Canadian Nuclear Society
Waste Management, Decommissioning and Environmental Restoration
For Canada's Nuclear Activities: Current Practices and Future Needs
Ottawa, Ontario Canada May 8-11 2005

COMPREHENSIVE REVIEW OF THE EFFECTIVENESS OF MINE ROCK MANAGEMENT AND DECOMMISSIONING PRACTICES

Ronald V. Nicholson[1], Donald L. Lush[1], Michael J. Rinker[2], Mahrez Ben Belfadhel[2] and Peter Flavelle[2]

[1] EcoMetrix Incorporated, 14 Abacus Road, Brampton, Ontario, Canada L6T 5B7
[2]Canadian Nuclear Safety Commission, 280 Slater Street, Ottawa, Ontario, Canada K1P 5S9

ABSTRACT

Decommissioning practices for waste rock are based on the characteristics of the waste rock, the associated "environmental drivers" for COC release, the nature and magnitude of transport pathways, and exposure and risk to human or ecosystems as a function of time. Safety assessments for decommissioning practices are used to estimate release rates from the waste rock, determine if any potentially significant quantities of COCs are anticipated, and to determine if or how the loadings may be modified before discharge to the receiver. In general, the largest uncertainties with safety assessments are associated with the estimates of release rates. Much of the effort related to mine rock safety assessments have focused on methods and procedures to determine mine rock reactivity, and the potential to release metals and other chemicals and radionuclides of concern, including acid. This paper represents a summary of a review (Stantec, 2003) that was initiated by the Canadian Nuclear Safety Commission on the assessment and effectiveness of waste rock management and decommissioning practices.

1. INTRODUCTION

Safety assessments for waste management and disposal practices must meet several requirements and criteria including technical criteria, regulatory criteria and public need. The proposed practice developed by the proponent must be scientifically sound and well thought out using several lines of converging evidence and must clearly justify, through a weight of evidence approach, that human health and the environment will be adequately protected in both the short and longer terms.

The proposed waste management practice put forward by the proponent must also meet the legislative needs of the responsible authorities and it must be clearly communicated to all stakeholders as to how this can be achieved. Finally, the public has the right to be fully informed by the proponent and regulator about the proposed practice and the environmental and human health benefits or costs that may be associated with the practice. This communication of what may be complex technical arguments must be presented in a clear and transparent manner.

Canadian and many foreign jurisdictions are recognizing these needs and implementing legislation to codify them in law. The overall package that addresses the legislative and public consultative components as well as the technical aspects is often referred to as the safety case for the proposed project in that its purpose is to make a "case" to the regulatory authorities and the public that the proposed management and disposal practice would be "safe".

Waste rock management at mining operations represents one of the major challenges that face the industry. Predictions of future behaviour of mine rock effects on nearby water quality continue to have uncertainties. The uncertainties related to potential future impacts represent a challenge not only to mine operators but also to regulators that have the responsibility to ensure that mine rock management practices uphold public safety and environmental protection legislation. The purpose of this review was to provide an overview of current approaches and practices related to the prediction of mine rock behaviour and of mine rock management.

2. WASTE ROCK ASSESSMENTS

Waste rock is, by definition, rock outside of an ore body that does not contain economic quantities of the mineral being mined. Because of the close proximity to the ore body there is often a higher quantity of trace mineralization in waste rock than found in the adjacent "country" or "background" rock. Much of the mineralization in the ore and the waste rock consists of thermodynamically reduced minerals that remain geochemically stable as long as it remains underground and isolated from weathering processes, especially atmospheric oxygen and meteoric water. In a general sense waste rock can be categorized into different classes based on the potential for chemical reactivity or physical degradation when exposed to weathering and, consequently, the level of management that may be required in order to minimize risks to the environment. Three classes of waste rock that may conceptually be used for management classification are illustrated in Figure 1. The classes are, in part, categorized using the sulphur (the most common/abundant reduced mineral associated with uranium ore waste rock) content of the waste rock although other reduced minerals such as Arsenides may be locally important.

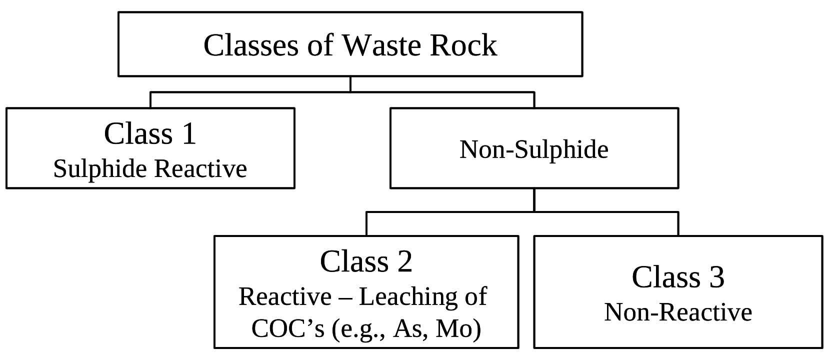

Figure 1: Example classes of waste rock in terms of reactivity.

The management issues related to Class 1 material are generally well understood early in the assessment process (i.e., barriers must be in place between the waste rock and the atmosphere to minimize oxygen contact with the reduced reactive minerals). More detailed work is required to classify waste rock into either Class 2 or Class 3 and the greatest technical challenge in an assessment resides in determining appropriate management options for material that is not clearly Class 2 or Class 3. Class 3 waste rock, which is considered non-reactive will not release contaminants to the receiving environment at levels that cause an adverse environmental effect, even if deposited on land using standard placement techniques with no special covering technology. In the case of Class 3 waste rock, the long-term management concerns generally focus around geotechnical stability and habitat availability for revegetation. In the case of Class

2 material the "environmental drivers" responsible for the release of contaminants to the adjacent environment may or may not be the same as the atmospheric oxygen driving the release from Class 1 materials. This makes the determination of the environmental factors driving the release of contaminants from Class 2 materials and how to possibly control them more of a challenge.

"Environmental drivers" are the natural processes that may exacerbate acid generation and leaching of COCs. The drivers associated with 'above-grade' disposal (Table 1) include meteoric water (solubility), atmospheric water, microbial metabolism and freeze-thaw conditions. 'Below-grade disposal insulates rock from atmospheric oxygen and freeze-thaw conditions.

Table 1: Examples of "environmental drivers" in different environments

Environment	Above-Grade	Below-Grade
Driver	Meteoric Water	Ground Water
	Atmospheric Oxygen	-
	Microbial Metabolism	Microbial Metabolism
	Freeze-Thaw	-

3.1 The Evaluation Process at the Planning Stage:

Waste rock characterization generally involves the collection and analysis of representative samples that are tested for sulphide minerals, metals, other trace elements, radionuclides and other characteristics associated with the potential for acid generation and leaching of contaminants. The potential issues are identified at this stage (e.g., acid generation, metal, trace element and radionuclide leaching). Leaching tests or kinetic tests may then be conducted to confirm the relevant issues under conditions that attempt to mimic exposure to air, water or other potential drivers of environmental release in a stockpile repository and to determine the rates of acid production and or potential contaminate release, if applicable. Once the potential contaminant issues and nature of drivers of reactivity are identified, management options that minimize potential contaminant release with associated human and environmental risk (e.g., underwater disposal) can be considered and, where warranted, tested in the laboratory. This testing of the waste rock focuses on the potential for release of chemicals or radionuclides of concern (COCs) in the managed setting. The overall objective of the testing program at this stage is to identify the environmental drivers and quantify the release or loading rates for chemicals or radionuclides of concern or of acid production.

3.1.1 Waste Rock Characterization

The general characteristics and issues related to the management of mine waste rock at the exploration stage of a project are typically based on results of the analysis of solids collected from exploratory boreholes. The solids are submitted for laboratory testing to determine the general geochemical characteristics of the solids. These tests generally include but are not limited to: sulphur content and speciation; carbonate content; acid base accounting (ABA); metal analysis, including relevant radionuclides; and mineralogical analysis. The purpose of these analyses is to determine the potential for the waste rock to be a source of constituents of concern including acid if the mine rock is deposited in the proposed mine rock management area. The ABA tests provide a screening analysis whereby the Neutralizing Potential (NP) and Acid-generating Potential (AP) are determined.

The NP and AP values are used as screening criteria and evaluation generally requires site-specific information. The AP value is calculated from sulphide measurements. The NP value is determined by leaching procedures. If mine rock poses a risk for acidic drainage with or without the release of other associated contaminants (i.e., Class 1), then this issue becomes a primary concern and management options are developed to mitigate this risk. If the mine rock does not pose a risk for acidic drainage, further evaluation is carried out in order to determine if there is the potential for the mine rock to leach potentially deleterious constituents over time (i.e., Class 2). The COCs in mine rock are generally inorganic constituents such as metals, arsenic, other potentially toxic trace elements and/or radionuclides. The COCs are identified by comparing the concentrations in mine rock to a benchmark value (e.g., natural background or clean-up criteria). A COC may be characterized by having a concentration that is below the cut-off for ore and higher than natural background, or it may exceed a concentration in the rock that would cause unacceptable loadings to water in contact with the rock.

Mine rock samples can be submitted for short term (~24 hour) leaching tests to further assess the potential for COCs to leach under different conditions. Standard tests conducted in Canada include the Special Waste Extraction Procedure (SWEP) (Province of British Columbia, 1992) and the Toxicity Characteristic Leaching Procedure (TCLP) (U.S. Environmental Protection Agency, 1996). These tests assess the leaching characteristics of samples under conditions that attempt to avoid solubility control by exposing the solids to an excess volume of water (solid to liquid ratio of 1:20) and at either neutral pH or at pH 5 with acetic acid. The results of these tests can be used to assess the potential for the COC to leach, the mechanism or condition under which leaching is promoted, and the leachable inventory of the COC. However, these types of tests are generally not appropriate to assess the potential for oxidative release of COCs from sulphide minerals that will release COCs over longer time periods, and may not exhibit any release during the leach tests.

Longer-term kinetic test work can be conducted during the design stage to assess the effects of weathering or oxidation. These tests include humidity cells or column tests. "Standard" humidity cell tests as well as column tests are described in Price (1997). The results can be used to estimate loading rates or leachate concentrations and evaluate how they develop over time. Both tests provide a conservative estimate to loading rates, but are not generally applied to estimate concentrations expected under field conditions because the samples are flushed with large volumes of water that dilute the COC loads from the rock. Many modifications of humidity cell and column tests have been proposed and applied for site- or material-specific conditions. The challenge of applying such tests is generally in the interpretation of the results and attempting to "scale-up" the results to field conditions.

The results of these tests can then be used in conjunction with the conceptual management plan for the waste rock in order to assist in the evaluation of the suitability of the management method for various stages of a mining project as shown in Table 2.

3.1.2 Evaluation of Potential Management Options

The proposed mine rock repository and its interface with the "receiving environment", that provides the "environmental drivers" responsible for release of COCs from waste rock and their potential effect on the receiving environment, also requires evaluation during the design phase. This evaluation process includes an assessment of flows, identification of pathways, and identification of the media through which COCs from the mine rock may migrate. This assessment provides the necessary information to establish flux rates of COCs from the mine rock to the environment, to evaluate the potential for attenuation of COCs along flow paths and to determine dilution factors in the receiving environment. Natural attenuation of the of the COCs within the waste rock may reduce the loading rates to the environment and is evaluated by a modeling exercise. The loading rate to the environment is then determined and converted to concentrations or dose within the environment that can be compared to regulatory limits, end point or triggers for acceptability for the mine rock management option being evaluated. It is anticipated that the modeling used to predict effects on the environment can also guide the monitoring program that will be applied to evaluate the performance of the mine rock facility. Once the preferred management option is determined, and studies have demonstrated that loadings to the "receiving environment" are acceptable, the management plan is submitted in Canada to federal and provincial authorities for approval.

Table 2: Evaluation Matrix

Stage of development	Type of Evaluation	Purpose of Evaluation	Example of Procedure
Planning	Static Tests - (sulphur, carbonate content), determination of NP/AP	Determine if rock is Class 1	Sobek/modified Sobek method
	Chemical analysis (metals, As, radionuclides)	Determine if rock is Class 2 or 3, identify COCs	ICP-MS, ICP-AES, IC
	Mineralogical analysis	Identify minerals responsible for leaching (and conditions that encourage leaching	XRD
	Short term leach tests	Assess potential for COC's to leach, conditions that promote leaching	SWEP[1] test, TCLP[2]
	Kinetic tests	Estimate loading rates, determine concentrations under expected conditions	humidity cells, column tests
Operation	Field assessments, including monitoring of seepage chemistry, testing of 'bulk' samples	Determine initial source term	Monitoring performance of waste disposal facilities
	Monitoring receiving environment, pathways to receiving environment	Determine the rate of migration of COCs, and how COCs are partitioned in the environment	Follow-up programs under CEAA
Decommissioning	Continuation activities under operational stage		

1 Special Waste Extraction Procedure (Ref. …)
2 Toxicity Characteristic Leaching Procedure

The quantity of mine rock that is generated during the operation of a mine is typically in the range of a few million cubic metres. This large quantity of material is expensive to move and management options available for mine rock disposal are restricted to those that can be implemented within the vicinity of the mine. Moreover, the management option is usually selected prior to mine operation so that the mine rock is moved only once. The drivers that determine the environments into which waste rock is typically proposed to be placed include the physical and geochemical stability of the environment; above grade or ground level where the mine rock can be exposed to atmospheric weathering conditions; below grade where the mine rock is isolated from atmospheric weathering; the proximity to human settlements and valued ecosystem components.

The nature and significance of transport pathways that will be available for dispersal of any materials released from the waste rock and control the potential exposure and risk to humans or valued ecosystems as a function of time are considered, including an assessment of things such as natural landscape weathering, climate change and cumulative effects.

One of the greatest technical challenges to date has been to make use of laboratory data to scale up to reasonably predict the long term behaviour of mine rock stockpiles or other waste rock repositories. In general, models (that, here, refers to any calculations to estimate the outcome for projected full-scale mine rock facilities as a function of time) are required for this purpose, but there is no general agreement on a modeling approach and many models remain in the realm of research. Most practitioners' models tend to rely on combinations of empirical data and more sophisticated models or spreadsheet calculations to assess long-term water quality evolution associated with mine rock facilities.

From a regulatory perspective, there is a need for transparent assessments that can be evaluated by technically knowledgeable reviewers who are not experts in every aspect of gas transport, heat convection, unsaturated water flow and chemical kinetics. One approach that may provide this transparency is the development of loadings models based on either laboratory or field estimates of release rates for COCs and acid, and on mass balance considerations. Among practitioners, variations of loadings models that can be developed in spreadsheet form are becoming increasingly favoured. These more straightforward models provide a transparent approach for a first-level assessment of effects from mine rock weathering. In some cases, refinement is required to add more realism because the simplistic assumptions are by necessity designed to be conservatively restrictive. More realistic and less conservative but justifiable modifications to the loadings models can be applied by adding a time dimension to the analysis (that is usually important for pulse-type source terms), or by considering chemical reactions that may limit concentrations and loadings of key COCs within the water exiting the mine rock stockpile. In any case, there are no accepted or prescribed recipes for assessing potential downstream impacts from weathering mine rock, and regulators will ultimately be evaluating such assessments on a case-by-case basis into the foreseeable future.

3.2 The Evaluation Process at the Construction / Operational Stage

Additional assessment studies may also be initiated during the construction and operational stages of mine development. These studies could involve field assessments conducted to determine the initial source term characteristics (through both bulk run of mine testing of waste rock and leachates derived from it) and how the source term may be developing or evolving with time (through the in situ or on-site monitoring of the waste rock). These studies can be used to validate (or invalidate) predictive studies that were conducted during the design phase. These studies may also entail the first work that is used to characterize the source term when studies conducted during the design phase were inadequate. Examples of assessment/test methods that may be carried out during the operational stage include: field test plots; monitoring downstream chemistry, groundwater chemistry, seepage chemistry, internal pore water chemistry; drilling/excavation programs to access bulk waste rock samples for laboratory studies (leaching studies); etc. The results of operational monitoring are used to determine whether or not implementation plans need to be modified or whether long-term decommissioning and abandonment plans require modification or refinement.

Under the Canadian Environmental Assessment Act (CEAA), monitoring is required during the construction and operational phases which, in general, is in addition to compliance monitoring that would be required to satisfy licence conditions. This follow-up monitoring provides a means to assess the performance of the mine rock facility and the adequacy of long-term predictions made during the planning stage. The monitoring feedback provides a form of validation and calibration of the models and overall assessment process or an indication of inconsistencies that require further refinement or evaluation. Adaptive management, or contingency plans can be implemented for mitigation of potentially negative outcomes. The contingency or mitigation is based on the potential for lack of performance required to prevent undesirable environmental consequences. The monitoring program should, therefore, be designed to assess the critical assumptions used to develop the management plan. This type of monitoring could include mine rock analysis and drilling/sampling programs within the management area and development and sampling of monitoring wells located below or immediately adjacent to the mine waste rock.

3.3 The Evaluation Process at the Decommissioning Stage

If a waste rock management plan was successfully designed and implemented, decommissioning and abandonment processes are an extension of activities that occurred during operation (i.e., follow-up monitoring). The processes designed to monitor the performance of the management program generally involve monitoring of aquatic biota, downstream surface water chemistry, sediment and/or soil chemistry, seepage and groundwater chemistry, and dose or toxicity. These monitoring programs may continue for the duration of institutional control or until the federal authority deems that monitoring is no longer required because there is no longer unreasonable risk of adverse environmental impacts.

Should monitoring programs indicate that the management plan is not adequate, then adaptive management measures would be implemented.

4. ASSESSMENT APPROACHES USED IN OTHER COUNTRIES

Some generalizations can be discerned from the perspectives of the various countries included in this review. All countries have a long history of mining of metals but uranium mining in Canada, Germany and Russia dates from the 1940s and in Australia from the 1970s. South Africa has not experienced uranium mining but has uranium associated with gold deposits that are similar in origin to the uranium deposits in the Elliot Lake region of Canada.

Current regulations that address uranium mining are relatively recent in most of the countries. The regulations have common themes for protection of humans from excess radiological dose that generally included consideration of dust and radon emissions in addition to aqueous releases. Most of the regulations also address water and air quality criteria for the protection of the natural environment from chemical and radiological toxicity.

All countries have altered the focus of mine rock management within the final decades of the 1900s from physical stability issues and radiological protection associated with direct exposure to more chemically and environmentally focused issues. With the exception of Russia, that has been challenged by major social reorganization issues in the 1990s, the other jurisdictions share similar approaches to the evaluation of mine rock for planning and permitting. The awareness of acid drainage and metal leaching associated with sulphide mineral oxidation in mine rock stockpiles, has driven assessments to address water quality issues in rock drainage as a primary concern for rock management.

Another common theme across most countries is the scarcity or absence of fully reclaimed and closed mines (either uranium or other non-uranium mines with other environmental challenges) that have been returned to the respective government jurisdictions. Only Germany has taken significant steps toward large-scale reclamation that was driven by reunification in the early 1990s and the legacy of uranium mining in the former East Germany where many operations were in close proximity to populated areas. The commitment of more than 6 billion Euros by the Federal government in Germany, and the development of the mine reclamation organization known as WISMUT provided the means to conduct significant reclamation activities. The reclamation activities in Germany will likely represent an important learning experience as ongoing monitoring provides a performance assessment for different strategies that have been applied in that country.

There are examples of reclaimed and closed uranium mines, including Elliot Lake mines in Canada that did not have mine rock issues, and Rum Jungle in Australia where the rock stockpiles were covered in the early 1980s. In almost all cases of reclaimed mines, however, there is a need for ongoing care and maintenance, including ongoing water treatment.

Risk assessment approaches are also common to a few of the countries. The risk assessment methods generally address human health and safety as well as environmental protection. In Germany, for example, reclamation focused on human health foremost but included consideration of water quality as well. In Australia, the active open pit mine (Ranger) will require reclamation with performance that will result in acceptable conditions for a National Park, including human health protection as well as ecological restoration.

5. CANADIAN APPROACH IN THE CONTEXT OF INTERNATIONAL EXPERIENCE

It is evident that all countries are in a learning mode for mine rock reclamation and closure planning in this first decade of the 21st century. There are a variety of approaches for mine rock management that have been suggested or are being carried out. In Canada, in-pit and underwater disposal of reactive rock is favoured at uranium and non-uranium mines especially for Class 1 waste rock materials. Examples of soil covers on reclaimed reactive rock (including non-uranium) are scarce and there are no known successes (“walk-away”) for cover systems involving reactive rock. There have been examples of blending of reactive and non-reactive (elevated AP with excess NP) rock at metal mines but again there is generally evidence of residual water quality issues that require treatment. In contrast to the Canadian experience, blending appears to be favoured in Australia. Most operations where blending has occurred are active and monitoring is ongoing. The one example of a covered rock pile in Australia (Rum Jungle) continues to require water treatment for rock drainage even though the cover has been shown to reduce the high rates of oxidation and acid generation that was evident before cover construction.

It is evident that there are differences in details related to evaluation methods among the countries reviewed. It is also evident that there are differences in interpretation of the test results within Canada and that these differences reflect the state of our knowledge. Ongoing learning and research are needed to address water quality issues associated with waste rock drainage. Overall, however, it is clear that the approaches to mine rock management in Canada are as technically advanced as those in the other countries reviewed. Indeed, the specific methods that were developed in Canada in the late 1980s and 1990s have been applied in other countries. For example, the German reclamation strategies were based on concepts and approaches that were developed or reported by the Canadian MEND program. The technical transfer that was one objective of the MEND program in the 1990s in Canada may be one of the reasons for the adoption of those methods in other countries. It is clear that mine waste management, with respect to water quality issues, is not a straightforward engineering issue. Much has been learned over the past two decades about the behaviour of sulphide mine rock subjected to weathering and oxidation, but we, as practitioners, researchers, mining companies and regulators are continuing to learn and adjust our thinking and approaches to managing mine waste.

In conclusion, it can be safely stated that the Canadian experience has not lagged behind those in other countries with respect to state-of-the-art practices for mine rock management.

6. SUMMARY

The Key Factors to be considered in the development of a waste rock safety assessment include the characteristics of the waste rock, the environments into which it is proposed the waste rock is to be placed and the associated "drivers" of COC release, the nature and magnitude of transport pathways that will be available for dispersal of any materials released from the waste rock, and exposure and risk to human or ecosystems as a function of time.

However, it is evident that there are various possible approaches to mine rock assessment with a focus on water quality. One approach that is developing as a dominant theme is based on an assessment of potential release rates from rock with subsequent transport through the near-field environment, and finally with transport into the receiving environment where the resulting concentrations are estimated. In this approach, it is necessary to estimate release rates from the waste rock, if any potentially significant quantities of COCs are anticipated, and to determine if or how the loadings may be modified before discharge to the receiver. In general, the largest uncertainties in the predicted outcome using this approach are associated with the estimates of release rates, but there are also uncertainties associated with the modifying chemical reactions as affected drainage migrates through the near-field environment toward the receiver. Much of the effort associated with mine rock assessment has focused on methods and procedures to determine mine rock reactivity, and the potential to release metals and other chemicals and radionuclides of concern, including acid.

Because we do not have a full understanding of the issues and because we cannot, with certainty, predict outcomes for water quality generated by mine rock in all environments over long time scales, we need to be able to adapt our management of mine rock to new findings and observations, and to ensure that alternatives and contingencies are in place to address the uncertainties. It is evident that we will continue to learn, by experience, to refine mine rock management strategies into the foreseeable future. We do not have the option of waiting for researchers to answer all of the questions, and therefore need to take practical steps in planning and implementing good practice for mine rock management that provide options for cost effective mitigation as required. This is the role of adaptive management.

7. REFERENCES

Province of British Columbia. 1992. Waste Management Act: Special Waste Regulation Schedule 4, Parts 1 and 2. Queen's Printer, Victoria, BC, p. 72-79.

Skousen, J.G., J.C. Sencindiver and R.M. Smith. 1987. A Review of Procedures for Surface Mining and Reclamation in Areas With Acid-Producing Materials. West Virginia University Energy and Water Research Center, in cooperation with the West Virginia Mining and Reclamation Association and West Virginia Surface Mine Drainage Task Force.

Sobek, A.A., W.A. Schuller, J.R. Freeman and R.M. Smith. 1978. Field and Laboratory Methods Applicable to Overburden and Minesoils. Report EPA-600/2-78-054, U.S. National Technical Information Service Report PB-280 495.

Stantec Consulting Ltd. (2003). Comprehensive Review of the Effectiveness of Waste Rock Management and Decommissioning Practices – Overview. *Report Prepared for: Canadian Nuclear Safety Commission, December, 2003*

U.S. Environmental Protection Agency. 1996. Test Methods for Evaluating Solid Waste - Physical/Chemical Methods (SW-846). US EPA, Washington, DC.