# ASSESSING THE RISK OF ARD[1]

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**Abstract**: Predictions of the potential for acid rock drainage (ARD) usually focus on assessing the probability that samples and waste units will generate contaminated leachate. The rate of ARD generation, its quantity, and the possible consequences of release are usually considered in far less detail. Such analyses are deficient and do not fully assess the risk of ARD. Risk can be quantified as the product of probability of an event occurring times consequences. The result is modified by the mitigative measures or contingency plans proposed to prevent or control the undesirable event. Several methods of risk assessment are available and might be applicable to assessing the risk of ARD. These include, qualitative assessments, "what if" analysis, point-scoring systems, failure mode and effect analysis (FMEA), and quantitative probabilistic analysis. The first three simple approaches are more appropriate for advanced exploration and mine projects, while the last two more detailed techniques could be used for existing minesites. Simple qualitative risk assessments have been used by regulatory agencies, either intentionally or unintentionally, in reviewing virtually all recent projects. The more sophisticated approaches have been applied relatively infrequently in mine assessments. Placer Dome Inc. is applying and developing several schemes for ARD analysis for all phases of mining development from exploration through closure. Risk assessments need to be applied more consistently to ensure that rational decisions are made in mine project development and that over conservative criteria are not used in project assessment.

## Introduction

Evaluating and accepting risk is a necessary part of deciding to proceed with any new mining project. Risk can be defined as a triplite of three questions:

- What can go wrong?
- How probable is it to go wrong?
- If it does go wrong, what are the consequences?

Mathematically, risk is often defined as the product of probability on an event occurring times consequences. The result may be modified by developing contingency plans.

In the context of Acid Rock Drainage (ARD) asessments, the above three questions could be restated as

- How could ARD be formed?
- How probable is it?
- What are the consequences of ARD generation?

The first question relates to possible sources of ARD, including ore and low grade stockpiles, underground and pit walls, waste rock dumps, leach dumps, road cuts, and borrow pits. If a prevention strategy has been defined for the project, the possible failure modes of the strategy may be examined in detail in a risk assessment.

The probability of ARD is usually examined in a geochemical testing program, e.g. acid/base accounting (ABA) and kinetic testing. The ABA results are often compared with criteria, or the researcher may use his or her experience to estimate a probability of ARD generation.

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ARD is not a concern if it does not migrate from the wastes. This is relevant in very arid climates or when rocks with significant acid neutralization capacity are down gradient of the seepage. Therefore, the probability of ARD generation needs to consider both the capacity of the rocks to generate acidic or metal contaminated leachate and the potential of contaminated drainage to migrate beyond the waste boundary.

The consequences of ARD release depend upon the nature of the ARD (strength and volume), the assimilative capacity of the receiving environment, and the proximity and value of aquatic resources. In short, not all impacts are equal.

To date, assessments of the potential for ARD often focus primarily on the probability that the waste will generate contaminated drainage. The migration potential is not usually considered in detail, and the possible consequences of ARD release are examined only in broad terms. Such assessments do not fully consider the risk of ARD.

Several methods of risk assessment are available that may be applicable to more completely assess the risk of ARD. These include ranking schemes, point scoring schemes, failure mode and effect analysis (FMEA), fault and event trees, consequence evaluations, modelling, and quantitative probabilistic analysis.

Simple qualitative risk assessments have been used by mining companies and regulatory agencies, either intentionally or unintentionally, in assessing mining plans. The more sophisticated techniques have been used infrequently. FMEA was used for the assessment of two mining projects in British Columbia (Pelletier and Dushnisky 1993, and Van Zyl and Bamberg 1992). Some techniques being developed by Placer Dome Inc. (PDI) and their applications are discussed in the remainder of this paper.

## Some Risk Assessment Techniques and Applications

### Issue Ranking Matrix

When evaluating new projects for possible acquisition, relatively little information is usually available to assess the risk of ARD. A simple approach is therefore required. A ranking matrix used by PDI is shown in figure 1. The probability of ARD and parameter migration potential are ranked according to subjective low, medium, and high ratings. The risk is categorized from 1 to 4 and can be modified by one level depending upon the degree of environmental sensitivity (consequences).

| Migration Potential | Probability of ARD | | |
|---|---|---|---|
| | Low | Medium | High |
| Low | 1 | 2 | 2 |
| Medium | 2 | 3 | 3 |
| High | 2 | 3<br>Waste dumps | 4<br>Tailings/Underground Workings |

- Add one level for high environmental sensitivity.
- Deduct one level for low environmental sensitivity.

**Explanation:**

- ARD Produced from historic underground workings
- massive sulphide orebody so ARD from tailings virtually assured
- mine adjacent to river with significant fishery (salmon) resource
- high snowfall/rainfall area (>1m)
- existing workings relatively small but will be expanded significantly in future mining
- limited space available for waste storage but potential for water cover given net precipitation area

**Figure 1: Issue Raking Matrix for ARD**

The probability may be defined by: observation of ARD from existing facilities or outcrop seeps, the presence of massive sulfides or carbonates in core, or the availability of mineralogical and geochemical data. The parameter migration potential reflects climatic conditions, possible isolation of sources (e.g., dry minewalls), or limited quantities of wastes (eg., small waste rock dumps in underground operations).

Because the analysis is entirely subjective, the information and assumptions used should be fully explained in supporting documentation.

## ARD Category Visualization

Acid/base accounting is often used to predict whether ARD is likely to occur. Unfortunately there is much debate as to interpretation of results for single samples and especially for mixed waste rock dumps composed of partly mixed acid and non-acid producing materials. Graphical techniques to visualize the data and to compare them to literature-reported criteria are important tools for the researcher to assess the probability of ARD.

**Table 1: Categories Used by PDI in Screening ABA Data**

| Category | NP/AP Range | Description |
|---|---|---|
| Likely | NP/AP < 1 | likely to generate ARD unless sulfide minerals are relatively unreactive |
| Possibly | 1 < NP/AP < 2 | possibly acid generating if neutralizing minerals preferentially depleted, coated, or unreactive. |
| Non-Acid Generating | NP/AP > 2 | not expected to generate ARD |

Criteria used to interpret the results of ABA were summarized by Ferguson and Morin (1991). Smith and Barton-Bridges (1991) proposed a neutralizing potential to acid production potential (NP/AP) criterion of 3 to 1 (3:1), and that samples below this ratio value should be subjected to kinetic testing. The authors noted that static tests assume the NP is instantly available, all sulfur converts to acid, and all sulfides are reactive. Since these assumptions are not valid for many samples, a safety factor is required for interpretations. However, the authors presented very little data in their paper to justify the chosen NP/AP ratio.

Ferguson and Morin (1991) and Cravotta et. al (1990) both presented theoretical arguments suggesting that the NP/AP criterion to separate potentially acid and non-acid generating samples could be about 2:1. However, in the database presented by the Ferguson and Morin, no sample with an NP/AP greater than 1 produced acidic leachate in 166 laboratory leaching tests. Moreover, there is no clear documented evidence of rock with a NP/AP greater than 1 producing ARD under field conditions.

The NP/AP ratio may be considered as a "safety factor" as used in other engineering analyses. Higher safety factors are probably required for mines in wet climates where carbonate minerals may be preferentially leached from the mine wastes relative to sulfide minerals. The criteria in table 1 have been used by PDI as an initial screen of <u>waste rock</u> ABA data.

An example application is shown in figure 2. The ore clearly has a higher probability of generating ARD compared to the waste rock and rip-rap material.

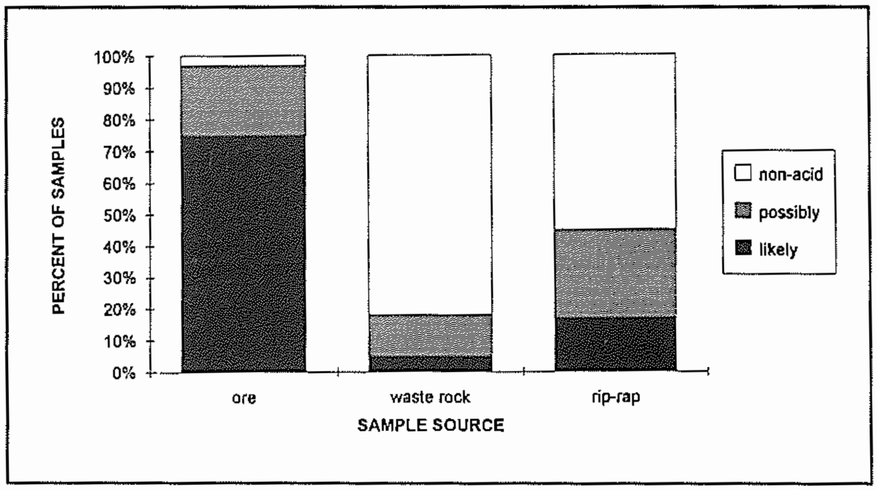

**Figure 2: ARD Potential by Category**

Tailings are finer grained and more homogeneous than waste rock. Ferguson and Morin (1991) combined data from 35 mines in Canada and Sweden and found a critical NP/AP of 1:1 was probably adequate to identify potentially acid generating tailings. A graphical presentation of AP and NP for tailings, adapted from Miller et. al. (1991), is shown in figure 3. The tailings are predicted to be potentially acid generating.

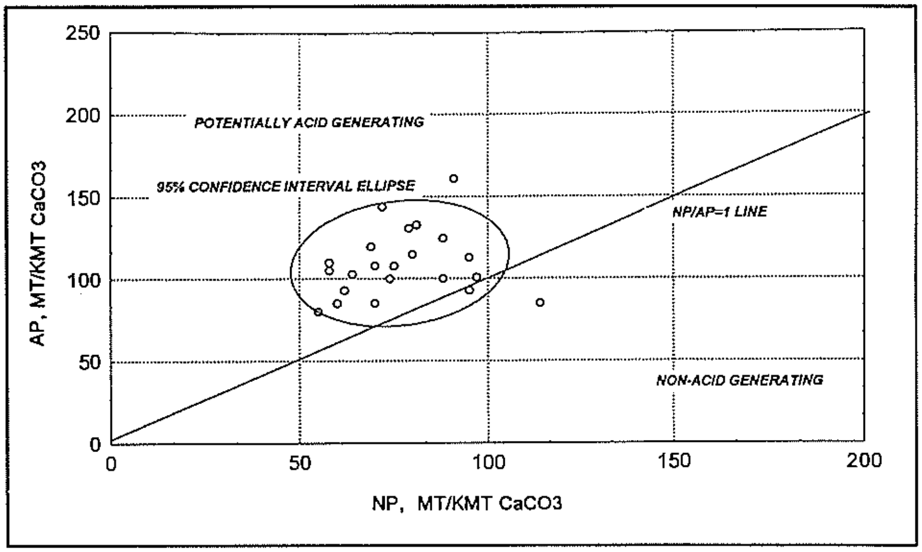

**Figure 3: AP versus NP for Tailings Composites**

## Fault Trees and Event Trees

The concept of examining possible "faults" and resulting "events" are integral parts of designing a mine but have rarely been applied in a rigorous manner to ARD assessments.

Fault trees are typically used to identify all the mechanisms by which an undesirable event could occur. The undesirable event is identified at the top of the tree, and all the subordinate events occur in the lower tree structure. The technique is well suited to examining the probable success of an ARD prevention plan. Figure 4 shows a fault tree for a plan to flood a tailings impoundment to prevent ARD formation. Probabilities can be assigned to each event, the total probability of failure calculated, and the most likely failure mode identified.

Event trees are used to examine the consequences of an initiating event in detail. For example, the effect of an excessive storm causing release from a tailings impoundment could be examined (fig. 4). The loading of contaminants could be estimated and possible impacts on the environment determined based on the presence or absence of aquatic resources.

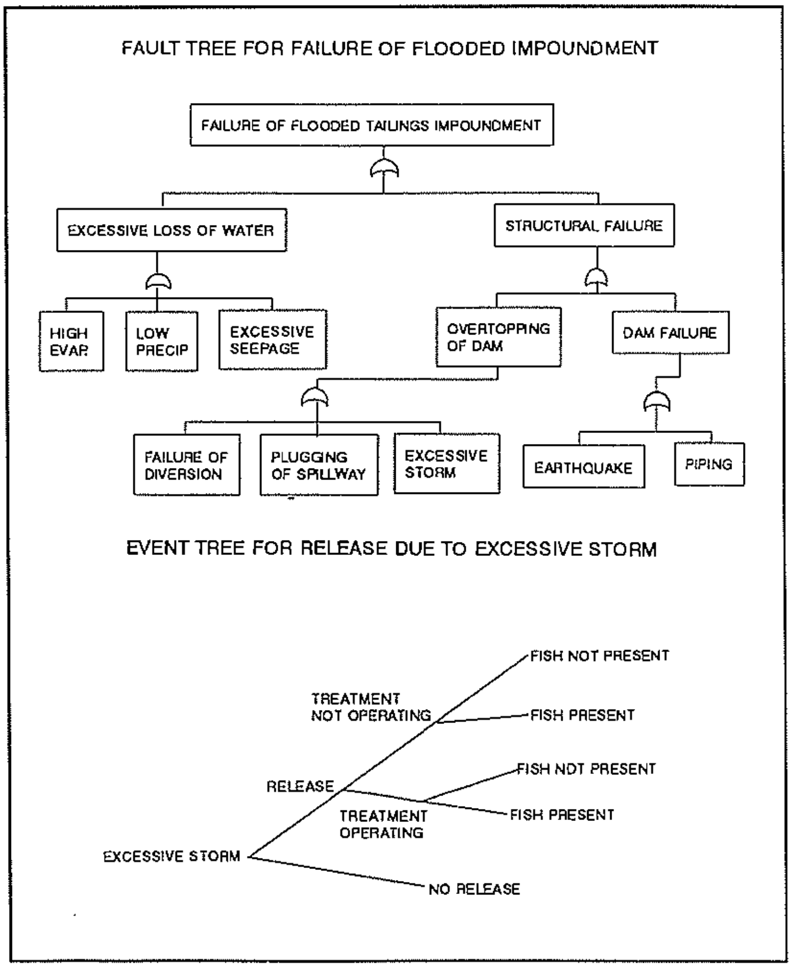

**Figure 4: Fault and Event Trees**

## Consequence Evaluation

Simple models can also be constructed to examine the consequences of ARD release. For example, in some cases, the natural environment may have a significant capacity to assimilate ARD. While this should not be relied on to control ARD, an evaluation of the possible consequences does help to focus effort. This is illustrated in the following example.

An open pit mine was proposed in an area of very high rainfall (greater than 4 m) with large streams containing high alkalinity (both as dissolved bicarbonate and as calcite in sediments). The question posed was "Could ARD from the waste rock dump and open pit cause a pH depression or problems with heavy metals in the adjacent river?"

The question was answered with the following assumptions:

- The pH in the river may fall if the total alkalinity reaches zero
- The total alkalinity is zero when the acidity load equals the alkalinity load
- Acidity and alkalinity behave as conservative pollutants
- The open pit and waste rock dump would not generate ARD concurrently

The critical acidity in the seepage from the waste rock dump and open pit was back-calculated using a simple mass balance equation and average monthly flows.

$$A_s = \frac{F_d * A_d - F_u * A_u}{F_s}$$

where $A_s$ = acidity (negative alkalinity) of acid water
$F_d$ = flow in river downstream of source
$A_d$ = alkalinity in river downstream of source (assumed 0)
$F_u$ = flow in river upstream of source
$A_u$ = alkalinity in river upstream of source
$F_s$ = flow of acid water from source

Results indicated the maximum acidity in the waste rock dump seepage that could be assimilated by the receiving streams without a pH depression ranged from 1,600 to 6,500 mg/L (as $CaCO_3$). Since seepage from other acid generating waste rock dumps of equivalent size has reached these acidity levels, ARD from the dump could be of concern. The dilution of seepage by the river ranged from 18:1 to 73:1 relatively low values, so the river could be sensitive to significant metal concentrations in any acidic drainage.

The maximum acidity tolerated from the open pit ranged from 5,500 to 22,000 mg/L (as $CaCO_3$); relatively high values and unlikely to be realized in the field unless the rock is extremely reactive. The dilution of pitwater by the river ranged from 63:1 to 251:1. Therefore, ARD from the pit is not as likely to cause a metal contamination problem as in the waste rock dump; less care is required for assessment and prevention of ARD from the pit.

## Probability Analysis

In quantitative analysis, a single discrete number in most instances does not adequately describe risk because input numbers in the assessment are uncertain. Probability analysis may assist in more fully describing risk. Probability analysis has been applied by Annandale and Chantler (1992) to a mine site water and contaminant balance in order to estimate the probability of achieving water quality parameters. The following case illustrates an application to estimate only the probability of ARD.

For one mine, PDI assessed the probability that mass-weighted and surface-area-weighted net acid production potential (NAPP)[4] for a waste rock dump would achieve criteria. The analysis was done in three steps. First, probability distribution functions were fitted to the NP and AP datasets for each of five rock types; lognormal distributions were found to provide the best fit. Second, a spreadsheet model was constructed to combine synthesized NAPP distributions according to the mass and the surface area of each rock type into single distributions for the entire waste rock dump. One rock type was extremely friable and slaked to a much finer grain size than the other four types

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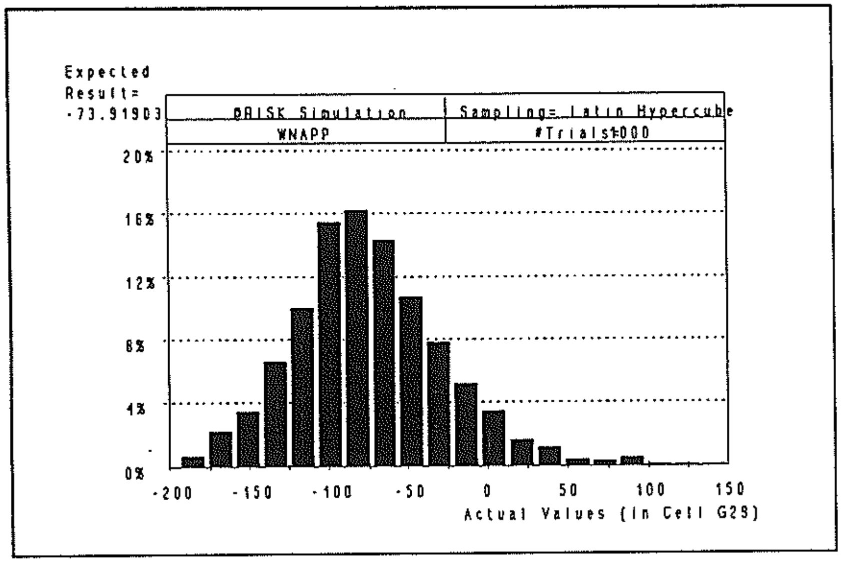
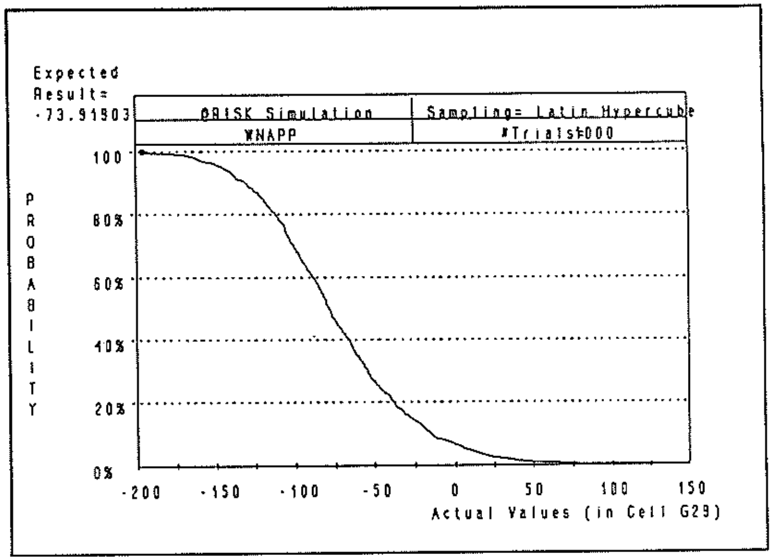
[4] The NAPP is used in South Pacific countries for prediction of ARD and is defined as AP minus NP expressed as kg $H_2SO_4$/t. The NAPP therefore has an opposite sign to the net neutralizing potential (NNP).

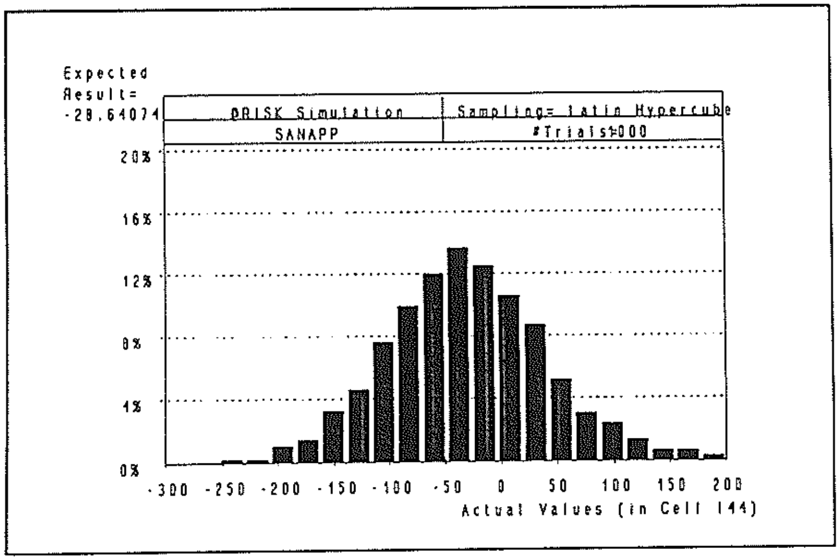
Figure 5: Frequency Plots for Mass and Surface Weighted NAPP



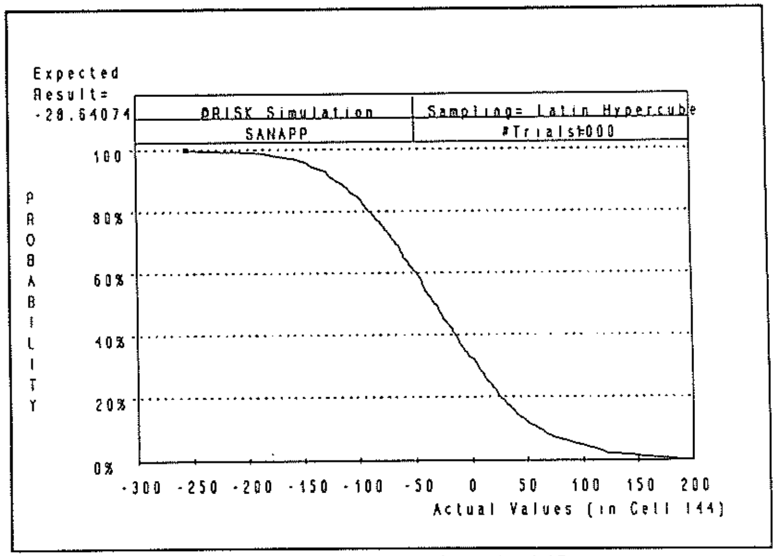
Histogram for mass weighted NAPP



Cumulative frequency for mass weighted NAPP



Histogram for surface area weighted NAPP



Cumulative frequency for surface area weighted NAPP and therefore had a greater contribution to the surface area weighted NAPP. Third, the distributions were sampled using a latin hypercube stratified sampling method to construct the weighted NAPP distributions (fig. 5). The probability of the entire dump achieving selected criteria could then be determined directly from the plots. For example, the probability of the mixed waste rock dump achieving a mass and surface area weighted NAPP value of greater than zero were about 7% and 30% respectively. Criteria should not be the sole basis on which predictions are made. The shape of the probability density functions also show the range, central tendency, and moments of the data. In the case described here, the analysis showed that the friable rock type caused a disproportionate increase in the acid production potential. Special material handling plans (underwater disposal) were developed to address the higher potential for ARD from that material.

## Modelling of Consequences of ARD

Even where waste has an intrinsic capacity to generate ARD, contaminated drainage may not exit from the waste deposit if sufficient neutralizing minerals are present in the flow path. This may be particularly relevant in a tailings deposit where carbonate minerals will be present below a water table. An example is discussed below.

The tailings contained on average of about 3.5% sulfur as pyrrhotite and pyrite and about 7% carbonate as calcite. Leaching tests indicated the sulfide minerals were amenable to oxidation and that in the long term, net acid would be produced if sufficient oxygen were present to support oxidation. However, the water table was relatively high in the deposit and may limit the depth of oxidation.

The model WATAIL (Scharer, et al., 1993) was used to study the effects of various depths of tailings below the water table on net acid production. The model was applied to four separate areas (nodes) of the deposit. For node 1 the depth to the water table was taken as 4 m, for node 2 as 2 m, and for nodes 3 and 4 as 1 m. Essentially the model examined the possible drawdown of a water table near a pervious dyke. The total depth of the tailings deposit was 5 m for all nodes. The model simulated 100 years of oxidation and seepage. Acidic leachate breakthrough did not occur for nodes 2 to 4, while breakthrough occurred from node 1 in 55 years (fig. 6). Even though acid breakthrough is not predicted for some nodes, migration of those metals mobile at alkaline pH, such as zinc and cadmium, may still occur. Based on this analysis, a decision was made to increase the depth of tailings in the lower portion of the impoundment and to raise the water table by constructing a water-retaining dam.

In a second example, a simple model was constructed to predict the sulfate and metal concentrations in drainage from a waste rock dump where potentially acid generating rock was to be placed on top of a dump because of the mining sequence. A geochemical rather than oxidation-limited model was used since the quantity of potentially acid generating rock was small and exhibited a low intrinsic oxidation rate from kinetic tests; calculations also indicated oxygen was not limited, given the depth and reactivity of the material.

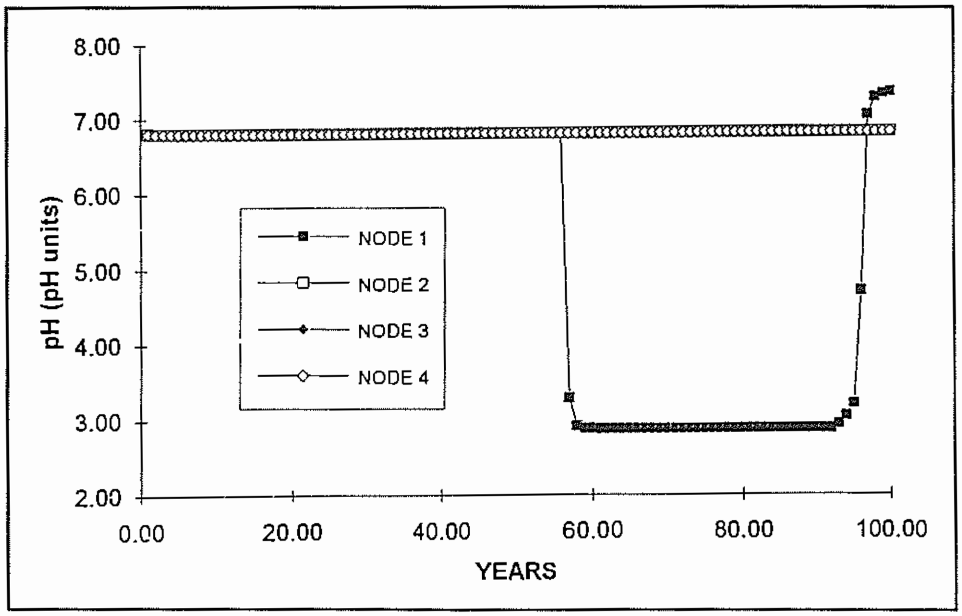


**Figure 6: Predicted pH in Seepage**

Results from a series of seven field barrel tests were used to determine oxidation rates (sulfate and metal production rates). A mean sulfate production rate was normalized to the percent sulfur in the sample and the number of days prior to leachate sampling. The normalized rate was found to vary by only two to three times. A decay rate was applied(time$^{-0.5}$) to account for the build up of coatings during long dry periods and the resulting decrease in sulfate production. To estimate metal concentrations, zinc, copper, and cadmium were correlated with sulfate for the barrel data. Correlations were not strong but were adequate for this level of modelling. For zinc, relationships were established for three ranges: high, medium, and low reactivity (sulfate production) (fig. 7).

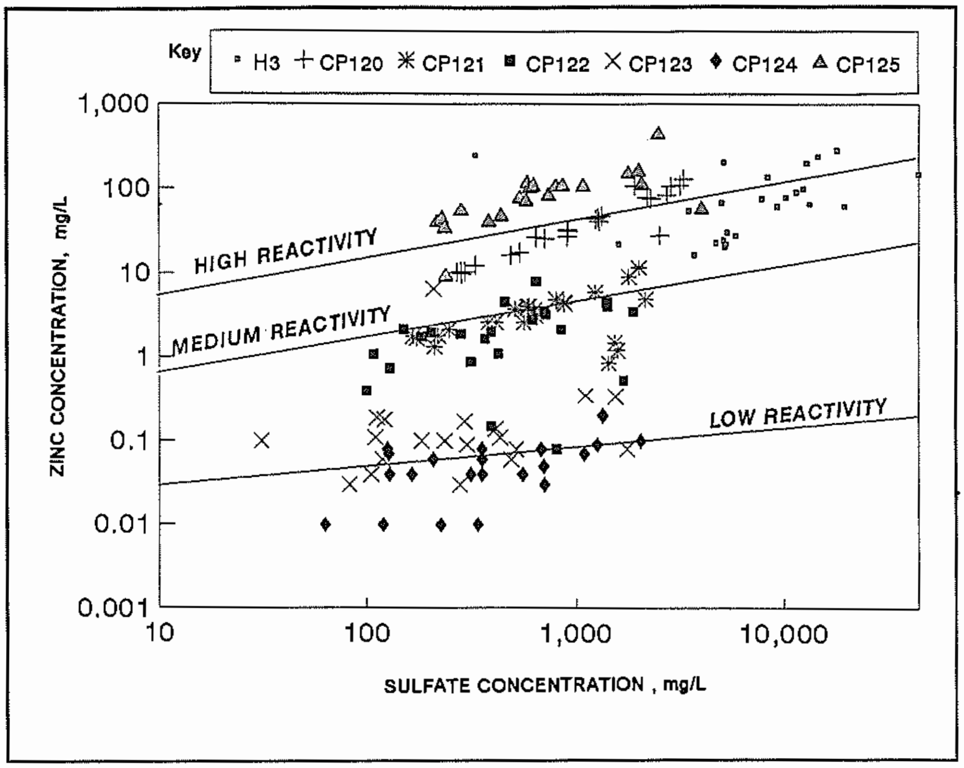


**Figure 7: Zinc Concentration versus Sulfate for Lysimeters**

The model was run to calculate sulfur and metal concentrations from the waste rock dump based on recorded precipitation and dry periods from July 1992 to October 1993 (duration of barrel experiments). The seepage from each class of waste (high, medium, and low reactivity and no acid generation) was weighted according to the possible tonnage and surface area of the dump. The seepage was diluted by the "uncontaminated" receiving water according to simple ratios of catchment areas.

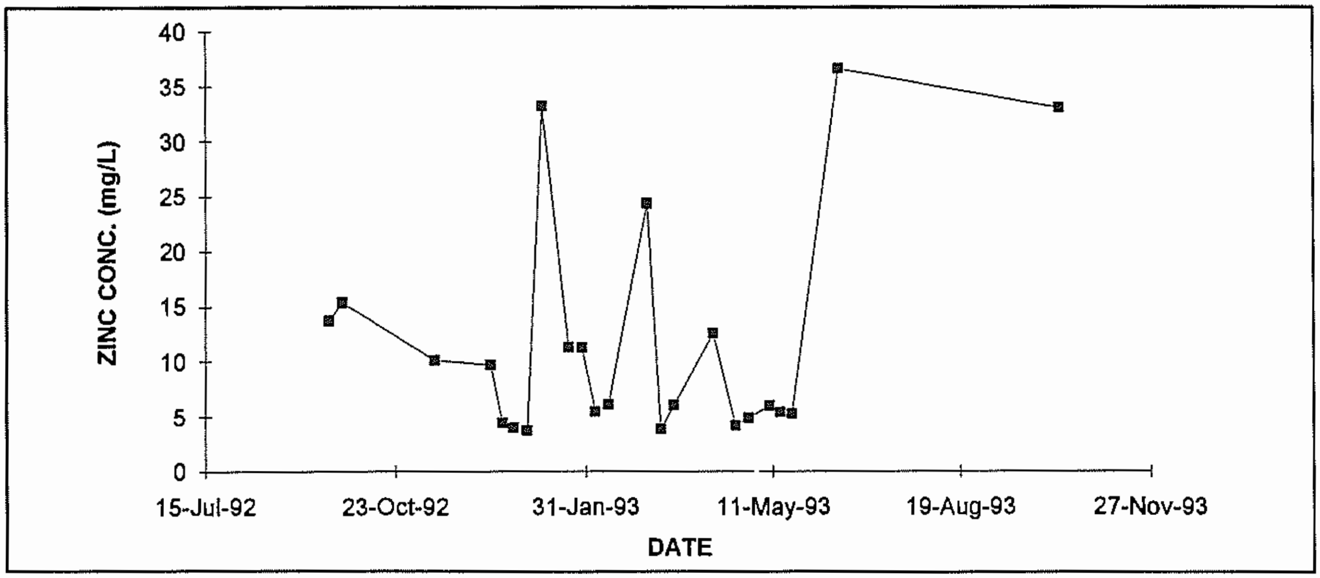


**Figure 8: Model Predicted Zinc Concentration**

Results for zinc are shown in figure 8. The model was very simple; results may not be highly accurate but are adequate to make management decisions. The results indicated that zinc concentrations could be significant in the receiving environment, and therefore mitigative measures including covers would be required.

## Conclusion

The formal application of risk assessment to environmental analysis in mining is rather new. The analysis need not be complex to provide a useful insight into the probability and consequences of ARD and the need or level of mitigative measures. Risk assessment techniques such as those discussed above show much promise for analysis of ARD problems, particularly since the assessment of ARD is still an inexact science.

Some possible applications of risk assessment techniques to the various phases of mine development are shown in table 2. These tools are applicable to both operators and regulators of mines. With the growing use of these techniques, more rational decisions in mine design, approval, and operation should be possible.

**Table 2: Possible Application of Some Risk Assessment Techniques to ARD**

| RISK ASSESSMENT TECHNIQUE | PROJECT PHASES | | | | |
|---|---|---|---|---|---|
| | Operators | | Operators/Regulators | | |
| | Acquisition | Pre-feasibility | Feasibility/Design | Operation | Closure |
| Ranking Matrix | ••• | •• | •• | - | - |
| Category Visualization | •• | ••• | ••• | •• | • |
| Fault/Event Trees | - | •• | ••• | ••• | ••• |
| Consequence Evaluation | • | ••• | ••• | •• | •• |
| Probability Analysis | - | - | ••• | •• | • |
| Modelling | - | - | ••• | ••• | ••• |

| | | | |
|---|---|---|---|
| - | probably not applicable | • | possibly applicable |
| •• | possibly applicable but may not have sufficient resolution | ••• | very applicable |

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