A Risk Assessment of ARD Prediction and Control

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ABSTRACT

Risk assessments are routinely conducted for many of the specialized aspects or features of a mine site or design, but rarely completed as a focussed evaluation of acid rock drainage and metal leaching, or ARD/ML risk. ARD/ML and water quality impacts however are often one of the most significant risks associated with mining projects in terms of long term environmental impacts, public and regulatory image and closure costs.

Risk assessments are often done via the Failure Modes and Effects Analysis (FMEA) methodology in which potential failure modes are identified, the anticipated effects of those failures are documented and the likelihood of occurrence and consequences of occurrence are rated. Failure modes as they relate to ARD/ML can arise from errors and uncertainties in predictions, as well as errors and uncertainties associated with control measures. The FMEA can be used as a tool to better mitigate and manage these errors and uncertainties.

This paper uses the FMEA approach to classify and share an understanding of relative risks for mines with respect to ARD/ML. By way of case studies and examples, a listing of failure modes that should be considered in ARD/ML prediction programs and management and control plans is provided, as are factors that contribute to each failure mode.

INTRODUCTION

A common risk management tool used by engineers in the mining industry is the failure modes and effects analysis (or FMEA). This analysis tool is meant to identify potential events that could cause a consequence that is unacceptable. In this way, unacceptable risks can be identified and mitigated or managed with the objective of reducing those risks to acceptable levels.

Acid rock drainage and metal leaching (ARD/ML) has been identified and is generally thought of as one of the larger risks associated with mining in sulphide rich deposits, with those risks including not only risks to the receiving environment (water quality, aquatic species, agriculture, livestock and wildlife as well as humans) but also risks to the financial health of mining proponents and their shareholders, tax payers and other stakeholders.

The potential occurrence of ARD/ML is therefore often included as a failure mode in a more encompassing risk assessment at any one project or site with the consequence ultimately being an impact to receiving water quality. When ARD/ML occurs, the view is often that there was a fundamental error in one, or more of the following; (1) the identification and characterization of the potential for ARD/ML, (2) the prediction of water quality effects and/or effectiveness of control measures, or (3) the performance of management of waste for the control of ARD/ML. Significant work goes into each of these aspects at considerable cost to a proponent and considerable implication to the overall risk profile for a project. In the authors' experience there are components of each of these aspects (characterization, prediction and management) that can affect the ultimate risk of a project related to ARD/ML. These components can be framed within the context of an FMEA for the purpose of ARD/ML characterization, prediction and management with the objective of better quantifying the overall ARD/ML risk and then applying applicable mitigation measures to lower risk of a project. In other words, what are the failure modes and consequences of ARD/ML evaluation and management programs themselves? What risk do these represent for the project, so that mitigation measures can be applied to reduce risk? This paper attempts to identify and describe those failure modes that are most common and/or have the highest consequences.

METHODOLOGY

The risk assessment approach used in this study was that of a Failure Modes and Effects Analysis (or FMEA), which consists of the quantification of the likelihood and consequence of a failure or event (Robertson, 2012).

A failure mode can be naturally initiated (e.g. 1:500 year flood event) or initiated by a failure of an engineered system (e.g. leakage from a contaminated water storage pond), or by an operational error (e.g. accidental release of contaminant to the receiving environment).

The assessment of the effects or consequences of these failure modes is site specific though in large part based on precedence, experience at other mines (case histories) and professional judgement by experienced personnel. A suggested basis or metric by which the likelihoods and consequences can be quantified is provided, each based on metrics defined in 5-point scales as detailed in Tables 1 and 2 below.

Table 1 provides the likelihoods of an event occurring ranging from not likely to expected. The not likely category is defined here as having a <0.1% chance of occurrence (or one in a thousand) while the expected case has been defined as a >50% chance of occurrence (or a one in two probability of occurring). The period of consideration may the annual likelihood or the likelihood over the life of the project. Likelihood increases for the period under consideration. The authors have a preference for working with the likelihood of the period of operation of the mine, or in the case of post closure risk, a period of 100 years.

Table 1 Scale used to define the likelihood of a risk.

Likelihood Class	Likelihood of Occurrence of event within the period of consideration
Not Likely (NL)	<0.1% chance of occurrence
Low (L)	0.1 to 1% chance of occurrence
Moderate (M)	1 to 10% chance of occurrence
High (H)	10 to 50% chance of occurrence
Expected (E)	>50% chance of occurrence

Consequences in Table 2 have been categorized or grouped in a manner used commonly for FMEAs in the mining industry; specifically as geochemical impacts (often compared to water quality guidelines or biological metrics), regulatory effects (compliance), social license, health and safety and costs. The example scalars used here to assess the consequences, or the severity of effects should an event occur range from negligible to extreme. A negligible consequence would be one that had no measurable geochemical impacts on the receiving environment, that did not exceed regulated limits, that did not result in social attention or a health and safety concern, and for which repair or mitigate costs less than $10,000. An extreme consequence on the other hand would be an event that resulted in a geochemical impact that was considered very large and irreversible, that resulted in exceedances of regulatory obligations at a level that might shut down an operation or impose severe restrictions on an operation, that resulted in social outcry and the loss of social trust, that may result in fatalities and cost $10 million dollars or more to clean-up or mitigate. This scale can be modified to suit the sensitivities of each mine or project and the site and project specific conditions.

Risk is the product of likelihood and consequence:

Likelihood x Consequence = Risk

The risk rank can be quantified as either a number (the product of the likelihood rank and the consequence rank) or as a colour.

The matrix provided in Figure 1 below illustrates this as a color-coded (or ranked) system with warmer colors representing higher risks (with higher likelihoods and consequences) and colder colors representing lower risks (with lower likelihoods and consequences). A numerical quantification is also provided with the risk value for each failure mode being the multiplication of the likelihood rank times the consequence rank.

A separate risk matrix can be generated for each risk consequence: Geochemical Impacts; Regulatory Effects; Social Licence; Health and Safety; and Costs. This paper addresses geochemical failure modes, likelihood, consequences and risk.

FAILURE MODES

Geochemical failure modes identified in this paper have been organized here into those that are related to (1) prediction of geochemical behaviour, (2) prediction of effectiveness of control measures and (3) performance of control measures. In addition, the dimension of time (or kinetics) as related to each possible failure mode is discussed. This temporal aspect can relate to prediction of geochemical behaviour (e.g. the rate of neutralization depletion), the prediction of the effectiveness of control measures (e.g. the predicted infiltration rate through covers) and the performance of control measures (e.g. the effect of climatic effects such as a 1 in 1000 year flood on control measure performance).

Table 2 Example of a scale used to define the severity of effects (consequences).

Consequences	**Geochemical Impacts**	**Regulatory Effects**	**Social License**	**Health and Safety**	**Costs**
Negligible (N)	No measurable impact	Meet regulatory obligations or expectations	No stakeholder (e.g. locals, NGO) attention	No concern	<$0.01 million
Low (L)	Minor impact on WQ (less than order of magnitude change)	Seldom or marginally exceed regulations. Some loss of regulatory tolerance, increasing reporting	Infrequent local, international and NGO attention addressed by normal public relations and communications	First aid required; or small risk of serious injury	$0.01 to $0.1 million
Moderate (M)	Moderate, temporary, reversible impact on WQ	Occasionally (less than one per year) or moderately fail regulatory obligations or expectations - fined or censured	Occasional local, international and NGO attention requiring minor procedure changes and additional public relations and communications	Lost time or injury likely: or some potential for serious injuries	$0.1 to $1 million
High (H)	Significant, irreversible impact on WQ or large, reversible	Regularly (more than once per year) or severely fail regulatory obligations - large increasing fines and loss of regulatory trust	Local, international activism resulting in political and financial impacts on company 'license to do business' and in major procedure or practice changes	Severe injury or disability likely: or some potential for fatality	$1 to $10 million
Extreme (E)	Catastrophic impact on WQ (irreversible and large)	Unable to meet regulatory obligations or expectations; shut down or severe restriction of operations	Local, international outcry & protests, results in large stock devaluation: severe restrictions of 'licence to practice'; large compensatory payments etc.	Fatality or multiple fatalities expected	>$10 million

		LIKELIHOOD				
		NOT LIKELY [1]	LOW [2]	MODERATE [3]	HIGH [4]	EXPECTED [5]
CONSEQUENCE	EXTREME [5]	5	10	15	20	25
	HIGH [4]	4	8	12	16	20
	MODERATE [3]	3	6	9	12	15
	LOW [2]	2	4	6	8	10
	NEGLIGIBLE [1]	1	2	3	4	5

Figure 1 Risk Matrix Illustrating the Combination of Likelihood and Consequence

Prediction of Geochemical Behaviour

Potential/common failure modes related to prediction programs aimed at characterizing the geochemical behaviour of a material have been identified below.

Failure Mode 1.1: Errors related to geological variability. Geotechnical engineers who use the FMEA tool extensively in the mining industry are used to working with variability in parameters such as shear strength and permeability where variability in values can be substantial but where there is a predictable range for a given rock type. Geochemical variability for a given rock type can result from a number of components that could include variations in the quantity of key minerals, variations in textures and particle sizes, variability in the liberation of key minerals and how each is exposed during blasting etc. Without substantive testing and quantification, geochemical variability for a given rock type therefore is difficult to predict and project specific.

Failure Mode 1.2: Errors related to representativeness of samples. Generally sampling for geochemical characterization is done, at least initially, on the basis of guidelines that suggest a number of samples be collected for a specific tonnage of waste for each key rock type. Prior to mining, this is further limited by the availability of drill core available to sample. This drill core is generally representative of rock within or close to ore zones and not necessarily encompassing of all likely waste. Uncertainties therefore arise from the frequency and spatial distribution of samples selected. During operations or on closure this uncertainty is often reduced by the fact that sampling can be much more targeted to the material of interest and/or can be done at a higher frequency, with better temporal and spatial certainty.

Failure Mode 1.3: Errors related to representativeness of models. Modelling tools are used extensively in the industry. Often models are used to extrapolate data from the samples collected and characterized spatially in order to forecast the geochemical behaviour of waste rock before it is mined. These models have great value for waste planning particularly on projects where there is waste handling of material with one geochemical characteristic that differs from others. Uncertainties in the models however exist. These uncertainties may be greater for some deposits than for others, for examples extrapolation of a sulphur value from one sample across many meters of rock in a model for a deposit where sulphides are present as veins may have a much higher degree of uncertainty than if the sulphides were evenly disseminated throughout the rock mass.

Failure modes related to the development or utilization of models exist as do failure modes related to the use of the output. Practitioners need to understand the limits of models when making decisions on the basis of those models. Misguided use or over-reliance on model outputs can therefore also lead to failure modes.

Failure Mode 1.4: Errors related to definition of operational waste management. Many projects have waste handling procedures that are intended to segregate one type of rock from another. These programs are often developed to support project licensing prior to obtaining an understanding of how rock will blast, how sulphides and carbonates will partition in blasted rock, how well operations will be able to forecast and identify zones of differing geochemical behaviour, how diligent and dedicated operations will be to segregating rock etc. Predictions of how effective waste handling will be are often optimistic and not practical or conservative and may be unrealistic in estimating effectiveness.

Failure Mode 1.5: Errors in quantification of oxidation rates. Uncertainties that related to the tools and test methods standardly used to quantify oxidation rates (e.g. humidity cell tests, intrinsic oxygen consumption tests etc.) can also lead to failure modes. Because these tests are long in duration they are expensive. Sample selection therefore becomes a critical component of these programs. Inadequate sample representation can therefore lead to failure modes. Additionally, because there are standard methods for this quantification, programs tend to use the standard methods as a default. Adaptation of the methods to better suit site specific needs is rarely done and the duration of testing is often dictated by guidelines (e.g. 20 weeks, 40 weeks) rather than being dictated by each individual sample behaviour.

Failure Mode 1.6: Errors in the extrapolation of lab-based kinetic data to field conditions. Lab-based kinetic tests are typically used to quantify the rate of sulphide oxidation, depletion rates of buffering minerals and release rates of elements of interest. Test conditions seldom represent field conditions and numerical modeling is often inadequate to reliably extrapolate test conditions to field conditions. Data is used to calculate the lag time or delay to the onset of ARD conditions, when they are predicted to occur, as well as using release rates to predict water quality associated with waste facilities. Uncertainties and errors in the way in which lab rates are used in these calculations and predictions represent another failure mode with potentially significant consequences.

Failure Mode 1.7: Deficiencies in the industry-wide knowledge base. Much of the characterization and predictive work relies in large part on case studies, analogs and the successes and failures experienced at other sites. Our ability to better predict water quality impacts and to better manage or sort waste on the basis of geochemical criteria therefore would have less uncertainties if operations and practitioners were able to, or required to, re-visit predictions and evaluate if there are differences in predictions and observed conditions what may have contributed to those differences. It is recognized that this is only really partially achievable, particularly at locations where there is a lag phase and sometimes decades between the period of time when predictions are made and conditions represented by those predictions occur. Comparing apples to apples therefore becomes a particular challenge when relying on case studies and analogs. However 'calibration' against precedence of other projects or historical behaviour on a given projects are important methods for improving prediction accuracy and risk mitigation.

Prediction of Effectiveness of Control Measures

Control measures most typically evaluated and utilized at mine sites in order to limit the effects of ARD/ML include measures aimed at (1) limiting sulphide oxidation (source control), (2) limiting migration of contaminants generated by sulphide oxidation (migration control), and/or (3) limiting the release of contaminants, if generated, into the receiving environment (collection and treatment). There are a number of potential failure modes related to the prediction of how these control measures may perform that should be considered.

Failure Mode 2.1: Effectiveness of source controls. This failure mode would include potential errors in waste management aimed at controlling ARD/ML which, depending on the waste management at any particular site, could include: ineffective prediction of, or design of, segregation and sorting programs for waste rock; ineffective prediction of or design of blending or layering strategies for waste rock; inaccurate prediction of performance of amendments to lower reaction rates or increase lag times, inaccurate prediction of measures to reduce oxygen ingress, and potentially errors related to the design of sub-aqueous disposal of wastes.

Failure modes could occur where there is inability to, or inadequate planning for, the potential partitioning of the neutralization potential (NP) and acid potential (AP) into different particle size fractions when rock is blasted versus how it is accounted for in samples available prior to mining (i.e. pulverized drill core). This could influence design of segregation and/or blending strategies.

Others could include insufficient planning of amendment application or dosage with the result that reaction rates and/or lag times are faster than anticipated.

Control of ARD/ML by sub-aqueous disposal could also have potential failure modes associated with it. For example, the inability to keep waste submerged resulting from errors in water balance predictions or resulting from severe climatic changes.

Failure Mode 2.2: Effectiveness of migration control measures. In the scenario where ARD/ML generation controls are not considered achievable or are cost prohibitive, control measures aimed at limiting migration are sought and are most often focussed on the design of covers aimed at reducing infiltration into a waste storage facility. Failure modes could occur in the design of appropriate covers for instance if test plots are too shallow or too narrow influencing the parameters which are used to design the most effective covers. Failure modes could also occur by errors related to assumptions or inaccuracies of modelling relied upon to design covers. Even if designed properly, failure modes can occur during construction and/or as a result of long term changes in cover properties (biotic intrusion, desiccation and settlement cracking etc.).

Failure Mode 2.3: Errors related to collection and treatment measures. If neither oxidation control nor migration control are achievable, the ability to collect and treat impacted waters becomes critical. Failure modes that could occur in the prediction and design stage of collection and treatment control measures might relate again to errors in water balance or site water quality models, inadequate baseline assessments of hydrological or hydrogeological conditions etc. with the potential result that there is either too much water or much less than engineered for and/or that the treatment technology does not treat effectively or for all the parameters of concern.

Performance of Control Measures

Beyond the potential errors involved in characterization of ARD/ML and errors that could occur during the prediction or assessment of control measures for ARD/ML there are failure modes related to the performance of control measures put in place. This could in part be related to a failure to implement a design as planned or a failure to plan and design for implementation challenges.

Failure Mode 3.1: Errors related to operational waste management and deposition. Many projects have waste handling procedures that are intended to segregate one type of rock from another. Operational errors can occur whereby a zone on a pit bench is marked as a non-potentially acid generating zone or domain where in fact it is potentially acid generating and that block gets moved to the wrong disposal area. This could result from blasthole sampling at an inadequate frequency for accurate waste block designation or as a result of operator error where a truck operator who is supposed to take rock to one dump takes it instead to another. Rock management could also be prone to failure modes resulting from other operational constraints (e.g. a road washes out) resulting in all rock going to one area for a period of time. The simple process by which rock is placed can also create variability in a dump. For end-dump waste piles, segregation by rock size can occur down slope, this may result in partitioning of one rock type, perhaps intended to add carbonate buffering to the mix being deposited in one zone and another rock type, perhaps a harder rock that blasts in larger particle sizes, segregating down slope in another zone.

Failure of blending and layering management could result from partitioning of the neutralization potential (NP) and acid potential (AP) into different particle size fractions post blasting whereby neutralization is not effective and the standardized NP/AP ratios are either overly conservative or not protective. Failures could also occur if neutralizing minerals get blinded by secondary mineral precipitation on particle surfaces.

Control of ARD/ML by sub-aqueous disposal could also have potential failure modes associated with it: for example resulting from severe climatic changes; containment structure breaches etc.

Failure Mode 3.2: Migration control failures. Failures in covers due to root action, frost action, erosion and/or deterioration of liners all fall within this failure mode. Often the consequences of these failures occur slowly and gradually over time.

Failure Mode 3.3: Collection and treatment control failures. Failure modes that would occur within the context of collection and treatment systems could include ice and sediment blockages in diversion ditches, landslides blocking water management structures, flood events. Failure modes could also include temporal changes in water quality resulting in changing treatment requirements and/or changing water quality standards and regulations resulting in changing treatment requirements.

EFFECTS

In the case of the failure modes above, be they related to prediction errors, error in the prediction of control measures or the effectiveness of those measures, the effects can be described as (1) that monitoring detects the failure mode and remediation is taken or (2) monitoring does not detect the failure mode and an impact, perhaps temporarily, to the receiving environment occurs. The likelihood and consequences of geochemical related risks are therefore intimately dependent on the monitoring programs and highlight the importance of appropriate monitoring and response plans. Where monitoring is not adequate and failure modes occur, it may be that emergency response and clean-up plans need to be initiated.

Effects are also tied intimately to the receiving environment in which a project is located, the assimilative capacity, cumulative effects etc. The risk of cover failure in an area of high rainfall may have a much greater effect than if the same failure were to occur over similar waste in a dry environment.

Risks are also cascading. For example, if source control fails – for example if PAG and non-PAG rock segregation or blending is not effectively executed, then migration controls become the primary reliance measure. If migration controls fail, then collection and treatment systems become more important. Collection and treatment controls may have greater assurance where the likelihoods of an event are diminished, however costs are increased.

EVALUATION

This FMEA approach can be illustrated by way of example. For instance, consider a porphyry style open pit project whereby sulphides are both disseminated and structurally controlled and where carbonate content is generally low and present in veinlets. In this example, pre-mining characterization work identified a variable range of both PAG and non-PAG rock that was not strongly lithological-dependent and an operational segregation and sorting plan was developed based on a sulphide value criterion. Waste management in this example is done on the basis of blasthole sampling, on-site testing for sulphur and flagging of dig blocks on the pit face on the basis of those results. Waste planning includes PAG rock disposal in one location and non-PAG rock identified as construction rock and or disposal in a separate facility. The closure plan assumed and allocated closure costs for a cover placement on the PAG rock pile to minimize infiltration and predictions indicated there would be no need for collection and treatment to protect the downstream environment.

Potential failure modes for the characterization program, the prediction of control measures and the performance of the plan are provided in Table 3.

Precedence for this type of deposit would suggest that one possible failure mode is that not all PAG rock is identified or segregated correctly because the original sulphide criteria was not sufficiently protective or due to variability on a scale not adequately represented by sampling etc.. This could result in the PAG rock getting placed in a non-PAG rock pile or used as construction rock. The effects could be very different depending on whether or not monitoring was sufficient to detect and mitigate for this failure mode. Monitoring for this type of failure mode could include a verification program initiated during construction and early operations aimed to identify whether or not that the criterion be adjusted and/or water quality monitoring detects increased concentrations of indicator parameters.

In the example provided, there were a few failure modes identified related to extrapolation of kinetic data. The first example illustrates a potential error related to oxidation rate expectations. If in a case where control of ARD/ML from a PAG pile is reliant on a cover for infiltration control, the lag phase needs to be sufficient to prevent significant ARD/ML generation until such time as a cover can be placed. Kinetic tests are also relied on for prediction of water chemistry of contact water from non-PAG sources. If the tests or predictions based on those tests are not conservative enough, one effect could be that water chemistry associated with a non-PAG pile is still not of discharge quality and would also potentially require cover placement and/or seepage collection. A robust seepage quality monitoring program becomes a key factor at early identification of these potential failure modes and allowance for early mitigation by additional cover placement in the control plan would reduce risk.

SUMMARY

The FMEA methodology, which has found great utilization in the mining industry particularly in the regard to stability of geotechnical structures (dams, slopes, waste dumps), can also be a valuable tool for risk assessment of ARD/ML control programs and waste planning. In this paper a number of potential failure modes have been identified with greater discussion, by way of example, provided for a subset of these. The importance of consistent, robust and targeted monitoring is illustrated as a key risk mitigation and management tool.

REFERENCES

Robertson, A. MacG. (2012). FMEA Risk Analysis: Failure Modes and Effects Analysis. Presentation at Gestao de Riscos e Seguranca de Barragens de Rejeitos, Seminario 2012. http://www.infomine.com/library/publications/docs/Robertson2012b.pdf, accessed May, 2014.

Table 3 Example output of FMEA for ARD/ML Prediction and Prevention Program.

FAILURE MODE	EFFECTS	LIKELIHOOD	CONSEQUENCES					Highest Risk Rating
			Geochemical Impacts	Regulatory Effects	Social License	Health and Safety	Costs ($M)	
Characterization Program								
Error related to geological variability	Sulphur criterion not adequate for PAG sorting, PAG rock to non-PAG pile	3	3	4	3	1	2	
Errors related to representativeness of samples	Blasthole sampling not spaced adequately to define PAG blocks, PAG rock to non-PAG pile	2	3	4	3	1	2	
Errors related to representativeness of models	Modeling of vein hosted sulphides and carbonates difficult and PAG waste volumes underpredicted	3	2	2	1	1	4	
Errors related to definition of operational waste management	Operational errors lead to occasional PAG rock placement in the non-PAG pile	3	2	2	2	1	1	
Errors in quantification of oxidation rates	PAG pile produces acidity before cover placement, seepage collection required	3	3	4	2	1	5	
Errors in the extrapolation of lab-based kinetic data to field conditions	Water chemistry different then expected and requires collection	3	3	4	2	1	5	
Deficiencies in the industry-wide knowledge base	Analogs or precedents not available to support predictions	1	3	4	2	1	1	

Table 3 Example output of FMEA for ARD/ML Prediction and Prevention Program (continued).

FAILURE MODE	EFFECTS	LIKELIHOOD	CONSEQUENCES					Highest Risk Rating
			Geochemical Impacts	Regulatory Effects	Social License	Health and Safety	Costs ($M)	
Prediction of Control Measures								
Effectiveness of source controls	Predictions for non-PAG pile to have good seepage chemistry not accurate	2	4	4	3	1	4	
Effectiveness of migration control measures	Predictions of infiltration through PAG pile not accurate, potentially higher seepage rates	4	3	2	1	1	4	
Errors related to collection and treatment measures	Not predicted to be required but as a result of other failures is needed	3	3	4	4	2	5	
Performance of Control Measures								
Errors related to operational waste management and deposition	Non-PAG pile contaminated by PAG rock, seepage not of discharge quality	2	4	4	4	2	4	
Migration control failures	Cover failure due to root action etc., seepage higher than expected requires collection	2	4	4	4	2	4	
Collection and treatment control failures	Collection and treatment not adequate to protect downstream environment	1	5	5	5	3	5	