).

Based on the available information in the literature, the information presented in Figure 4, as well as the information collected during numerous workshops with experienced blasters and mining engineers, a list of mitigation measures was developed to reduce ammonia loading at the Meliadine underground mine. These mitigation measures include:

- Data acquisition improvements: refining the KPI assumptions, developing a spill tracking system, and improving ammonia monitoring underground.
- Behavioural changes: providing specific training on ammonia considerations to all employees handling explosives, as well as the engineering team.
- Engineered solutions: improving explosive storage facilities layout and lighting, reviewing designs of emulsion containers and transfer pumps, and substituting explosive material for perimeter holes on development rounds.
- Governance: reviewing SOPs for each task involving emulsion handling, updating the site's ammonia management plan, and establishing an auditing system to track best practice compliance.

To date, most of these mitigation measures are in progress. Since raising awareness and providing training were identified as low effort/high reward tasks, this mitigation measure is already well underway.

Interpretation of specific trends in the monthly KPI (Figure 5) prior to October 2021 would be hazardous due to the high level of imprecision on these values. On the other hand, this KPI is averaging 4.8% since November 2021. This represents a loading rate of 5.9 g NH_3-N/kg explosive, or about 19% below the 2021 average presented in Table 1. These preliminary results are deemed encouraging and seem to confirm the attainability of the company objective to reduce ammonia loading by more than 30%.

Conclusions and future considerations

Ammonia nitrogen is a common contaminant found in hard rock mining applications, and reduction of the contamination at the source is considered best practice. In this paper, ongoing efforts to understand and reduce ammonia loading rates at the Meliadine underground mine were documented. The main findings from these efforts are:

- With an average loading rate of 7.0 g NH3-N/ kg of emulsion used in 2021, the loading rate observed at the Meliadine underground mine is similar to what was previously observed at the Lapa underground mine. This loading rate also appears to be on the lower spectrum of what is reported in the literature, but limited information is available on mines using 100% emulsion.
- Spillage at the explosive storage facilities accounts for approximately 11% of the released undetonated explosives, whereas development rounds and production rounds accounted for 43% and 46% respectively.
- Release from breakage and misfires appears to represent 50% of all undetonated explosives linked to development rounds, and over 80% of the undetonated explosives linked to production rounds.
- Preliminary results indicate a 19% reduction of the ammonia loading rate following the establishment of a training and awareness campaign.

On a final note, the KPI discussed above does not capture how much explosive is used per ton of rock fractured, otherwise referred as the powder factor. There is little doubt that using fewer explosives to break the same amount of rock would reduce the mass of NH_3-N dissolved in the mine water. Furthermore, the findings and calculation methods presented in this paper do not account for the undetonated emulsion trucked outside of the mine alongside the ore and waste material. Considering the leaching rate reported by Watson (1991) for emulsion explosives (1.2% after 144 hours), large quantities of this explosive are likely to remain at the surface of such ore and waste material. According to Jermakka et al. (2015), this sink could account for as much as 50% of the total quantity of undetonated explosives. Recognizing this as a major factor influencing the concentration of ammonia in its mine water, the Meliadine underground mine will continue to study this occurrence.

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