

PERFORMANCE OF MICROBUBBLES OZONATION FOR THE REMOVAL OF NITROGEN-BASED CONTAMINANTS IN MINE IMPACTED WATER

Pascal Marcotte^{1,2}, Elizabeth Aubé¹, Christian Dubé¹, Carmen M. Neculita³

¹ ASDR Canada Inc., Malartic, Québec, Canada

² Now working at Agnico Eagle Mines – Meliadine Mine, Rankin Inlet, Nunavut, Canada

³ Research Institute on Mines and Environment (RIME), Université du Québec en Abitibi-Témiscamingue (UQAT), Rouyn-Noranda, Québec, Canada

ABSTRACT

The increasing exploitation of low-grade and refractory ores requires more aggressive separation conditions of valuable minerals and generates high flows and loads of mine impacted water. Available technologies for the removal of nitrogen-based contaminants (thiocyanate, cyanide, cyanate, ammonia nitrogen and nitrite) have often limited performance for such mine water. In the context of sustainable mining operations, the development of innovative water treatment technologies becomes mandatory. In this study, the performance of microbubbles ozonation for the removal of nitrogen-based contaminants in mine impacted water was evaluated at laboratory pilot scale on synthetic mine effluents, as well as four real mine effluents. Results showed that: (i) pH has high impact on the process efficiency, while temperature and hydraulic retention time have lower impact; (ii) removal rates of ozonation on thiocyanate and weak acid dissociable (WAD) cyanide were above 97% while removal rate for ammonia nitrogen and cyanate varied from 59 to 99%, and from 47 to 99% respectively; (iii) effluents that were non-acutely toxic to *Daphnia magna* were observed on three out of four real mine effluents trials.

RESUMÉ

L'exploitation croissante des minerais à faible teneur et réfractaires nécessite des conditions de séparation plus agressives des minéraux précieux et génère des débits et des charges élevées des eaux minières contaminées. Les technologies disponibles pour l'enlèvement des contaminants à base d'azote (thiocyanate, cyanure, cyanate, azote ammoniacal et nitrite) ont souvent des performances limitées pour ces eaux. Dans le contexte des opérations minières durables, le développement de nouvelles technologies de traitement de l'eau devient obligatoire. Dans cette

étude, la performance de l'ozonation à microbulles pour l'élimination des contaminants azotés dans l'eau minière contaminée a été évaluée à l'échelle pilote de laboratoire sur des effluents miniers synthétiques, ainsi que sur quatre effluents miniers réels. Les résultats ont montré que: (i) le pH a un impact important sur l'efficacité du procédé, tandis que la température et le temps de rétention hydraulique ont un moindre impact; (ii) les taux d'enlèvement par ozonation du thiocyanate et des cyanures dissociables se situaient au-dessus de 97%, tandis que le taux d'enlèvement de l'azote ammoniacal et du cyanate variait entre 59 et 99%, et entre 47 et 99%, respectivement; (iii) des effluents non toxiques pour *Daphnia magna* ont été observés dans trois des quatre essais sur les effluents miniers réels.

1. INTRODUCTION

When operating in positive water balance environments, mining companies are required to discharge excess volumes of mine impacted water outside of the boundaries of their properties. In countries with strong mining legacies, such as Canada, this water must meet strict discharge criteria prior to being released into the environment. Varying from one jurisdiction to another, these discharge criteria tend to become more stringent as new technologies emerge to quantify and treat the various mixing contaminants found in mine water.

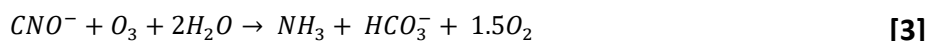
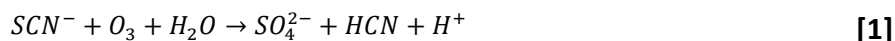
Among these contaminants, ammonia nitrogen ($\text{NH}_3\text{-N}$), nitrite (NO_2^-) and nitrate (NO_3^-) are often found in hard rock mining applications, where nitrogen-based explosives are frequently used to free the valuable commodities from the ores (Jermakka et al., 2015). Other nitrogen-based contaminants, such as thiocyanate (SCN^-), free cyanide (CN^-), weak acid dissociable (WAD) cyanide and cyanate (CNO^-), are also common in water from mining operations relying on cyanide solutions used to extract precious metals such as gold and silver (Mudder et al., 2001). Moreover, owing to the depletion of high-grade and native gold deposits around the world, recent exploitation of low-grade refractory deposits leads to the production of highly contaminated effluents (Coudert et al., 2020). Due to their potential toxicity on aquatic life, and because stricter regulations on these contaminants are expected in the future, these compounds were identified as Contaminants of Emerging Concern (CEC) for the mining industry (Neculita et al., 2018, 2020).

Various conventional technologies are currently available to treat nitrogen-based contaminants in mine impacted water. These technologies are well documented in the scientific and technical literature, with noteworthy publications covering this topic (Jermakka et al., 2015; Mudder et al., 2001; Pouw et al., 2014). However, as thoroughly discussed in these previous studies, conventional technologies have several limitations. As such, most situations need to be addressed by a case-by-case approach, a process which increases the risk and cost of mining companies seeking to manage nitrogen-based contaminants on their properties.

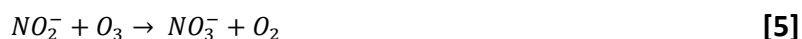
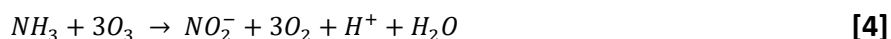
This context allows for the development of newer technologies for the proper management of mine water contaminated by these contaminants and the sustainability of mining operations. Among the emerging technologies, the use of ozone, a strong oxidizing agent, to oxidize all the aforementioned nitrogen-based contaminants into NO_3^- has previously shown promising results on real mine effluents in laboratory and pilot settings (Gervais et al., 2020; Marcotte, 2020; Ryskie et al., 2020).

2. OZONATION PRINCIPLES

Ozonation is currently used at a commercial scale to remove cyanide in mine effluents (Gottschalk et al., 2010). This oxidation process can also remove SCN^- and CNO^- in mine water, according to the Equations 1 to 3 (Botz et al., 2001; Carrillo et al., 2000; Khuntia et al., 2012).



To treat NH_3-N in mine effluents, ozonation was investigated at a gold mine operation located in Ontario, Canada. However, the industrial scale system has not yet been installed and additional information on this project is not publicly available (Pouw et al., 2014). Laboratory and pilot studies have also been carried out by Ryskie (2017) and Marcotte (2020) on synthetic and real mine effluents. The ozonation of NH_3-N into NO_3^- , with NO_2^- as an intermediate product, is governed by the Equations 4 to 5 (Khuntia et al., 2012).



According to Neculita et al. (2019, 2020), ozonation of mine water presents several advantages over other conventional technologies, including fast kinetics, oxidation of several contaminants at the same time and little to no impact on the residual salinity of the treated water and its associated toxicity. However, according to the same authors, additional research on the scaling-up and techno-economic aspects of this technology are still required.

3. PROJECT DESCRIPTION AND OBJECTIVES

In 2018, ASDR Canada Inc. (ASDR) partnered with the Université du Québec en Abitibi-Témiscamingue (UQAT) and funded a Master research project to investigate the performance of ozonation on nitrogen-based contaminants in mining effluents at a field pilot scale. This study was a follow-up of the laboratory-based study (Ryskie, 2017; Ryskie et al., 2020). The results of this second project, which was completed in 2020, highlighted encouraging performance and economic prospects for this technology (Marcotte, 2020).

Based on these results, ASDR then developed an 18-month project aimed at commercializing this approach. Funded by the Ministère de l'Économie et de l'Innovation du Québec (MEI), the National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP), Eldorado Gold (EGO), Agnico Eagle Mines (AEM) and ASDR, this project is subdivided in following three phases: 1) laboratory pilot trials, 2) field pilot trials, and 3) detailed engineering of the commercial plant. The main objectives of the study are:

- 1) Evaluate the performance of ozonation for the removal of nitrogen-based contaminants in mine effluents.
- 2) Demonstrate the non-acute toxicity of ozone-treated effluents, in compliance with the Metal Mining and Diamond Mining Effluent Regulations (MDMER, 2018).

This paper presents some of the main results of the laboratory pilot trials phase, which was completed in December 2020.

4. DESCRIPTION OF THE LABORATORY PILOT UNIT

Trials were carried out in the Unité de Recherche et de Services en Technologie Minérale (URSTM) laboratories, at UQAT. A simplified flowsheet of the URSTM laboratory pilot scale ozonation unit is presented in Figure 1. This unit allows for batch treatment of 18L samples. Ozone is produced using an ozone generator (GM-01 by Primazone) and injected using a microbubble pump (model KTM20N by Nikuni) followed by a OHR static mixer. The open top reactor is also equipped with cooling and pH adjustment apparatus.

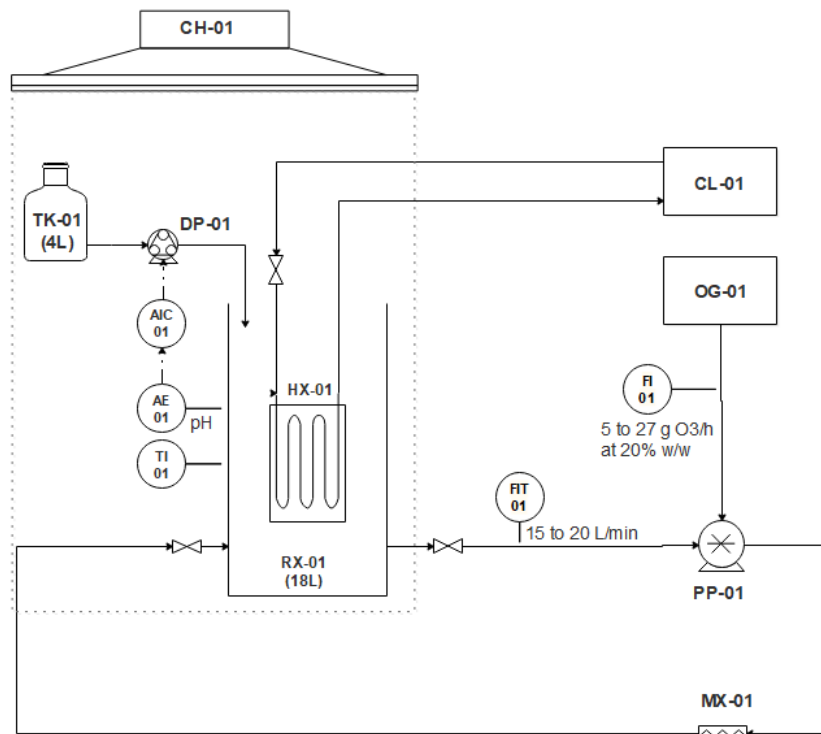


Figure 1. Simplified Flowsheet of the URSTM Laboratory Pilot Unit, including: Chemical Hood (CH-01), NaOH Tank (TK-01), NaOH Dosing Pump (DP-01), Heat Exchanger Coil (HX-01), Chilling System (CL-01), Open Top Reactor (RX-01), Ozone Generator System (OG-01), Microbubble Pump (PP-01), Static Mixer (MX-01).

5. STOICHIOMETRIC OZONE DEMAND AND OZONE UTILIZATION EFFICIENCY

Produced onsite as a gas, ozone needs to be dissolved in water to react with targeted contaminants. Since ozone production is the single most expensive component of an ozonation system (Gottschalk et al., 2010), efficient ozone dissolution and utilization is paramount to keep the cost of this process reasonable.

By rearranging Equations 1 to 5, and by assuming that the contribution of the other oxidable compounds in mine water is negligible, the stoichiometric ozone demand to obtain a given removal of nitrogen-based contaminants can be expressed as in Equation 6.

$$\frac{mg\ O_3}{L} = A (\Delta SCN) + B (\Delta SCN + \Delta WAD\ CN) + C (\Delta SCN + \Delta WAD\ CN + \Delta CNO) + D(\Delta SCN + \Delta WAD\ CN + \Delta CNO + \Delta NH_3) \quad [6]$$

Where:

- “Δ” represents the difference between the concentration of a species in the influent and the effluent, expressed in mg N/L.
- “A” represents the stoichiometric ratio O₃:SCN-N, as per Equation 1, expressed in mg (3.4 mg O₃:mg SCN-N).
- “B” represents the stoichiometric ratio O₃:WAD CN-N, as per Equation 2, expressed in mg (3.4 mg O₃:mg WAD CN-N).
- “C” represents the stoichiometric ratio O₃:CNO-N, as per Equation 3, expressed in mg (3.4 mg O₃:mg CNO-N).
- “D” represents the stoichiometric ratio O₃:NH₃-N, as per Equations 4 and 5, expressed in mg (13.7 mg O₃:mg NH₃-N).

By measuring the SCN⁻, WAD cyanides, CNO⁻, and NH₃-N concentrations in the influent and the effluent, as well as recording the applied ozone injection rate during these trials, the Ozone Utilization Efficiency (OUE) can be calculated using Equation 7.

$$OUE (\%) = 100 * \frac{\text{stoichiometric ozone demand}}{\text{applied injection rate}} \quad [7]$$

6. RESULTS AND DISCUSSION

6.1 Trials on Synthetic Mine Effluent

The ozonation process was first applied on synthetic mine effluent. Tap water was spiked with ACS grade ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$ to obtain a 50 mg $\text{NH}_3\text{-N/L}$ solution. Using this solution, major process parameters were varied one at a time, to assess their impact on the overall process efficiency. In each case, the initial and final concentration of ammonia nitrogen, as well as the amount of ozone injected during the trial were used to calculate and compare the OUE.

6.1.1 Process Reproducibility

Before interpreting the parametric trials results, the reproducibility of the laboratory pilot unit had to be clearly defined. To do so, several trials were performed on the synthetic mine effluent at identical conditions, otherwise referred to as “baseline trials”. Such conditions are listed below:

- 18 L sample
- pH 9.5
- 20 °C
- 16.5 g O_3/h injection
- 18.5 L/min flow rate in the recirculation loop
- 1.6 seconds of Hydraulic Retention Time (HRT) in the recirculation loop
- 60 PSI in the recirculation loop

Results from these trials are presented in Table 1. These results highlight that, even if all parameters are constant, a variation in the system response can be expected. The OUE observed was about $78 \pm 8\%$. This variation is expected to be the sum of the uncertainty on several components of the system (ammonia selective electrode, pH probe, ozone generator, pressure sensor, flowmeter, measurement delays, etc.). From these trials, it was concluded that any variation smaller than 10% compared to the baseline trials should be deemed inconclusive.

TABLE 1. OUE Results of Baseline Trials Performed on Synthetic Mine Effluents

Trial	OUE (%)
Baseline 1	85.9
Baseline 2	84.5
Baseline 3	70.6
Baseline 4	72.1
Baseline 5	80.6
Baseline 6	76

6.1.2 Parametric Trials

Results from the parametric trials are presented in Table 2. For each trial, process parameters were kept identical to the baseline trials, unless stated otherwise.

TABLE 2. OUE Results of Parametric Trials on Synthetic Mine Effluents

Parameters	Trial	OUE (%)
pH	5	< 0
	7.5	14.7
	9.5	49.6
	11.5	34.0
Temperature	13 °C	65.2
	13 °C	71.8
	20 °C (baseline)	76
	40 °C	74.6
	40 °C	69.5
Temperature and pH	20 °C, pH = 9.5 (baseline)	75.5
	10 °C, pH = 9.5	58.3
	10 °C, pH = 10.0	73.5
Injection rate	8.0 g O ₃ /h	86.3
	12.0 g O ₃ /h	82.2
	16.5 g O ₃ /h (baseline)	80.6
Pressure	60 PSI (baseline)	76.0
	40 PSI	75.5
	40 PSI	79.7
HRT	1.6 seconds (baseline)	80.6
	111 seconds	97.6
	111 seconds	86.6

Impact of pH on ozonation of ammonia nitrogen is well documented in the literature (Hoigne & Bader, 1978; Khuntia et al., 2012; Ryskie, 2017; Zuttah, 1999). However, this parameter was varied first to allow the testing of the ozonation system performance. As expected, the best OUE was observed at pH 9.5. However, even at that pH, the OUE observed was considered low. After further investigation, a leak on the ozone feed line was found. This leak was fixed prior to continuing the parametric trials.

Temperature has the potential to impact ozone efficiency in many ways. Solubility of ozone decreases as temperature of the water increases, which may negatively impact the mass transfer efficiency of an ozonation system. However, reaction kinetics increase with a temperature increase, thus having the opposite effect of positively impacting the process. Contrary to pH, the impact of temperature on the ozonation of ammonia nitrogen in the literature is less documented. Ryskie (2017) observed that high temperature (30 °C and above) negatively impact ammonia removal, while Zuttah (1999) reached consistent conclusions but for a lower temperature (10 °C). Finally, an increase in temperature favors the presence of unionized ammonia, which is known to be more reactive with ozone than ionized ammonia.

Results from the duplicate tests performed at 40 °C indicated that higher temperature did not negatively impact the ozonation process, i.e., the ozone mass transfer is not the limiting factor on the laboratory pilot unit. As for the impact of lower temperature, trials performed at 13 °C appear slightly less efficient, although this could also be attributed to the imprecision of the system. To confirm these results, additional trials were performed. When comparing the OUE of the baseline trial (75.5 %) with the OUE of the trial performed at a temperature of 10 °C and pH of 9.5 (58.3 %), a decrease in the process efficiency can be once again observed. However, if the pH of the solution is maintained at 10 instead of 9.5, OUE similar to the baseline are obtained. This seems to indicate that ammonia speciation at lower temperature may be the cause of the decreased efficiency. At these temperature, the ionized form, which is less reactive with ozone, is favored. In this case, an increase of the reaction pH could overcome this limitation. As a result, additional trials at temperature below 5 °C are required before clear conclusions can be drawn.

Trials at different ozone injection rate (variation of the ozone generator output) were also performed. During these trials, it took roughly 60 minutes to remove 30 mg NH₃-N/L at an injection rate of 8 g O₃/h, 40 minutes at 12 g O₃/h and 30 minutes at 16.5 g O₃/h. Based on these results, and since the OUE of these trials are all similar, it was concluded that the amount of ozone added to the system is indeed what limits the reaction rates. Precisely, it is expected that with a larger ozone generator, the duration of these batch trials could be further reduced.

Pressure has also a considerable impact on the ozone solubility in water, and consequently the mass transfer efficiency. As already mentioned, most of the trials were conducted with a pressure in the recirculation loop of 60 PSI. However, a few trials were also performed at 40 PSI. Since the OUE of these trials are similar, it was concluded that a 20 PSI difference on the recirculation loop had minimal to no impact on the overall efficiency of the system.

Finally, the impact of HRT in the recirculation loop was investigated. This loop had an approximative volume of 0.5 liters. At a flow rate of 18.5 L/min, the HRT in this loop is about 1.6 seconds. After this time, the solution enters RX-01 under atmospheric pressure. Based on this information, the opportunity to include a pressurized vessel within the recirculation loop to increase the HRT and potentially improve the mass transfer efficiency arose. This was done by adding a pipe reactor in the recirculation loop. With an internal volume of 33 L, this reactor increased the HRT to approximately 111 seconds. Although the accuracy of the system makes a definitive conclusion hazardous, it appears that the trials performed with longer HRT yield better results. In one case, an OUE of 97.6% was observed, which is very close to the stoichiometric requirement. In the light of these results, increasing HRT may improve the mass transfer efficiency, but additional tests are required to clearly conclude.

6.2 Trials on Real Mine Effluents

Following the parametric trials, the ozonation process was evaluated on four real mine effluents: A, B, C and D. For these trials, the conditions listed above for the baseline trials were applied. Effluents A and B were sampled in the tailing ponds of two gold mines, while effluent C and D were collected from the underground working of these two same mines. Ammonia concentrations as a function of the amount of ozone injected during these trials are also presented in Figure 2.

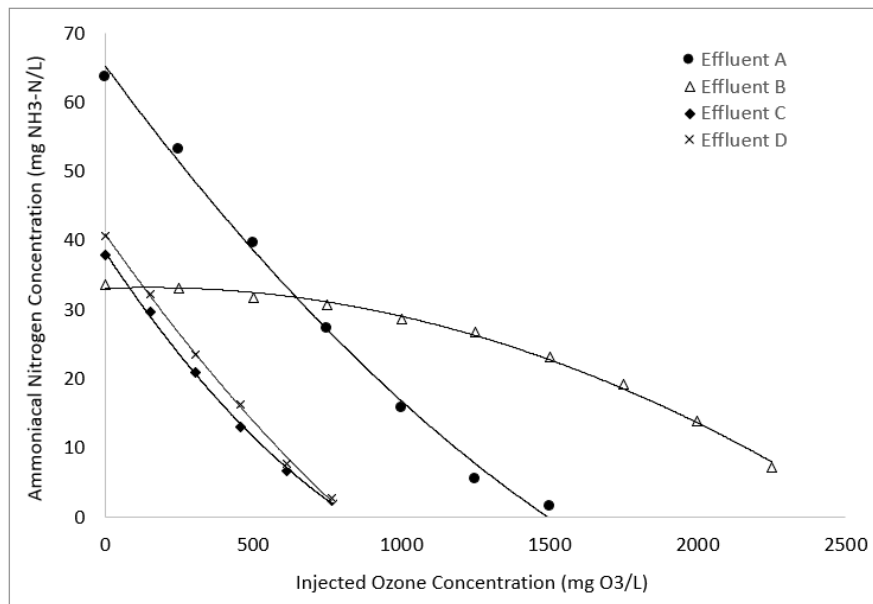


Figure 2. Ammonia Nitrogen Concentration During the Real Mine Effluents Trials. pH and temperature controlled at 9.5 and 20 Celsius, respectively. Pressure in the recycling loop set at 40 PSI.

Ozone requirement to treat real effluents can vary widely depending on the load of contaminants. Slightly contaminated effluents (e.g., from underground mining) required approximately 750 mgO₃/L to reduce ammonia nitrogen below 5 mg/L, while strongly contaminated (e.g., supernatant from tailings impoundment facilities), such as sample D, required more than 2000 mg O₃/L to achieve similar results.

These findings show that better knowledge on the nature and concentration of the contaminants to be removed is a key factor when evaluating the performance of ozone on mine impacted water. Initial and final concentrations of nitrogen-based contaminants, as well of their respective removal rates and the overall OUE of these trials are presented in Table 3.

TABLE 3. Ozonation Results on Four Real Mine Effluents

Parameters	A	B	C	D
SCN-N initial conc. (mg/L)	1.81	107.4	< 0.05	0.084
SCN-N final conc. mg/L)	< 0.05	< 0.05	< 0.05	0.036
SCN-N removal rate (%)	97%	N/A	N/A	N/A
WAD CN-N initial conc. (mg/L)	< 0.001	3.85	< 0.001	< 0.001
WAD CN-N final conc. (mg/L)	0.011	0.01	< 0.001	0.001
WAD CN-N removal rate (%)	N/A	99.6%	N/A	N/A
CNO-N initial conc. (mg/L)	11.87	10.83	< 0.01	0.04
CNO-N final conc. (mg/L)	3.10	5.7	0.14	0.29
CNO-N removal rate (%)	74%	47%	N/A	N/A
NH ₃ -N initial conc. (mg/L)	89.65	17.82	53.4	64.42
NH ₃ -N final conc. (mg/L)	1.40	7.3	2.97	5.3
NH ₃ -N removal rate (%)	99%	59%	94%	92%
NO ₃ -N initial conc. (mg/L)	14.9	13.4	15.3	17.6
NO ₃ -N final conc. (mg/L)	89	85.5	72	51.7
NO ₃ -N removal rate (%)	-497%	-538%	-371%	-194%
Total N initial conc. (mg/L)	109.9	144	63.4	85.6
Total N final conc. (mg/L)	99	102.7	76.1	58
Total N removal rate (%)	10%	29%	-20%	32%
OUE (%)	93.6	127.4	90.5	106.4

Consistent with previous findings (Marcotte, 2020), observed removal rates of thiocyanate and WAD cyanide were around 90%. Removal rate for ammonia nitrogen and cyanate varied from 59 to 99%, and 47 to 99%, respectively. Higher removal rate would have probably been possible if the trials were extended. As observed in Figure 2, the amount of ammonia nitrogen removed per ozone injected tend to decrease with lower ammonia nitrogen in solution (first order reaction). Under these conditions, greater quantity of ozone is required to remove a given mass of ammonia nitrogen. Consequently, extended trials could have potentially yielded better removal rate, but the OUE would have been negatively impacted.

As expected from Equation 1 to 5, NO₃⁻ was generated in all trials. However, still according to these equations, the total nitrogen within the system should have remained stable. The imprecision of the analytical method may explain some deviations, but the removal rate observed for effluents B and D (29 and 32%, respectively) seemed high. Also, the OUE observed for these two trials was above 100%. This may indicate the presence of catalytic ozonation, i.e. reaction pathways different than the one previously assumed.

Nevertheless, with OUE above 90% for all trials on real effluents, these trials demonstrate that the laboratory pilot unit used for this project allows for good mass transfer efficiency. Since the unit used during this project lacked the instrumentation required to monitor ozone going in and out of the system, this indirect method of quantifying the mass transfer efficiency had to be employed. High OUE values also show that most of the ozone generated is utilized towards the desired reaction.

6.3 Toxicity Trials

As already stated, one major objective of this project was to demonstrate the non-acute toxicity of ozonated effluents, in compliance with the Metal Mining and Diamond Mining Effluent Regulations (MDMER, 2018). These regulations require acute lethality tests to be conducted on *Daphnia magna* (*D. magna*) and rainbow trout (*Oncorhynchus mykiss*). Table 4 below show toxicity trials performed on *D. magna* using both raw and treated real effluents. On some of these trials, pretreatment and post treatment were applied to remove other contaminants than the nitrogen-based compounds. *D. magna* trials were preferred over rainbow trout during laboratory pilot trials due to the smaller volume requirements (1 L versus 40 L, respectively). Nevertheless, a single acute toxicity trial using rainbow trout was also performed on the ozonated effluent A. Moreover, additional rainbow trout trials are planned in the field pilot phase of this project.

TABLE 4. Toxicity Trials Results on Ozonated Effluents

Sample Description	pH	Ammonia (mg N-L)	Dissolved Cu (mg/L)	CL ₅₀ <i>Daphnia magna</i> (%)
Raw effluent A	8.26	96.9	0.4	12.8
Raw effluent B	7.53	28.7	15.2	< 6.3
Raw effluent C	7.54	53.4	0.01	>100
Raw effluent D	6.65	64.4	0.4	< 6.3
Ozonated effluent A + acidification	N/A	N/A	N/A	70.7
Ozonated effluent A + Cu post-treatment	7.93	9.5	<DL	>100 ¹
Ozonated effluent B + Cu post-treatment	7.13	13	0.01	8.8
Ozonated effluent C + acidification	7.61	3	0.05	>100
Ozonated effluent D + Cu pre-treatment	7.29	5.3	0.01	>100

¹CL₅₀ on Rainbow trout also >100%

Except for the effluent C, all raw effluents tested in this study were acutely toxic to *D. magna*. High concentration of dissolved copper, silver and zinc were presumably assumed to be the main contributors to this toxicity.

Consistent with previous findings (Marcotte, 2020), ozonation of effluent A and acidification to pH near 7.5 (with sulfuric acid, alone) resulted in some mortality. However, when a copper post-treatment is applied (successive injection 85 µL/L of Metalsorb® HCO 40%, 75 µL/L of ferric sulfate 60% and 5 ml/L of flocculent 0.1%, followed by 2 hours of settling), the resulting effluent is non-acutely toxic to *D. magna* or rainbow trout. A similar approach was applied to effluent B, but with lime precipitation as a post treatment. Although this approach showed good removal rates on ammonia nitrogen and dissolved copper, the treated effluent remained very toxic, with a CL₅₀ of 8.8%. Additional trials on this effluent are planned during the field pilot phase.

Both effluents collected from underground mine water (C and D) were nontoxic to *D. magna* once treated. These results demonstrate the addition of ozone itself is not acutely toxic to *D. magna*. A lime precipitation pre-treatment was required on effluent D, to remove copper and manganese. Otherwise, a strong purple coloration (presumed to be permanganate) would form during the ozonation step.

7. CONCLUSION

This paper presents selected results from the laboratory pilot trials done by ASDR Canada Inc. to evaluate the performance of microbubbles ozonation to remove nitrogen-based contaminants in mining effluents. Using a laboratory pilot scale microbubbles ozonation unit, trials were performed on both synthetic and real mine effluents. The main conclusions from these trials are the following:

- pH variation has high impact on the ozonation efficiency. Temperature and HRT have less impact on the process, while pressure and injection rate have little to no impact under the conditions that were tested.
- When applied to real effluents, removal rates of ozonation on thiocyanate and WAD cyanide were around 90%. Removal rate for ammonia nitrogen and cyanate varied from 59 to 99%, and from 47 to 99%, respectively.
- Ozone Utilization Efficiency (OUE) of 90% and above was observed on all real effluents trials, with two trials yielding efficiency above 100%. Catalysts already present in some effluents could probably explain these results.
- Ozonated effluents were found to be non-acutely toxic to *Daphnia magna* for three of the four real effluents tested. Copper removal was required on two of these effluents to achieve a non-toxic effluent. The source of toxicity observed on the fourth effluent is still under investigation.

Acknowledging that additional work is required before commercializing this technology, ASDR is currently performing field pilot trials, and intend on completing the detailed engineering of the commercial plant by the end of 2021.

RÉFÉRENCES / REFERENCES

- Botz, M. M., Dimitriadis, D., Polglase, T., Phillips, W., & Jenny, R. (2001). Processes for the regeneration of cyanide from thiocyanate. *Mining, Metallurgy & Exploration*, 18(3), 126-132.
- Carrillo, P. F., Nava, A. F., & Uribe, S. A. (2000). Cyanide oxidation by ozone in cyanidation tailings: Reaction kinetics. *Minerals Engineering*, 13(5), 541-548.
- Coudert, L., Bondu, R., Rakotonimaro, T. V., Rosa, E., Guittonny, M., & Neculita, C. M. (2020). Treatment of As-rich mine effluents and produced residues stability: Current knowledge and research priorities for gold mining. *Journal of Hazardous Materials*, 386, 121920.
- Gervais, M., Dubuc, J., Paquin, M., Gonzalez-Merchan, C., Genty, T., & Neculita, C. M. (2020). Comparative efficiency of three advanced oxidation processes for thiosalts treatment in mine impacted water. *Minerals Engineering* 152: 106349.
- Gottschalk, C., Libra, J. A., & Saupe, A. (2010). *Ozonation of water and waste water: A practical guide to understanding ozone and its applications*. Berlin, Germany: John Wiley & Sons.

- Jermakka, J., Wendling, L., Sohlberg, E., Heinonen, H., & Vilkmán, M. (2015). Potential technologies for the removal and recovery of nitrogen compounds from mine and quarry waters in subarctic conditions. *Critical Reviews in Environmental Science and Technology*, 45(7), 703-748
- Khuntia, S., Majumder, S. K., & Ghosh, P. (2012). Removal of ammonia from water by ozone microbubbles. *Industrial & Engineering Chemistry Research*, 52(1), 318-326.
- Marcotte, P. (2020). Performance evaluation of pilot scale ozonation system for nitrogen-based contaminants removal in mine impacted water (Unpublished master's thesis). RIME, UQAT, QC, Canada, 111 p.
- MDMER (Metal and Diamond Mining Effluent Regulation), (2018). SOR/2002-222. Minister of Justice Canada. Available at: <https://laws-lois.justice.gc.ca/eng/regulations/sor-2002-222/FullText.html>. (last access: February 2021)
- Mudder, T. I., Botz, M., & Smith, A. (2001). *Chemistry and treatment of cyanidation wastes*. London, United Kingdom: Mining Journal Books.
- Neculita, C. M., Coudert, L., Genty, T., Drapeau, M., Ryskie, S., & Delay-Fortier, S. (2018). *Emerging contaminants in mine effluents: operational challenges of their treatment and research needs*. Paper presented at the 6th CIM-UQAT Mines & Environment Symposium, Rouyn-Noranda, Canada, June 17-20 (p. 20).
- Neculita, C. M., Coudert, L., & Rosa, E. (2019). *Challenges and opportunities in mine water treatment in cold climate*. Paper presented at the Geo-Environmental Engineering, Concordia University, Montreal, Canada, May 30-31 (p. 11).
- Neculita, C. M., Coudert, L., Rosa, E., & Mulligan, C. (2020). Future prospects for treating contaminants of emerging concern in water and soils/sediments. In: *Advanced Nano-Bio Technologies for Water and Soil Treatment*. Filip, J., Cajthaml, T., Najmanová, P., Černík, M., Zbořil, R. (Eds.), Springer International Publishing, pp. 589-605.
- Pouw, K., Campbell, K., & Babel, L. (2014). *Study to Identify BATEA for the Management and Control of Effluent Quality from Mines. MEND (Mine Environment Neutral Drainage)*, Report No. 3.50.1, 615p.
- Ryskie, S. (2017). *Traitement de l'azote ammoniacal dans les effluents miniers contaminés au moyen de procédés d'oxydation avancée*. MScA Thesis, IRME, UQAT, QC, Canada, 129 p.
- Ryskie, S., Gonzalez-Merchan, C., Neculita, C. M., & Genty, T. (2020). Efficiency of ozone microbubbles for ammonia removal from mine effluents. *Minerals Engineering*, 145, 106071.
- Zuttah, Y. (1999). *Destruction de l'ammoniac dans les effluents miniers*. MSc Thesis, Departement of Miens and Metalurgy, Université Laval, QC, Canada, 107 p.