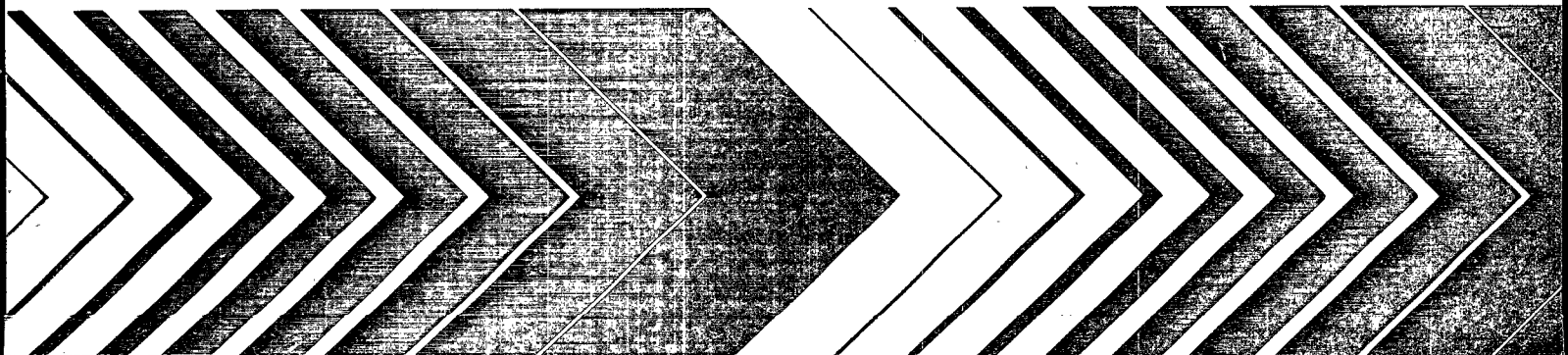
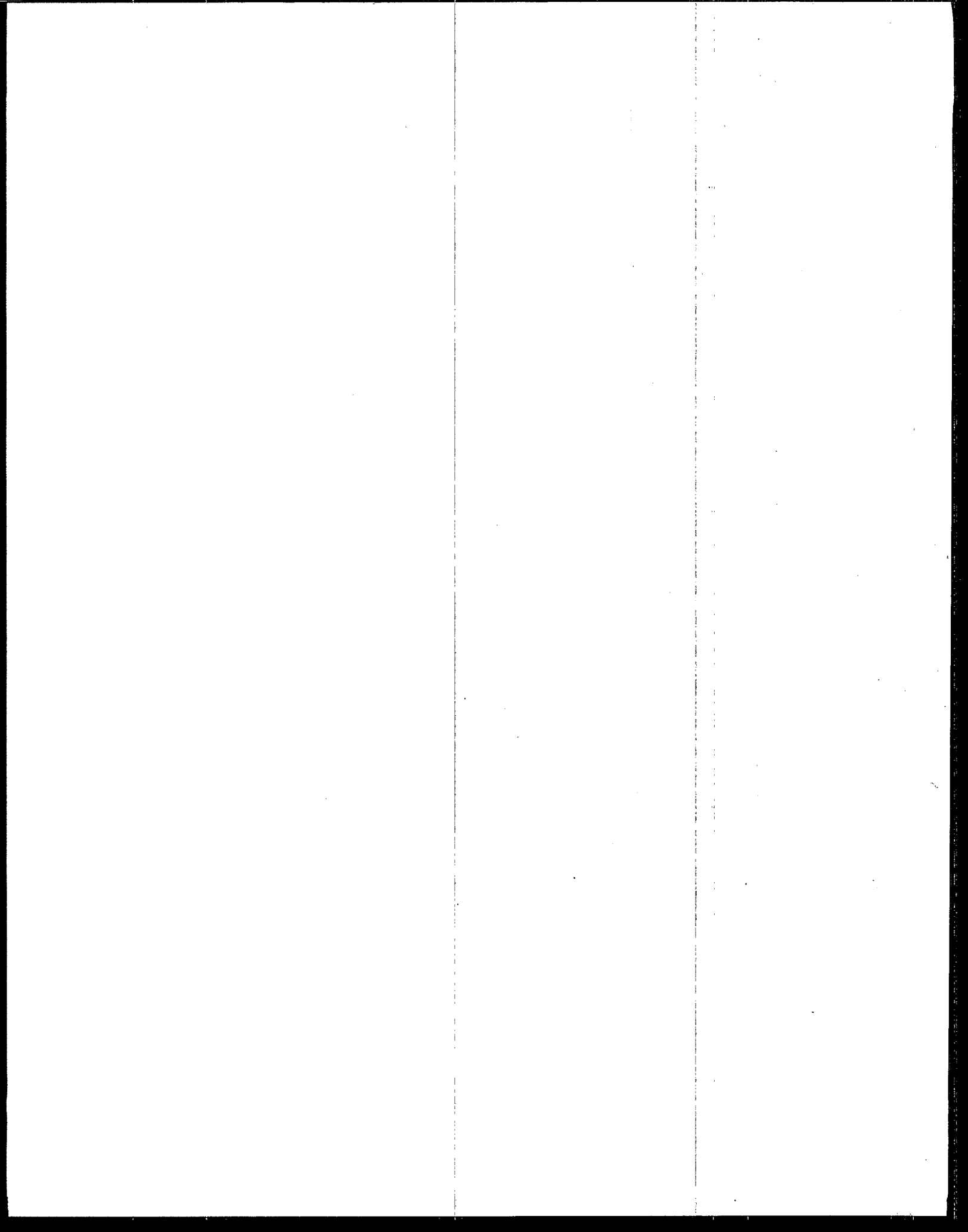




# **Predicting Acid Generation from Non-Coal Mining Wastes**

Notes of  
July 1992 Workshop





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**PREDICTING ACID GENERATION  
FROM NON-COAL MINING WASTES:  
Notes of the July 1992 Workshop**

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## INTRODUCTION

Acid generation is a major environmental problem at many mining sites where certain sulfides, primarily iron pyrite ( $\text{FeS}_2$ ), react with water and oxygen by natural processes to form sulfuric acid. This acid can increase the concentrations of toxic components (such as metals) in drainage from the mining wastes or from soil exposed to the drainage. Reliable procedures are needed to predict acid generation from future mining operations to prevent or mitigate this environmental impact.

The U.S. Environmental Protection Agency's Office of Research and Development (EMSL-LV, Methods Research Branch) sponsored a Workshop on Predicting Acid Generation from Non-Coal Mining Wastes. The Workshop was held in Las Vegas, Nevada on July 30 and 31, 1992. The purpose of the Workshop was to identify reliable analytical-testing procedures that may be useful in the prediction of acid generation from mining wastes. EPA assembled a panel of experts in the area of acid generation measurement techniques from the regulated community, the private sector, and Federal and state regulatory agencies. EPA also invited interested parties to attend and share their observations on the selected topics and on the panel's discussion. Panel members and workshop attendees are listed in Appendix A. Appendix B contains brief biographies of the technical experts on the workshop panel.

The objective of the workshop was to assist EPA's Office of Solid Waste in the development of a program, under Subtitle D of the Resource Conservation and Recovery Act, that addresses wastes generated by the extraction and beneficiation of ores and minerals. In preliminary stages of development, this program clearly will have to address acid-generation potential, because acid drainage has proved to be one of the more significant long-term environmental problems at sulfide mines.

While predicting the actual amount of acid generation from mining wastes is certainly desirable, it could be premature in 1992 to identify specific kinetic tests for long-term regulatory use. In the 1991 Proceedings of the Second International Conference on the Abatement of Acidic Drainage,<sup>1</sup> Keith Ferguson (as Head of the Mining and Metallurgy Program at Environment Canada) stated that "little is understood about the factors that control ARD [acid rock drainage] in the long term, especially for waste rock." If kinetic testing of a waste material produced a false-negative prediction for the long term, the unanticipated acidic drainage could cause significant environmental degradation and costly remediation. A false-positive prediction could cause needless expenses in management and monitoring of the waste material as potentially hazardous.

Published reviews with guidance on acid prediction are available. A study funded by EPA's Risk Reduction Engineering Laboratory contains an assessment of testing procedures.<sup>2</sup> Detailed method descriptions with comments on interpretations, advantages, and limitations are provided in a 1991 technical manual.<sup>3</sup> A chapter on the "Prediction of Acid Generation Potential" is included in a recent publication<sup>4</sup> by the California Mining Association. Government scientists with relevant experience have reviewed and provided guidance<sup>5,6</sup> on predictive methods for acid mine drainage. Fundamental references on this subject include reports by Caruccio et al.<sup>7</sup> and Sobek et al.<sup>8</sup>

The Workshop opened with a welcome from Christian Daughton, Chief of the Methods Research Branch of EPA's Environmental Monitoring Systems Laboratory in Las Vegas. The Workshop organizer, Tom Hinnners of the Methods Research Branch, gave a brief introduction concerning the purpose of the Workshop, discussion topics and format, followed by the introduction of the Panel Members. He emphasized that the workshop was intended to foster a discussion of ideas, not to reach specific conclusions.

## WORKSHOP SUMMARY

Topics addressed during the workshop (with post-meeting summaries) include the following:

- **Representative Sampling**

The actual acquisition of mining waste samples that are representative of the acid drainage potential has critical importance. Some failures to predict acid drainage have been traced to inappropriate or insufficient sampling. Average or composite values may not reflect the acid generation potential of sulfide-rich veins or pockets. During a mining operation, the sulfide content of the ore or overburden may change. Sampling plans for evaluating the potential for acid generation should consider the approach used in mapping the ore body, with the focus changed to mapping the reactive sulfide body. Using a blocking design for material of different geological types can reduce the number of samples that need to be analyzed to characterize the mining wastes in contrast with random geographic sampling.

- **Static and Kinetic Testing**

Static testing is sufficient to identify wastes that have strong or negligible potential to generate acid. When the neutralization potential (NP) of a mining waste is 2 or 3 times the acid potential (AP), the material is considered to have a negligible potential to yield acidic drainage. When the neutralization potential is less than the acid potential, the waste is considered to have a strong potential to produce acidic drainage. Depending upon the geological region, this may account for about 50 percent of the mining wastes. When the neutralization potential exceeds the acid potential by less than 2 or 3 fold, kinetic testing is recommended to assess the probable acid generation by the waste. Testing recommendations are available in the literature<sup>1-3</sup> and in Appendices C and D.

- **Acid Prediction and Mine Planning**

Prediction of acid generation and drainage for mining wastes under field conditions involves many factors. These include sampling, geology, mineralogy, static testing, kinetic testing, climate, disposal arrangements for the mine wastes, and accuracy of decision values or rates in long-term models. The mine plan needs to address acid generation not only before and during mine operation but also after mining ceases.

- **Identification of Research Needs**

Research needs identified at the workshop include (1) more data from field studies (using old and new waste piles with control measures) to evaluate factors and to allow correlations with predictions, (2) an assessment of reactive sulfide and neutralization potential that are "available" under field conditions including factors affecting depletion rates for each, (3) the relationships between mineralogy and reactivity, (4) cheaper methods to predict acid generation (such as the peroxide test described by Miller's group in Australia), (5) the effects of climate, (6) the determination of a minimum sulfur value, (7) an assessment of acid generation from underground mine walls, (8) a better understanding of the bacterial role in acid generation, and (9) as the factors above are better understood, develop both simple and complex models for acid drainage from tailings, waste rock, and mine walls.



Each of these major topics was discussed in a separate session during the workshop, although there was some overlap among sessions. This document describes the discussions among panel members and audience participants on each of the topics. It does not represent a verbatim transcription of the proceedings; rather, it is a condensation of the discussions by the various participants. In a few cases, comments or discussions that occurred in one session have been moved when they were more relevant to another session. Otherwise, the comments are presented in chronological order.

## REPRESENTATIVE SAMPLING

**Steve Hoffman** (U.S. EPA) opened the sampling discussion by describing EPA's interest in selecting methods of analysis for predicting acid generation from mining wastes. He wondered whether a lengthy debate on representative sampling of wastes for analysis was necessary.

**Richard Humphreys** (California Water Resources Control Board) suggested that sampling requirements should be based on consistency, yet allow for flexibility to account for the extreme variability between mines, their rock type, and sulfur concentration. He also noted that mines have to have a sampling plan.

**Keith Ferguson** (Placer Dome, Inc.) stated that the sampling representativeness is critical and must be dealt with. Some mines are easy to characterize, while others require thousands of samples to determine a mine's acid generation potential. It is important to understand the mine's geology and to describe it in detail and link this to the sampling program and test results.

**Linda Broughton** [Steffen, Robertson and Kirsten, Inc. (SRK)] wanted clarification on whether the concern is for predicting acid generation potential or predicting drainage quality, as the testing procedures and interpretation are very different. She observed that sampling should not focus on the total mass of the rock, but concentrate on the samples or rock types that are a potential problem. **Steve Hoffman** asked about variability and suggested step-wise sampling with continuous evaluation based on input from existing sample data. **Richard Humphreys** stated that from a regulatory perspective, if staff members feel existing sampling is insufficient, they ask for additional samples to be taken. **Steve Hoffman** asked if it was possible to establish a set of criteria (7 or 8) to guide sampling requirements and identified geology and waste units as examples.

**Andrew Robertson** [Steffen, Robertson and Kirsten, Inc. (SRK)] made several suggestions to help organize the sampling discussion:

- He asked if the group was addressing only wastes and wondered how rock walls, mine disturbed rock, and collapse zones would be dealt with.
- He noted that EPA had not emphasized contaminated drainage but rather acid generation (he felt that not enough attention was given to contaminant generation and oxidation).
- He noted that if acid or contaminant sampling is to be for the purpose of comparison with some regulatory standard value, then a high-quality test would be required.
- He suggested that mining wastes could be subdivided by mineralogy and particle size, and that the geology could be characterized by lithology and mineralogy.

Steve Hoffman asked if such a system could differentiate between waste types. Andrew Robertson responded that it could not, stating that it looks at rock type independent of waste; the waste type would be accounted for by knowing the mineralogy and particle size.

Keith Ferguson stated that in determining the risk of acid generation, it is important to consider climate (e.g., a sampling program in an arid climate may not be as detailed) and sensitivity of the environment (e.g., salmon). Climate has a critical effect, for example, on the migration of acid and the ultimate impact. In addition to climate, he raised some additional factors including:

- Composite versus discrete sampling. Although composites may underestimate acid potential (by disguising variation), compositing over the heights of benches may be effective.
- Quality assurance/quality control
- Using all relevant data is important: core logs, visual categorization, metal scans, etc.
- Must account for planned pit limits (depths, bench heights) and/or rock type in a sampling program to assess variability. For example, the first level of testing could involve a few hundred samples to assess the variability and determine the need for additional sampling.

Steve Hoffman asked how mines could be directed to sample and by which method. Keith Ferguson stated that from his experience roughly 50 percent of mines will yield a good indication of the acid generation potential from the initial sampling; the remainder will require more sampling.

Patricia Erickson (U.S. EPA) suggested that initial sampling could be used to establish the variability of acid potential and/or contaminants in rock and the variability would be a factor driving the resultant sampling regime.

Andrew Robertson offered the following papers prepared by SRK on aspects of the workshop topics:

Robertson, A. MacG., and L. M. Broughton, Undated. Reliability of Acid Rock Drainage Testing. Unpublished report available from the authors at the address in Appendix A.

Broughton, L. M., and A. MacG. Robertson, Undated. Acid Rock Drainage From Mines - Where We Are Now. Unpublished report available from the authors at the address in Appendix A.

Broughton, L. M., Chambers, R. W., and A. MacG. Robertson, April 1992. Mine Rock Guidelines, Design and Control of Drainage Water Quality. (See Reference 9.)

Tom Hinnners (U.S. EPA, ORD, EMSL-Las Vegas) then asked the panel to summarize the sampling discussion and recommended the classification of waste material. Steve Hoffman suggested that a series of issues covering sampling be identified, and mentioned a multi-tiered approach.

**Linda Broughton** offered the following issues for consideration in the design of a sampling program:

- Level of concern for potential impact
- State of operation
  - new site
  - control of an old operation
- Scope of problem
- Accessibility
- Composition/variability
- Spatial Coverage
- Quality Assurance/Quality Control

**Ms. Broughton** asked **Keith Ferguson** if his sampling programs reflect the different sizes of operations. **Mr. Ferguson** noted that from his experience, there is a great deal of variability among sites. **Placer Dome** does not sample based on tons of waste generated; he stated that this issue was a primary concern on his research list at **Placer Dome** and that at this time he did not have a critical sample number to characterize the contaminant or acid-generation potential. **Steve Hoffman** asked if a range could be developed and used widely, and then be further refined with experience.

**Richard Humphreys** offered **California's** experience with the **Penn Mine**. They selected a 3:1 ratio of neutralization potential to acid potential (NP:AP) to provide for a margin of safety at that site, but felt that a single number was not plausible for all situations. **Keith Ferguson** agreed, stating that it is difficult to accurately characterize hundreds of millions of tons of waste rock. Therefore, it is important to set a sample size, monitor, test the assumptions, and then to revise the sampling regime as necessary. **Keith Ferguson** noted that the **Canadian Province of British Columbia** requires large bonds, prediction plans, prevention plans, and contingency plans. **Steve Hoffman** asked if the development of a contingency plan depended on the sampling network. **Keith Ferguson** said it could be, in that initial sampling may be used to locate potential problems and to develop a detailed mine plan. **Steve Hoffman** asked about the operating plan. **Keith Ferguson** said the mine plan was described in the **Environmental Impact Plan**. **Steve Hoffman** expressed interest in the steps of the process, and noted that the sampling issue must be raised during the development of the operating plan or pre-operating plan.

Following the panel discussion, several of the observers offered comments.

**Gene Farmer** [U.S. Forest Service (USFS), Ogden, Utah] made the following observations:

- Representative sampling [as an assumption behind static testing] is a fantasy since certainty in the area of representative sampling does not exist. It is more important to give a qualitative answer to the question of whether material will be acid-generating. However, most mines will fall in a gray area. One answer to that uncertainty is a continuing sampling program during the active life of the mine: **USFS** takes that approach. He suggests one sample per 20,000 tons of waste (which can include samples of the ore body, because most of the ore body becomes waste).

- He suggested that active mines be separated from inactive mines and from re-mining situations.
- He agrees that sampling programs are the most important, with specific reference to sampling procedures and numbers, including sample size and location.
- He noted a strong tendency to composite samples, particularly for in-pit sampling of reverse circulation cores. He noted a need to avoid compositing samples because it reduces variability, and the population mean is not of concern.
- He agrees with the use of block models to describe sulfide distribution in a given ore body, not static or kinetic testing.
- He observed that real neutralization potential (NP) does not exist. It only exists in the laboratory, in that none of the static tests has been shown to correlate with those in the field. This has led to a 3:1 (NP:AP) as the rule-of-thumb for some investigators. Accurate tests of percent sulfur and NP may be incapable of predicting acid drainage. Sulfur content, ratios, etc. are all used because of this lack of correlation.
- He also noted two phases of acid generation: the oxygen cycle and the iron cycle.

Tom Card (Nevada Division of Environmental Protection) offered the following comments:

- Sampling is a major concern for regulation of mining operations.
- Incremental sampling based on tonnage is not always necessary if tests are consistent.
- He emphasized the nature and importance of the risk. In Nevada, he indicated that the low atmospheric precipitation minimizes the environmental risk, and thus the concern is different from, for example, Vancouver Island.
- There is no simple recipe for sampling, but it may be possible to develop a matrix based on risk.

Glenn Miller (University of Nevada) stated that predicting land uses over centuries is problematic, therefore current risk may not be the proper driving force behind sampling and regulatory decisions/requirements. He asked whether any retrospective prediction studies have been conducted (e.g., by going to old mine sites that exhibit acid drainage, by sampling and predicting acid potential, and then correlating field and laboratory data).

Richard Humphreys stated that there are different definitions of risk depending on perspective. In California, for example, there is a policy of non-degradation of surface water quality. In addition, the concepts of ecological risks versus human health risks are changing (in revising the Hazard Ranking System used in the Superfund program, for example). Steve Hoffman said water quality standards are based on "risk" to aquatic organisms; there are no analogous standards for terrestrial organisms.

Pat Rogers (Independence Mining Company) stated that mines are fairly adequate in developing sampling programs to address risk. He recommended that the real focus should be on testing methods and the real-world reliability of laboratory tests.

Michael Smith (Barrick Goldstrike Mine) described a general approach to sampling: an unbiased geostatistical estimator approach is a systematic method of sampling exploration hole data. He indicated that this can be used for reserves estimation and that the resolution is high. It allows an estimation of the 3-dimensional distribution of NP:AP values. He raised the issue of sampling at the exploration stage because most sites never go to the production stage.

## STATIC TESTING

Tom Hinners began the discussion by asking if false negatives (i.e., cases where laboratory testing indicates no significant acid-generation potential when, in reality, there is) were a major issue of concern.

Richard Humphreys stated that testing was not the issue, but whether the material is acid generating or not. Measuring acid generation potential as a prediction tool in the disposal environment [e.g., standard excess (acid)] may be useful for materials with low sulfur content. He recommended that a conservative NP:AP ratio of 3:1 may provide a margin of error. A net NP of 50 tons  $\text{CaCO}_3$ /1000 tons was not always predictive of acceptable water quality.

Frank Caruccio (University of South Carolina) added that through his work with mines in the northern Appalachian coal field he was able to empirically determine that a 2:1 NP:AP ratio can be used as a reasonable guide toward identifying potential acid problems. And certainly the 3:1 proposed provides a wide margin of error.

Kim Lapakko (Minnesota Department of Natural Resources) stated that inherent in static testing is the assumption that all acid-producing and acid neutralizing components are accurately measured. It is tacitly assumed that the neutralizing components will react to maintain a neutral drainage pH. Acid-producing components can be quantified to a reasonable degree. However, neutralization potential (NP) measurements tend to overestimate the ability of a mine waste to neutralize acid in the field.

The methods for NP measurements specify the addition of acid to the mine waste sample to produce a sample/solution pH which is often 3.5 or lower. For discussion purposes, this value will be denoted  $\text{pH}_A$ . The amount of acid neutralized is then measured either directly or by back-titrating the solution to pH 7.0 or 8.3. This measures the acid that would be neutralized when drainage pH reaches  $\text{pH}_A$ . This value will be greater than the acid neutralization available to maintain a drainage pH of 6.0 or above, which he believes is a common water-quality standard. The concept of overestimation of NP, as well as data confirming this concept, is presented in the Draft Report to the Western Governors' Association (WGA), "Evaluation of Tests for Predicting Mine Waste Drainage pH," Lapakko, K.A., 1992., pp. 22-30. Other factors contributing to NP overestimation are also discussed in this report.

This problem can be partially addressed by using an endpoint greater than or equal to the desired drainage pH for the "downward" titration (that is, the addition of acid to the mine waste sample as opposed to the back titration.) Information on the mine waste composition (e.g., mineralogy, petrology, particle size, etc.) will help compensate for the weakness in static testing. Quantification of the NP available above pH 6.0 is presently being examined in cooperative research between the U.S. Bureau of Mines and the Minnesota Department of Natural Resources.

Fiona Doyle (University of California at Berkeley) asked if current sulfide analysis is enforceable - and noted that total sulfur content is not a measure of acid production potential (i.e., non-pyritic sulfur does not contribute acid). She noted<sup>10</sup> that the Sobek  $\text{H}_2\text{O}_2$  method<sup>8</sup> is a better technique for pyrite testing, if careful testing procedures are followed (control of sample temperature during testing is critical). Temperature rises from the exothermic reaction as pyritic sulfur is oxidized. She suggested that the test may be more reliable if excess peroxide is used.

- Patricia Erickson stated that the accuracy of the standard sulfur analysis or speciation was an important factor, noting QA/QC problems from several projects. Pyritic-sulfur analysis using peroxide is not common; sulfur analysis is the standard. She cited a round-robin study in which a single material was found to contain 0.3 to 1.3 percent sulfur, NP of 0.1 to 2.5 tons  $\text{CaCO}_3$ /1000 tons, and a net NP of -30 to +14 tons  $\text{CaCO}_3$ /1000 tons. This has to be considered in methods development.

Frank Caruccio suggested that the analysis of pyritic sulfur could also be performed through the digestion of a pulverized sample in a 2N nitric acid solution, bringing the solution to a constant volume, and determining the iron concentration of the solution that is stoichiometrically related to the iron disulfide concentration. Prior to digestion, the sample is stripped of non-pyritic iron with dilute hydrochloric acid. This technique circumvents the necessity of partitioning of sulfur species and makes pyritic sulfur determinations more direct.

William White [U.S. Bureau of Mines (BOM)] noted that their analysis of the Sobek NP test method<sup>f</sup> yielded "crazy" numbers. Samples were screened to <60 mesh, HCl digested, titrated with base, and boiled; the analysis had a standard deviation of 12 to 13 units. A modified method with agitation for 24 hours instead of boiling gave lower standard deviation numbers. They got different NPs depending on endpoint pH (e.g., 14 for pH 6, >95 for pH 3.5). BOM assessed the neutralization potential of four different sizes of the same sample, using both a modified and regular Sobek method<sup>g</sup>, and a modified version of the BC Research Initial Test. All lines crossed at about pH 6, with a NP of about 15. His conclusion was that NP was a function of particle size. When asked what test should be used, White answered that the Bureau uses all three. The BOM is currently assessing particle size in tests and will report on their findings.

Keith Ferguson noted that static tests are not precise for determining the amount of acid production, and that the NP is not a precise measure of consumption. These should be considered as indicator tests. The key is to understand how static tests compare with kinetic tests, and more importantly, how they compare with field tests. In the absence of something better, Sobek<sup>g</sup> is the method of choice. If nothing else, it is used extensively and, therefore, has a large database which allows for comparisons. William White cautioned against boiling because it may be a source of variability. Kim Lapakko observed that the pH required for drainage must be considered when determining NP. If a drainage pH of 6.0 is desired, the NP available to maintain this pH must be quantified. Quantifying the NP available to maintain a pH of 3.5 may yield an upper bound for the NP available to maintain a drainage pH of 6.0, but this upper bound may be considerably higher than the value of concern. Consequently, it is more useful to quantify the NP available to maintain a drainage pH of 6.0 directly.

Frank Caruccio stated that temperature plays a critical role in the dissolution of  $\text{CaCO}_3$ . Thus, whole rock analyses that include boiling or heating the samples may selectively dissolve the carbonates, isolating the acid component (pyrite) from further interactions, and modifying the chemical weathering attributes of the sample. One common problem in analyzing samples containing siderite ( $\text{FeCO}_3$ ) is a masking affect that this mineral has on the true NP value of the sample. Through the acid digestion of the sample, in preparation for the NP analysis, siderite is consumed by the acid and registers as an NP component, when in fact under natural conditions it is a neutral reactor. A modified NP analysis that includes hydrogen peroxide addition to complete the ferrous oxidation has been proposed. In addition, within the coal mining sector, it has been proposed that the 31.25 conversion factor for the  $\text{CaCO}_3$  equivalent to the acid derived from the pyritic sulfur content be changed to 62.5 to accommodate, in part, the siderite masking and to adjust alkalinity equivalents from limestone dissolution. (The 31.25 conversion factor is based on the assumption that each molecule of carbonate can neutralize two  $\text{H}^+$  ions, and the 62.5 conversion factor is based on neutralization of one  $\text{H}^+$  ion per carbonate.) Under natural conditions, the coal-associated strata with NP values in excess of 20 tons  $\text{CaCO}_3$  equivalents/1000 tons are generally non-acid generating. The pH of drainage from these strata commonly is around 6 to 6.5, which effectively precludes bacterial intervention and retards the acid producing reactions.

Linda Broughton believes static and kinetic tests should be tied together - a definition of static test is needed. Kim Lapakko agreed with Linda that static and kinetic test results can be more useful if considered jointly. Both the availability and the dissolution kinetics of NP can influence the accuracy of static tests. Static tests assume all NP is available for reaction and will react fast enough to neutralize acid present in drainage that contacts the neutralizing minerals. Thus there are assumptions on both the availability of NP and the rate of its neutralization. Fine grained calcium carbonate and magnesium carbonate minerals dissolve rapidly, and therefore determining the availability of these minerals would be of greater benefit than the rate of reaction (which is known). Larger particles are less effective, although they will neutralize to some degree. Quantifying this degree will similarly be beneficial in assessing the true NP of a waste.

In contrast, calcium feldspar minerals dissolve more slowly, and the rate at which they neutralize acid within the mine waste disposal unit may be more important than knowing their availability. For example, Duluth Complex rock contains over 50% calcium feldspar, which is highly available. However, the calcium feldspar dissolution rate is very slow, and this slow rate of dissolution (as opposed to calcium feldspar availability) limits its neutralization.

Frank Caruccio stated that acid-base-accounting analysis (ABA) is applicable to soils, but was developed for assessing suitability of coal-mine sites for revegetation, not for estimation of water quality.

Richard Humphreys stated that regulators were concerned with the confidence interval boundary, and did not deal with changes in particle size. Tom Hinnners asked Richard Humphreys if static tests were most appropriately used for tailings. Richard Humphreys said he thinks static testing is useful for tailings but not for waste rock. Keith Ferguson responded that NP is inherently variable. He recommended that initial sampling tests be used to establish potential to generate acid. If there is no potential acid generation, there should be no concern. He also noted that, from his experience, siderite was rarely a problem in metal mines. With respect to the ratio of neutralization potential to acid generation potential, he thought 3:1 was high and recommended 2:1 (based on theoretical considerations) be used as an initial screening of ABA data for waste rock. If a conversion factor (percent sulfur to  $\text{CaCO}_3$  equivalent) of 62.5 tons per 1000 tons of waste (at 1 percent sulfur content) were selected, the ratio would be 2:1. He noted that these ratios apply to samples, not to waste units.

Steve Hoffman reviewed the factors affecting the variability of static tests, and identified temperature control during testing (boiling versus agitation); particle size; and petrology.

William White added that variability can occur as a result of:

- Reproducibility of the test method (e.g., whether samples are boiled or agitated)
- Particle size
- pH (values of 6, 5, and 3.5, for example, can give different results)
- The amounts of total sulfur, sulfide sulfur, and sulfate sulfur. If barite ( $\text{BaSO}_4$ ) and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), which do not generate acid, are present in the sample and total sulfur analysis is used, the acid generating potential will be over-estimated because the sulfur in these minerals is non-reactive.

Frank Caruccio added that cations should be added to this list noting that calcium and magnesium, in particular, affect the leachate quality. He also suggested that pyritic-sulfur analyses using the nitric acid digestion be considered as an alternative to the conventional methods to resolve the sulfur speciation problem. Instead of using the furnace method for sulfur, he measures iron in  $\text{HNO}_3$  digests of material pulverized to a particle size  $\leq 63 \mu\text{m}$ . Linda Broughton stated that sulfur speciation is not warranted at total sulfur values below 1 percent.

## KINETIC TESTING

Tom Hinners introduced the topic of kinetic testing and asked the panel for recommendations on methods. He noted that Kim Lapakko was reviewing kinetic methods for the Western Governors' Association. Frank Caruccio commented that since 1978 there have been several breakthroughs concerning the Sobek kinetic method.<sup>8</sup> These updates should be incorporated, and a modified method should be issued. A manual<sup>9</sup> of procedures and recommendations prepared by Rick Lawrence could serve this purpose.

Linda Broughton asked Mr. Lapakko the following questions:

- Was the purpose to predict field water quality or acid generation potential?
- What are the flushing rates for the samples?
- What was the particle size used?

Kim Lapakko stated that the WGA study examined the capability of such tests to predict whether a mine waste would produce acid. The ability of a test to describe field drainage quality in greater detail was not addressed. The influence of flushing rates in predictive testing was not specifically addressed, although flushing rates did vary in the tests examined. Other design parameters also varied among the tests; consequently, a rigorous analysis of the effect of flushing rate was not conducted. Particle size varied as a function of the protocol prescribed in the predictive tests examined.

Richard Humphreys stated that kinetic testing was the "black art" of geochemistry, and that interpreting long-term data is a difficult task. From a regulatory perspective, this is compounded by the fact that permit writers may not be geologists. Also, for mitigation, one can manage acid-generating waste or change the characteristics of the waste so that it does not require management.

Andrew Robertson stated that SRK had examined the issue of kinetic testing. He felt that a humidity cell had no relevance for waste rock; however, it does have yes/no potential if run long enough. It is not reasonable for water quality measures. Humidity cell tests also tend to flush everything out. By contrast, in the real world (waste rock pile) what comes out may be only a small portion of what is actually generated. Both the fine and coarse fraction are important; SRK uses four-inch diameter material to represent the large fraction, with sample sizes ranging from 25 to 50 kilograms. Column sizes are greater than or equal to 15 inches in diameter, greater than or equal to 18 inches high, and may be stacked.

He noted that time and how the sample is treated are important to consider. For example, crushing may release alkalinity and inhibit Thiobacillus. Other procedures such as the initial flush are important; trickle vs. flush vs. field conditions must simulate field conditions as closely as possible. The low levels of flow in the field are difficult to mimic in the lab. In laboratories, more water may be added, which reduces storage time/retention. The time required for reactions to occur in lab settings is often too slow so samples may be inoculated or spiked with bacteria to accelerate; it is necessary to compare spiked and unspiked samples. He explained the value of field tests (e.g., piles) to predict field behavior. He emphasized that tests must simulate field disposal conditions.



Frank Caruccio offered two reasons for using crushed samples; first, if the sample is a composite of heterogeneous strata, mechanically riffing splits for analysis will be more representative of the whole the finer the samples are crushed. At his laboratory it has been found that crushing samples to pass 4-mm pores provides both adequate drainage from weathering cells as well as suitability for riffing. Second, within a waste-rock backfill the rapid, acid-forming reactions are produced by the smaller material (generally the relationship is asymptotic peaking rapidly for the material at around 4 to 6 inches in diameter). Thus, the smaller-size fraction enhances chemical weathering processes, yet, at the same time, more closely simulates field conditions.

Keith Ferguson reviewed quantitative vs. qualitative prediction of drainage, stating that qualitative prediction is easier but still difficult. Factors include sample selection, the numbers of samples, analytical procedures, and time. However, he questioned whether the quality of the drainage could be predicted in the laboratory at the present time. Quantitative factors include temperature, particle size, and flushing rates.

Steve Hoffman asked if there was some reasonable way to deal with water balance issues. Andrew Robertson said there was and referred to landfill work to determine infiltration rates (HELP model). This gives a first estimate of infiltration rates, budgets through dumps (including measuring). But, in the laboratory, to mimic low precipitation (<30 inches), flushing is necessary. Keith Ferguson identified some factors to consider: flush in terms of volumes and loadings, acid production during dry periods followed by flush during snow melt (e.g., Equity Mine) or storm events, and length of dry period.

Steve Hoffman asked how a regulatory agency could deal with the unpredictable nature of acid generation given these observations. Keith Ferguson correlates results from the static and kinetic tests, and examines mineralogy. This requires a good database of kinetic tests.

Kim Lapakko summarized a test plot study started by the Amax Mining Company and carried on by the State of Minnesota.

- In 1977 the company set up a series of six test piles composed of waste rock of Duluth Complex material (1,000 tons each) with varying sulfide content. There has been long-term monitoring by the State to assess the quality and quantity of drainage, as well as other questions. The data increased the State's confidence in prediction. To date, 15 years of data have been collected.
- They have obtained "fairly good" information on what the critical sulfur content is in the Duluth Complex material. He emphasized that the numbers themselves cannot be extrapolated to other situations; however, the State has good information on the Complex in the event that another firm begins operation.
- They are able to correlate laboratory test results with field results fairly well. Lab data that agree with field data makes the State more comfortable with laboratory efforts.
- The laboratory took into account the usage of reduced particle sizes when making predictions. They also took one pile apart to characterize particle size; this allowed for a comparison of sulfide surface area between laboratory and field material.

Gene Farmer observed that many mines will be permitted even though the mine's acid generation potential is unknown. When there is doubt, "we want these kinds of long-term (>3 years) testing programs." Regulators and miners finally agree that long-term testing programs are necessary, so that the State knows when it releases the bond whether there will be acid generation.

Steve Hoffman stated that the EPA must consider what materials will be exposed, not necessarily all materials (some of which may be capped, etc.). It must be recognized, however, that over time, these caps can fail. While monitoring is important, reliance on ground and surface water monitoring can only identify already-existing problems. Thus, field validation of kinetic tests is important. He observed that there is much variation in results using humidity cells among laboratories; what is needed is a preferred method for comparing field tests and laboratory results.

William White stated that the Bureau of Mines and the American Society for Testing and Materials (ASTM) are looking at a standard method for accelerated weathering (kinetic testing). An ASTM committee will put forth a draft recommendation at the October 1992 ASTM meeting in Miami, Florida, for distribution to ASTM members using humidity cells. So, there is some movement toward standardization.

Andrew Robertson explained that there are two reasons for kinetic tests beyond the "yes/no" question of acid generation. Kinetic tests examine material properties but if the concern is prediction in field, system properties are of increasing concern. Examining how "system" tests vary from "materials" tests is of value.

Richard Hammack (U.S. Bureau of Mines) discussed an evolved gas analysis (EGA) technique that may incorporate aspects of both static and kinetic test methods. It gives an idea of the reactivity of pyrite (kinetic aspect) and gives carbonate and sulfur (sulfate and sulfide sulfur) content (static aspect). This technique involves crushing the material, heating it gradually in a furnace while passing 10 percent oxygen and 90 percent nitrogen gas over the sample, and determining at what temperatures  $\text{CO}_2$  and  $\text{SO}_2$  are lost (similar to LECO Corporation method for sulfur). This technique allows for discrimination between sulfide and sulfate sulfur, which helps in acid-base accounting. It can also discriminate between how much calcite and dolomite are in the sample (carbonates that contribute to NP). If both marcasite and pyrite are in the material, however, this can confound the results. Their laboratory abandoned the EGA approach because of instrumental problems (using a mass spectrometer with a capillary tube presented problems with low ranges of sulfur values). Now, there are commercially available instruments that do not have this original problem.

Steve Hoffman asked if this method was currently in use by anyone present. Richard Hammack noted that Penn State was going to take over the BOM's work in this area. Mr. Hoffman asked if it needed to be examined as a possible technique, and Mr. Hammack noted that the instrument cost was about \$20,000 (compared to \$30,000 for a LECO Sulfur Analyzer). A new system, considered top-of-the-line, runs about \$80,000 (Bomem Inc., Maarssen, The Netherlands). It is not based on mass spectrometry, but uses Fourier transform infrared spectroscopy. BOM work was on coal mines; tests on metal mine waste samples in conjunction with a study by Richard Lawrence have not been completed.

Tom Hinnert raised the question: if kinetic testing does not predict acid generation, how are results to be interpreted and extrapolated? He noted that one approach is to determine how fast neutralizing material is being consumed. Keith Ferguson summarized a paper presented in 1991 by Kevin Moran and himself in Montréal.<sup>1</sup> They looked at 200 kinetic data sets from 25 to 30 mine sites; relatively few have produced acid drainage from the initial neutral condition (roughly 75 percent have remained alkaline during the 10 to 20 weeks, or longer, of testing). Twenty percent were acidic from the beginning, 15 tests went from neutral to acidic (pH 1). They plotted NP:AP ratios vs. time to acid production and roughly fitted a curve to the plot. The equation provided a rough idea before testing whether there was any expectation of a sample generating acid. The curve showed that the NP:AP values had to be less than 0.3 or 0.5 for there to be a chance for acid generation within 20 weeks. He noted this was strictly for standard kinetic laboratory tests (7 days: 3 days dry air, 3 days wet air, and on the 7th day rinse the test material with water).

Steve Hoffman asked what the policy implications of these results were. Keith Ferguson stated that if the criteria to decide if a sample is going to go acid is based on a kinetic test that generated acid, the NP:AP should be less than 0.3; if it is 0.3 or higher, extrapolation may be required. There is a problem in extrapolation: available sulfur and carbonate versus the total amounts. A test is needed to show how much carbonate and sulfide is available on the surface of particles. One promising test<sup>2</sup> is the Net Acid Generation (NAG) method using hydrogen peroxide to oxidize the reactive sulfides before titration to pH 7. If a reliable test of net acidity were available and a line could be drawn from the kinetic tests of the rates, then it should be possible to predict the time the waste drainage is likely to go acid. There is a proposal from Australia (Stuart Miller) for a research program (\$200,000) that should begin in the next 2-3 months; the results would allow quantitative assessment of this method. This is also part of the Canadian Mine Environment Neutral Drainage (MEND) program. With a low NP:AP ratio (high sulfur and low carbonate), then it is worthwhile to conduct a kinetic test as it should give a fairly definitive answer (i.e., pH drops from 7 to 3.5), and then one can measure the metals in the extract. With samples having an NP of about 50, there is a long lag period, and this makes interpretation difficult.

Frank Caruccio noted that the chemistry of the ore processing fluid in copper mines in Arizona had a dominating affect on the leachate quality and on the chemical behavior of the tailings samples. Although the whole rock analyses showed samples to have high concentrations of pyrite and low NP (projected to be high acid producers), the leaching tests consistently produced alkaline leachates. Several samples that were leached for over one-and-a-half years did not produce acidity. Samples "as received" when bathed in dilute HCl were rendered acidic. It is therefore important to factor in the effects of the carrier fluid of tailings when making determinations of leachate qualities.

Andrew Robertson stated that non-acid kinetic testing should remain part of the water quality testing procedure; these tests offer other results that are helpful in understanding impacts. As an example, he cited a mine in British Columbia with a drainage pH of 8.4 where there is molybdenum dissolution as a result of the sulfides oxidizing (alkali leaching). Also, he indicated that examining ("cutting into") existing dumps may show they are not currently acid-generating, but it can provide an idea of conditions and possibly identify a "trigger" point. He suggested adding the trigger point to kinetic tests, but expressed concern for biasing the test.

Keith Ferguson felt that we are approaching the stage where for many samples it is possible to predict whether they will go acid on the basis of static, kinetic, petrography, EGA, and other data. The next stage, mixing samples of different acid generating character, will be much more difficult to evaluate. Predicting behavior of different (or mixed) rock types is even more complex than for single types (e.g., mixing samples: acid-generating and acid-consuming layers). The complex reactions of flushing, coating formation, relative reactivities, and the biological factors expressed by Andrew Robertson are critical. Determining how to blend and establishing the stacking sequence are goals that are difficult to achieve. Laboratory tests are being set up with stacked column designs. A mathematical model will help, but for now an empirical approach will do. Using a 1976 coal mine data set of 20 mines (they are reluctantly using weighted acid-base accounts), they found that if the weighted NP:AP ratio is  $\geq 2.5$ , it appears that these mines have not generated acid. These results are tenuous, but are the best available at this time.

Richard Humphreys noted that in California waste segregation is being tried at one site. Pre-mine testing concluded that the waste was not acid-generating, but there was an acid-generation problem. The pile has been re-engineered to allow encapsulation. Test plot work on an encapsulation technique would have increased the state's confidence in the practice.

Keith Ferguson observed that notwithstanding all the uncertainty, there are many sites (about 50 percent) that can be predicted accurately. The other 50 percent are the concern. One must conservatively assume such units will generate acid. For such wastes Canada uses aqueous disposal in tailings impoundments, other water bodies, or saturated covers. If segregation or blending is to be used, some sort of blending test may be the only recourse. Even in clear-cut "benign" cases, there has to be continued awareness (e.g., watch for increasing sulfides in the rock wastes if there is low carbonate content).

Linda Broughton said they were trying to characterize the drainage water quality at the toe of waste dumps and to compare it with laboratory data. They found that fresh samples from the dumps were not available, and information on the material was not available. She asked for data on old dumps.

Richard Humphreys indicated that establishing test plots before a mine is developed is problematic. At an existing mine, the mine serves as the plot. They are trying to encapsulate to mitigate acid drainage problems. Kim Lapakko's experience with the Duluth Complex was unique, but offered a valuable tool to study the waste problem. The issue is who will be interested in the study over the long term. Andrew Robertson observed that there is much more to be learned from existing waste piles rather than from small test piles. These are full-size piles with all the reactions occurring under the actual field conditions. It is fairly easy to sample waste piles, to conduct paste pH tests, and to analyze the pore water. This allows one to characterize where in the waste pile acid generation is taking place before there is any sign of acid drainage in the toe discharge from the waste pile. Sampling with the Becker Hammer Drill (air is the flushing medium) works well. It does cause some crushing and does liberate a certain amount of the alkali. But it is cheaper than column tests.

Gene Farmer asked how deep sampling was conducted in the waste dump, and if it was below the point of oxidation. Andrew Robertson noted that oxidation penetrates very deeply. Coarse material below creates a chimney effect and pulls oxygen in. As an example, in low-grade stockpiles, oxidation is seen throughout.

Michael Smith asked about humidity cell tests and what variables should be considered in assessing why or whether it went acid (e.g., sulfate production, alkalinity, acidity, pH, and iron). Keith Ferguson reviewed kinetic tests and indicated that he uses them to validate static test results. For each kinetic test, the sample is studied for petrography, the sulfide mix, morphology, grain size, and the spatial position of the sulfides and carbonates. Sulfate production rates are compared with values in a database to determine what percentile it is.

Linda Broughton agreed on the importance of sulfate production versus alkalinity consumption (mineralogy is important). Extrapolating to the long term requires discriminating among carbonates/acid neutralizers and buffering due to silicates. The two relative rates and the near-neutral drainage water quality are critical to determining if there is or will be a problem. Zinc was found to be good indicator, and aluminum was also useful as a "clue" in prediction. Keith Ferguson gave an example where static testing showed the sample was an acid producer, and kinetic tests said it was not. They simply had to make conservative decisions, which included monitoring.

Frank Caruccio stated that humidity cell leachate data could be normalized to adjust the variations in weight and pyrite contents to a common base. The adjusted data can then be plotted on a cumulative acid (or sulfate, metals, etc.) versus time graph, the slopes of which reflect the kinetics of the sample's reactivity and allows comparison between samples. In so doing, samples can be ranked as strongly acid producing, moderate, and weakly acidic. In his work, involving hundreds of samples leached in humidity cells, he was able to divide the samples into four groups based on cumulative acid production versus time for a given time frame and percentage pyrite by weight; 2 mg/L, 20 mg/L, 200 mg/L, and 2000 mg/L acid produced as calcium carbonate equivalents.

This is significant because samples in the first two groups can be treated *in situ* with limestone additions, which normally generate 65 mg/L alkalinity (as calcium carbonate) and provides for adequate neutralization and buffering capacity.

Keith Ferguson noted that it is very important to check with the geologist who has a good idea of the variability, because only minute portions of the waste can be tested. There should be an initial geological model, initial acid-base accounting, and possibly block modeling, check benches, etc. The degree of rigor of testing depends on the variability. Steve Hoffman asked if prescriptive standards were possible. Keith Ferguson recommended that even in "benign" cases (about 50 percent of mines are easy calls) there should be some continuation of testing.

Tom Hinners asked about contaminants that may be released, even if the drainage is not acidic. He identified work conducted by Richard Doecker (BOM) with leaching tests, and pointed out that Andrew Robertson expressed the opinion that humidity cell tests were not suitable for determining drainage-water quality. Richard Doecker (Bureau of Mines, Spokane, WA) stated that he is currently conducting column leaching. He has looked at 30 to 40 different tailings to determine acid generation and metal release, and the parameters that affect this process. He cautioned that a major concern was equating acid formation and metals release. He has analyzed many samples that show high metals release but no acid. Thus, water quality and metals must be addressed as well as acid generation.

He noted that columns do allow metal mobilities to be studied and, if designed and constructed well, acid formation. However, he emphasized the limitations of columns; they are slow, particularly if they are correlated to field conditions; if the column is shallow, it can have strong wet-dry cycles and cause changes in pH or metal loads as a result of oxidation of sulfides. Field variability is reflected in columns: CO<sub>2</sub> pockets, flow changes, etc. They are not predictive per se, but long-term studies can provide a lot of information. In their studies, mineralogy information is often not available and tailings are hard to characterize, but they can infer from chemical analysis of leachates.

They made no attempt to simulate field conditions; instead, they are looking at how different parameters affect rates of dissolution (how temperature changes oxidation, how pH changes leachates, ionic strength effects, etc.). Most of this work is nearing completion, and they know most of what they can know from simple columns. They are now looking at specific mineral dissolution (besides the obvious pyrite). How different sulfide minerals behave and how removal of these sulfides from the waste stream before reaching tailings can affect later behavior (i.e., what are the problem sulfides, and whether they can be removed). With this work they do some blending (pyrite, galena, sphalerite, etc.) to determine the effect on total dissolution for comparative, not predictive, purposes.

George Watzlaf (U.S. Bureau of Mines) is looking at coal pyrite and the factors influencing pyrite oxidation. He noted that there has to be a distinction between leaching tests as "yes/no" statements of acid generation potential and column leaching tests used to characterize field conditions. He was skeptical that any column test could do that and referenced Keith Ferguson's comment that a factor of two was described as "good."

Linda Broughton presented a discussion of the SRK papers (cited above by Andrew Robertson). These reports consider the stages in acid generation. These reports include results from spiked and inoculated humidity cells using phyllite composite. At the start of a test, there is often a peak from the flushing of stored products or of oxidation products. A second peak may occur following a flush if conditions of acid generation and contaminant leaching recur.

Frank Caruccio agreed that this dual peak for acid production is common to samples that have undergone some weathering and have stored acid salts. Based on the results of numerous cell tests, the dual peak was never found with fresh samples collected directly from the cores.

George Watzlaf added that pore-volume replacements take more time. In trying to predict water quality, it may be necessary to flood the sample to determine total production. In this type of column test, however, it is best to try not to flood, but to allow flow patterns to be established. Generally, higher concentrations are seen during higher flow events. Columns were examined following the tests to look at flow paths,  $\text{Fe}(\text{OH})_3$  stains, and coating on sulfide minerals. The coal column cells held 15 kilograms and were 12 inches in diameter. There were differences between flow paths (in precipitation, coating, etc.) within the column (smaller-size columns may be more uniform even if they are trickled rather than flooded). In some cases, it may be appropriate to flood to get total release and oxidation rates. Also, comparing flood and non-flood tests can be useful.

Steve Hoffman asked about the effect of freeze/thaw cycles. George Watzlaf noted there are differential temperatures in and out of a pile, and indicated there is no right answer on how to deal with that. Some research on the effects of temperature seems to affect timing but not the end result. With freeze-thaw, it is more complex. Some parallel tests (one at 4 °C.) have shown effects on bacteria.

Steve Hoffman asked if anyone was looking at movement of oxygen through tight rock (and referenced Ben Ross' Yucca Mountain work for the Department of Energy). Keith Ferguson has considered it. He indicated that this work deals only with convective flow and does not link oxidation with gas transport and identified more advanced Australian work on gas transport in rock. Diffusive and convective gas transport are linked, but geochemistry of the drainages are not available. The MEND program is examining this. It may be possible to use this in a comprehensive waste rock model (by linking this gas transport with hydrological and geochemical components). They are trying to begin a 3- to 4- year, \$1,500,000 project.

George Watzlaf said there were restrictions on tailings in kinetic cells [e.g., the amount of water retention (which leads to saturation), cracking and edge effects for the test sample, and the fact that (if there is much sulfur present) gypsum saturation can occur]. Richard Doepker agreed, saying columns have an advantage (for tailings) even though there are some problems with shrinkage and channeling. Generally, this is overcome during cycles. For one pore-volume, 5 percent is lost within the sample if near-saturation conditions are maintained; for dry cycles, add excess water to obtain one pore-volume to give good flush-out. Waste rock presents major problems. The question is the objective of the test sequence. The WGA article by Kim Lapakko addresses a lot of the shortcomings. Overall, Mr. Doepker did not feel humidity cells worked with tailings.

Frank Caruccio reported on a recent study<sup>2</sup> conducted with tailings samples provided by the MEND program. In this study, samples of a common size (hence the surface area variations were minimized) were tested using whole rock analysis, column tests, humidity cell tests, and Soxhlet extractors to determine which testing procedure best approached the drainage quality of the areas from which the samples were collected. The sample mass was about 360 g, and the samples were flushed on a weekly basis with about one pore volume of deionized water. Of all the methods used, only the humidity cell tests produced a leachate quality similar to that observed in the field. Examination of the columns showed that the fine texture of the tailings inhibited free drainage and some of the samples became air locked, thereby inhibiting the oxidation process and production of acid. In these columns, the sulfate contents were well below the gypsum saturation, and the low sulfate contents can only be ascribed to lack of pyrite oxidation. The Soxhlet extractor tests, because of the high temperature of the leaching solution, selectively dissolved the carbonates, and converted all samples to high pyrite/low NP qualities, destroying the integrity of the samples. In this study it was concluded that of all the testing methods used, the humidity cell test was the most accurate.

Richard Doecker reported that 9- to 11-inch columns for waste tailings are the maximum if you want a good wet/dry cycle. He suggested common particle size and chemistry were critical. In their study, acid-base accounting predicted acid generation correctly for 7 of 11 materials. In dry cycles, there was oxidation on side surfaces, but when wet it sealed nicely. Steve Hoffman asked if compaction rates were simulated when columns were packed. Richard Doecker indicated that the columns are packed dry, and four columns are prepared to evaluate repeatability. Generally, good agreement is achieved among the replicate columns. He noted that things get confusing when secondary oxidation begins. They tried slurry packing, and he emphasized that they do not try to simulate field conditions, except for *in-situ* samples.

## COMMENTS AND QUESTIONS FROM THE AUDIENCE

Gene Farmer asked about closing a tailings pond: what is the relationship between vertical and horizontal transmissivity through the tailings? Andrew Robertson stated that transmissivity varies depending on placement of material, but that vertical transmissivity is typically 0.1 of horizontal transmissivity. He indicated that horizontal permeability is seldom less than 5 times the vertical permeability. Richard Humphreys noted that tailings impoundments begin to behave like waste rock piles when dewatering; the surface starts to crack. If there are lenses, the unit may need to be treated like waste rock. Keith Ferguson described some work with silt and sand layers that had been done at the Westmin minesite. They sampled sand under the silt layer and found that where there was a continuous silt layer, there were high pH values near 7. Because silt holds water, it prevents oxygen migration. Conversely, sand does not hold water, and oxygen penetrates easily. Near cracks in the silt layer, there were low pH values near 3. The cracks served as conduits for oxygen when the silt barrier was broken.

Glenn Miller asked if it is a common practice to inoculate humidity cells with *Thiobacillus* bacteria. Keith Ferguson indicated that it is generally not necessary but it depends on what is being investigated. If the interest is in low pH, inoculation is necessary. For neutral pH and higher, the role of bacteria is unclear. If the cell is expected to be alkaline, inoculation is unnecessary. Also, how to add bacteria to alkaline cell adds procedural complexity. Still, bacteria may be present in site micro-environments. Frank Caruccio noted that regulatory agencies require inoculation, but he has found that samples contain abundant bacteria naturally. Generally, the introduction of the iron bacteria is through the addition of 1 mL of culture medium (the medium serves as the host vehicle). In so doing, the leachate chemistry is impacted by the addition of 8 mg of acidity, 20 mg of sulfate, and a difference in specific conductance of about 250  $\mu$ S, in a solution with a pH of 1.7. These affects should be factored out from the quality of the leachate collected following inoculation. Richard Humphreys offered that there is no control on the strain of bacteria used in inoculation tests. Andrew Robertson stated that as pH changes, strain changes, but some bacteria are always present in samples. Some strains operate more effectively in different pH ranges.

John Woodward (Nerco Minerals Company) gave the following scenario for Nerco's new operations: (1) exploration drilling; (2) if drilling yields promising information for mining, start doing geological inspections on cuttings to determine whether oxide or sulfide type mineral; (3) also examine previously mined material. Based on these tests, the alternatives are:

- If oxide mineral, they consider the material not to be acid-forming.
- If sulfide mineral, conduct static tests, with three alternatives depending upon NP:AP ratio (<1:1, consider acid-generating material; >1:1 but <3:1, conduct kinetic testing; >3:1 consider non-acid generating material).
- Look at previously mined material. If it is acid producing, no more testing necessary. If it is non-acid generating, conduct kinetic testing.

Gene Farmer gave a regulator's perspective. He noted that kinetic tests cost from \$1,500 and up per sample, and there may be thousands of samples required. Thus, an option is to do real-time sampling during operation and set triggers with regulators. For example, a mine could sample initially at about one sample per 20,000 tons until variability can be assessed. Then, the results can be correlated to determine the need for more tests. Over the life of a mine, its acid generation problem can be assessed, and this can give an operator alternatives. Although there is a need to know before operations begin, often it is not realistic to expect to know before permitting. As a result, real-time sampling/testing is necessary so that problems can be identified.

## ACID PREDICTION AND MINE PLANNING

Linda Broughton summarized a report<sup>9</sup> prepared for the office of Saskatchewan Environment and Public Safety on evaluating the potential for acid generation and metal leaching. The figure in Appendix C outlines an approach to evaluating the potential for acid generation and metal leaching. The approach is presented in 3 stages:

- Stage 1:       Geology and mineralogy: discussions with geologist, rock classification, representative sampling in consultation with geologists, preliminary static testing and geochemical analyses. All this serves to define the level of concern.
- Stage 2:       Static testing, preliminary design and controls: Integrate geological and geographical information; define geological units from an environmental (as well as from an ore and operational) perspective; develop preliminary mine rock management plan (e.g., identifying when in the mine's life acid generating rock will be mined); sample each defined unit; perform range of static testing; evaluate results and classify rocks; determine if potentially acid generating or leaching. This step allows the development of a preliminary control plan.
- Stage 3:       Kinetic testing, detailed rock/waste management plans: Select samples for kinetic testing to define rates of acid generation and leaching; conduct kinetic testing; use results to guide the design of controls for drainage water quality; conduct more tests if necessary; perform environmental impact assessment (extrapolation modeling); and develop the final rock management plan. Stage 3 may be more flexible. Objectives must be defined at the beginning of the stage—it may be necessary to take steps to better understand variability (block modeling, mineralogy studies, field or laboratory kinetic programs, etc.) rather than simply progressing through the steps. Block modeling may be added at the water quality modeling stage. As for the accuracy of the final stage, more and more certainty and more quantitative data on water quality loadings are being required by regulatory agencies, but it must be recognized that uncertainty remains. Regardless of uncertainty, however, there must be prediction of at least a reasonable range of "hard numbers" to meet specific standards.

Ms. Broughton noted that following these stages, an operation would proceed with approval, operation, and monitoring. It should be noted that this may not necessarily be a linear process. There can, and should, be various loops, especially as one step identifies the need for more information. In British Columbia, operations must have a closure plan before commencing operation, which makes these steps necessary. Also, from a company's point of view, the long-term environmental liabilities have led to the recognition that these stages are necessary.

She presented the table in Appendix D on identifying sources of information and samples.



**Keith Ferguson** commented that there was a need to study mineral controls before deciding on field or laboratory tests and on a detailed acid-base-accounting program. He noted the need to make the model more holistic to account for more factors.

**Andrew Robertson** stated that the three-stage process was demonstrated "technology." He clarified that static tests conducted in Stage II could include more than ABA testing. He also noted that where there is a receiving-water standard, the standard must be modeled. Wherever there is a risk of environmental problems, they must be mitigatable by existing technology. Requirements are making their way down to the level of the Canadian provinces. By mine closure, operations are required to have 100 percent bonding to cover closure (reclamation) and long-term maintenance; bonding is incremental and by the mine's life or 10 years, whichever is lesser, it should be fully bonded.

**Kim Lapakko** mentioned that it is possible to determine the maximum potential of a mine waste to produce acid (by analysis for acid-producing sulfur species) and the maximum potential for the waste to neutralize acid (by analysis for calcium carbonate and magnesium carbonate and/or direct titration of a sample, although the second technique requires verification). If a mining company designs a mitigation scheme that assumes "worst case" water quality for its mine waste, these detailed analyses become academic as does the frequency of sampling for representative wastes. In such a case the resources expended on a detailed mine waste characterization procedure would be better spent on mitigation.

**Gene Farmer** expressed a concern with the numbers of samples and statistical reliability. He emphasized the danger that one can produce data that are not reliable unless guidelines provide for statistical uncertainty. He noted that a sampling program over a mine's life is the only remedy for uncertainty. It can be simplified if, instead of a long list of activities, a block model were used with thousands of core samples. If the mine operators began thinking about sulfides and acid generation early, they could prevent problems.

**Patricia Erickson** noted that Miller and Murray in Australia conducted a comparison of net NP for 30 base- and precious-metal mines using four classifications. They could divide these mines into barren, acid, potentially acid, and not acid. The level that would not produce acid was set at 10 tons excess NP/1000 tons. The data were not convertible to ratios. She referred to Keith Ferguson's paper on tailings (NP:AP break point about 1.0) and Kim Lapakko's paper for tailings (break in pH at about 0.8 percent sulfur, specific to that particular rock).

**Keith Ferguson** described ABA data for waste rock from six dumps at three base-metal mines. Mean NNP and NP/AP were calculated for drill-hole samples from each of the six waste rock dumps. The break between acid and non-acid generation was at a mean NNP of 0 or at a mean NP/AP between 2:1 and 3.4:1. These values agree generally with data from the coal mining sector. He noted a case where some sections were acid generating and some were not, with problems occurring where acid-generating rocks were concentrated in one area.

**Richard Humphreys** asked Keith Ferguson about what sort of variance is found in the population ABAs for waste rock. **Keith Ferguson** noted that there was a fair amount of variance from site to site. For drilling of existing waste rock dumps, they divide the data into categories of NP:AP of <1, 1 to 2, and >2. For the base-metal dumps (cited above) that generated AMD, the vast majority of samples had an NP:AP <1. One dump [Island Copper (sic)] that is producing acid had about 50 percent of the samples with acid-predictive NP:AP <1.

**Richard Humphreys** said that in California, there are a couple of gold heap leach piles ready to be closed (about one million tons). The company did a drilling study to demonstrate that they would not generate acid. Statistics on sulfur content of 80 samples gave average of 2.5 percent with much variance. The NP:AP

ratios were all high. Steve Hoffman noted that various cyanide species may affect the geochemistry driving acidification. Thus, the application of knowledge to heap leaches may be risky.

Michael Smith discussed the use of standard cutoff (decision) values. He suspected that they were applicable to wet climate areas, but they may not be applicable to arid conditions. He would hesitate to use wet climate ratios in arid areas. He emphasized the need to look at old dumps in the west; some may have 20-30 percent sulfides but no acid generation. Thus, any sort of cutoff values should accommodate climatic conditions in the area; also, site-specific factors must be considered (e.g., a dump above a spring).

Keith Ferguson agreed that site-specific conditions are critical. In wet climates, they see a preferential stripping of carbonates, so in general they would want a higher NP:AP ratio as a safety factor. Thus, all the data are an initial screen before looking at the specific site and assessing site-specific data.

Kim Lapakko indicated that the waste rock type can also influence cutoff. The use of different analytic procedures also affects Acid Production Potential data results.

Linda Broughton, referring to the three-stage process, indicated that mine rock classification should be beyond the geologist's description of the drill core, to include factors important from the ARD view (e.g., do sulfides and carbonates occur in veins or disseminated). This information should be used in the sampling plan.

Richard Humphreys noted that permits may be based on faulty predictions; though based on science, this does not address problems when they develop.

Steve Hoffman noted that EPA is confronted with operational mines with existing piles. The mine operators may have had good intentions and may have conducted acid prediction tests, but it simply did not work out. A regulatory agency then is faced with a noncompliance situation; the ability to alter management practices is limited due to the volume of materials. The concern is that regulators cannot take action until there are violations, and by then it is too late. Richard Humphreys responded that, if he were a permit writer (and he is not), he would like to know about the uncertainty beforehand, during the permitting phase. One problem is that permit writers may not have expertise, and reports may not explain uncertainty well. Budgets and time are another issue. Gene Farmer responded that mines should not be permitted forever. If a Plan of Operations is approved, it should have trigger points and action limits built in. For example, the plan could provide for re-examination if sulfide or ABA hit certain limits. As an example, oxide heap-leach operations are finding it difficult to avoid sulfide zones (because there is gold there), thus making continuous examination necessary. In addition, the sulfide and oxide "zones" are actually a continuum, with transition zones. So, if a regulator pays attention and sets trigger points, the problem Steve Hoffman described may be avoided.

Patricia Erickson cautioned that using the terminology "acid mine drainage" or "acid rock drainage" tends to make us forget about sulfate and the metals that are dissolved by the acid. Part of the monitoring program on the flow chart should look at a range of indicator parameters (sulfate, calcium, etc.) in seeps as a forecast of future regulated-contaminant migration.

Keith Ferguson offered some advice concerning Steve Hoffman's points:

- The mining company (industry) is liable, so they must do the lion's share of work and planning. The government also has a responsibility.
- Both parties must be involved during planning, operation, and closure; and these steps should not be separated.

- Regulators must be involved in the process from beginning to end or not at all (cannot effectively enter midway in the process).
- There must be flexibility (by both parties) to address unpredicted or unpredictable conditions.

Andrew Robertson noted that this type of approach is being increasingly followed by Canadian provinces. For reference, see the Ontario legislation/guidelines for closure (*Rehabilitation of Mines, Guidelines for Proponents*, Ontario Ministry of Northern Development and Mines).

## IDENTIFICATION OF RESEARCH NEEDS

Tom Hinnners and Steve Hoffman requested panelists and audience participants to identify the research needs considered to be the most critical. They also asked about the appropriate role of EPA in conducting or assisting research.

Keith Ferguson noted that some research is currently underway in which there is long-term testing to characterize waste rock and the factors affecting acid generation. Key needs include:

- Waste rock model: Both a simple and a complex model are needed. The purpose of a MEND meeting in September 1992 in Toronto is to coordinate research on a complex model conducted on an international basis. A model should address climatic conditions, variability of samples, stacking, blending (i.e., factors that physical testing can not address).
- Available sulfur and NP: We can determine total sulfur and total NP, but we do not really know what is available under field conditions. If we knew that and the rates of acid and alkalinity release, we could extrapolate the timing of net acid production.
- Factors that control sulfur and NP depletion in the long term: Coating, slaking potential, preferential leaching. This, unfortunately, requires long-term tests, but would address some important complex relationships, particularly under neutral pH conditions.
- Cheaper methods to characterize samples for acid generation potential: Acid-base accounting is currently about \$50 per sample.
- Geostatistical and modeling approaches: Gold-reserves modeling is now common, and there are some models being started for acid drainage as well.
- Relation between mineralogy and reactivity: Factors include grain size, morphology, sulfide mix, the position of carbonates and sulfides. There are many tests, but the linkages are not known. Some projects under the MEND program are considering this issue.
- Climate: The effect of dry climate is a key in terms of acid production and migration in arid regions.
- Low-sulfur cutoff (decision) value: Is a value of 0.6 percent sulfur a reasonable minimum for concern about potential acid generation?
- Prediction techniques and sampling for underground mine walls: This is very poorly understood.

- Linkage of prediction to field conditions: Field data are critical, and there is a need for much more. A case study book based on more field plots and old dumps would be valuable.

Richard Humphreys indicated he would like to see some research directed at biological activity. The general assumption is that bacteria become important at pH 3.5 or below, but there is a need to understand the mechanism much better because it may be related to surface activity and the microenvironments.

Steve Hoffman summarized two major areas: EPA will soon request the WGA Mine Waste Task Force to identify possible research topics and laboratory research. Both areas need more industry involvement, and the Office of Solid Waste needs suggestions early in 1993. There are limited funds for mine waste research available through OSW, but OSW will continue to participate (along with the Bureau of Mines) in international conferences. Mr. Hoffman asked about the cost of a study for dumps.

Richard Humphreys indicated it can be fairly expensive, especially at abandoned mines (e.g., about \$500,000 for the Penn Mine). Where there are numerous dumps, it is complex and costly to characterize materials. Andrew Robertson gave a cost of around \$100,000 for an existing 3-million ton dump for outside trenching, drilling, lab testing, etc., for detailed ARD and water-quality predictions. Keith Ferguson indicated that for existing mine operations a comparison of field data with predictions from laboratory methods would cost about \$25,000 per site (using previously collected cores and existing geological and operating records).

Andrew Robertson: A site reconnaissance costs about \$10,000 for a 3.5-million ton dump (looking at geologic information, sampling the dump surface, and measuring paste pHs). Add on a small amount of ABA testing, and it will cost about \$15,000. Andrew Robertson added that we have discussed mainly prediction testing ahead of mining and the prediction of water quality associated using essentially uncontrolled testing. When we observe a problem, our thinking actually changes. We need to do the predictions under the controlled conditions to be installed (e.g., if covers are added, there are very low leach rates, so limited work on water quality may be necessary).

Also, we need research into various levels of pH control (blending, or adding finely crushed limestone) and testing at a controlled level of continued acid generation. As to Keith Ferguson's concern for test costs, there is a lot to do with kinetic testing. To control costs, one can cut out the dry cycle and put samples through a crude device. It should be possible to develop a standard, crude kinetic test.

In response to a question from Tom Hinners, Patricia Erickson described the use of the Finkelman peroxide test<sup>11</sup> where the rate of pH change (10-minute test) is monitored. They were not able to get correlation between sulfur content, NP, and peroxide results for coal samples. There may have been problems with the laboratory procedures because they did not precisely follow Finkelman's procedure. Testing on coal may be more complicated than hard rock due to the organic content. It may be possible to determine whether it should be pursued with metal mines.

Fiona Doyle described the use of peroxide with coal. They found excess acid production because peroxide was oxidizing coal and surface organic acids. It would not be reliable for coal, but might be for hard rock. Keith Ferguson indicated that there is currently Australian work<sup>12</sup> on the Net Acid Generation (NAG) test involving peroxide use. Placer Dome is finding good correlation between the NAG test and ABA at some mines and poor correlation at others.

Frank Caruccio described his work with peroxide oxidation coupled with leaching chambers, where he found that organic matter content interfered with the solution in contact with the peroxide. Michael Smith observed that mining material in Nevada's Carlin Trend may have 2-3 percent organic carbon, so peroxide may not be useful in tests of Nevada mining wastes.

Tom Card commented that statistics may be useful in determining the number of samples to establish confidence limits to satisfy regulators. A research project to gather useful statistics to increase sampling confidence may help. He would like to see some guidance provided on statistical treatment of test data. Keith Ferguson expressed his opinion that standard sampling programs are not appropriate for mining wastes. Sampling must be site-specific. Standard methods for presenting data, however, are appropriate. Placer Dome, for example, is developing systems of presentation. They are trying various nonparametric statistics to compare data sets. Statistics are a very critical part of the entire assessment package.

Richard Humphreys indicated that in the area of water quality, there is movement toward having large data sets submitted to regulators on diskettes so data can be statistically manipulated.

Patricia Erickson noted problems with accuracy and precision, particularly in the way tests are used. For at least static tests and some of the kinetic tests, there need to be standard methods in place. Tom Hinnners noted that the National Institute of Standards and Technology (NIST) released in 1991 a pyrite ore reference material (RM 8455) that could be used in method evaluations.

Ben Haynes (Bureau of Mines, Washington, DC, deceased 12/25/92) noted that BOM has been involved in acid generation research for some time. BOM is able to direct attention to specific short- and long-term projects. He noted BOM's work with EPA, the Forest Service, and the MEND program. As for abandoned sites, he noted that there can be improvements in water quality even if strict standards cannot be met. Finally, he noted that BOM is co-sponsoring (with EPA and other Federal and State agencies) the Third International Conference on Abatement of Acidic Drainage in April 1994 in Pittsburgh.

Michael Smith recommended a study of existing dumps. He suggested they be broken up by geographical areas within the west (different domains, climate zones), then survey dumps at abandoned sites, and design the sampling plans - overall, a thorough documentation of a range of dumps similar to the Saskatchewan process described earlier. He emphasized that it is critical to get good representation of different climatic zones. He also added that when site-specific expertise is needed, it is more appropriate to use experts who are there whether or not they are registered geologists (as specified in proposed California regulations).

## CONCLUSION

Tom Hinnners then closed the meeting by thanking the panel members and the audience participants. He reiterated that the workshop was intended to foster a discussion of ideas, not to reach specific conclusions. Official notes of the workshop (i.e., this document: Predicting Acid Generation from Non-Coal Mining Wastes - Notes of July 1992 Workshop) will be provided to the attendees after a draft document provided by Science Applications International Corporation is reviewed by the panel members and EPA personnel, the document is revised as appropriate, and it has been formally cleared by EPA. EPA will consider the recommendations provided during the workshop in planning research efforts.

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## APPENDIX A

### PANELISTS AND ATTENDEES AT WORKSHOP ON ACID GENERATION FROM NON-COAL MINING WASTES JULY 30-31, 1992

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## APPENDIX B

### BIOGRAPHIES FOR TECHNICAL EXPERTS ON THE PANEL

#### LINDA M. BROUGHTON

Steffen, Robertson and Kirsten, Inc.  
Vancouver, BC, CANADA

Linda M. Broughton, P. Eng. is a mining engineer specializing in acid rock drainage (ARD) and environmental impact assessment from mining projects. Ms. Broughton has developed expertise in the prediction and control of acid rock drainage. As head of Steffen, Robertson and Kirsten's Acid Rock Drainage Division in Vancouver, she is responsible for the development and design of ARD prediction and control technology on SRK projects.

Ms. Broughton is involved in projects both for prediction of ARD for new operations, assessment of ARD and design of control technologies for existing mines, and closure and remediation for old mines. Over the past year she was the principal author of the "Mine Rock Guidelines for Design and Control of Drainage Water Quality" prepared for the Saskatchewan Mines Pollution Control Branch and of the "ARD Prediction in the North" for Department of Indian Affairs and Northern Development. She is currently involved in a number of projects related to ARD prediction for the B.C. Acid Mine Drainage Task Force and the National MEND committee including "Compilation of ARD Prediction Rules" and a model to predict drainage water quality from waste dumps. She has extensive experience in the evaluation of acid drainage conditions from mine sites and recently participated in a study tour of ARD remediation sites in Sweden.

Ms. Broughton is the co-presenter of ARD and mine closure short courses with Dr. Andy Robertson which have been presented in Canada, the U.S., Sweden, the U.K. and South Africa.

#### FRANK T. CARUCCIO

Department of Geological Sciences  
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Ph.D. in Geology, 1967 Pennsylvania State University  
M.S. in Geology, 1963 Pennsylvania State University  
B.S. in Geology, 1958 City College of New York  
(Professor of Geology, May 1983 to present)

Over the past 20 years most of my research has been concerned with the identification of the hydro-geologic variables responsible for the occurrence of acid mine drainage in the bituminous coal fields of Appalachia and abandoned gold mines in South Carolina. With funding (exceeding \$2 million since 1972) from the Environmental Protection Agency, the National Science Foundation, the Bureau of Mines and the Office of Surface Mining, we have investigated the acid problem in West Virginia, Pennsylvania, eastern Kentucky, Ohio, Tennessee, and South Carolina. The results of these studies have led to the formulation of a predictive model, through which mine drainage quality can be predicted from cores of exploratory drill holes. The results of my studies dealing with rock - water interactions are currently used in mine plans to minimize acid production. My research in this field has expanded to the point whereby laboratory results have been translated to field trails through the use of active, large-scale coal and gold mines. Publications include over 35 papers and chapters in refereed journals and books dealing with the problems of occurrence, prediction and abatement of acid mine drainage. Field ground water monitoring networks established in several mines in central West Virginia

provided the basis for the formulation of a unique model and the characterization of groundwater flow and occurrence in reclaimed mine backfills. Numerous presentations and papers have been presented and appear in the proceedings of symposia dealing with the environmental impacts of acid drainage on surface and groundwater regimes.

Appointed to numerous national (including NATIONAL RESEARCH COUNCIL/NATIONAL ACADEMY OF SCIENCES) and international committees (including BEIJER INSTITUTE, ROYAL SWEDISH ACADEMY OF SCIENCES) dealing with the acid mine water-related problems throughout the United States, southern Africa, northern South America, and Canada. Five separate gubernatorial appointments to the South Carolina Mining Council, representing non-governmental conservation interests continuously serving since 1974; served as the Council's first chairman.

Research specialty relates rock-water interactions to leachate quality and the potential impact on the quality of surface water and the groundwater regime and flow systems. Research efforts are toward the development of an in-situ technique for the abatement of acid mine drainage.

**RICHARD D. DOEPKER**

U.S. Bureau of Mines  
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Richard Doepker was born in Findlay, Ohio, educated at Xavier University (BS and MS chemistry) and Carnegie Institute of Technology, (now Carnegie Mellon University), Ph.D. in physical chemistry. After two years military duty at the Army Chemical Center, MD, (research in the anti-material program) and two years National Academy of Science, National Research Council post doctoral research fellowship at the National Bureau of Standards, Washington, D.C., with 7 publications in the area of radiation and photochemistry, Dr. Doepker joined the chemistry faculty at the University of Miami. During the eighteen years of tenure at U of M, Prof. Doepker headed a graduate research program in gas phase kinetics, and vacuum UV photochemistry which lead to 17 jured publications, four granted Ph.D.'s and five Masters. Funding for the most of this graduate research program was furnished by the National Science Foundation. In addition to his physical chemistry research Prof. Doepker took over as Head of Analytical Chemistry and conducted research in the chemical characterization of the exhaust from methanol powered engines for the Dept. of Energy.

Dr. Doepker and family moved west in 1983. After two years of university teaching in Washington, he joined the research staff at the Spokane Research Center, U.S. Bureau of Mines as a research chemist and principle investigator in the dissolution mechanism of metals from mine waste. This research has led to 10 publications mainly related to the parameters affecting metal dissolution from metal-mine tailings. Studies have also been carried out on metal dissolution and the oxidation mechanisms of waste rock (manuscript in preparation). Current research interests still include long-term metal dissolution characteristics of aged tailings and the apparent inhibited oxidation of fresh tailings. Methods for the determination of the rate of oxidation of waste rock is under investigation as well as studies of the metal release, oxidation mechanism and rates of dissolution from individual mineral of mining interest. Through this latter project it is hoped that particular minerals or combinations of minerals can be identified that are instrumental in the formation of mobilized metal from mine wastes.

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Ph.D. Hydrometallurgy, Imperial College of Science and Technology, University of London, England, 1983. Thesis title: "Hydrolytic Stripping of Mixed Metal Carboxylates"  
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1983: Graduate Trainee, David McKee, Metals and Minerals Division, Stockton-on-Tees, England  
1983-1988: Assistant Professor, Department of Materials Science and Mineral Engineering, University of California at Berkeley  
1990: Acting Associate Dean, Special Programs, College of Engineering, University of California at Berkeley

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TMS, American Institute of Mining, Metallurgical and Petroleum Engineers, Institution of Mining and Metallurgy, The Electrochemical Society, American Chemical Society, Materials Research Society, Chartered Engineer, Great Britain

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Intramural: 1990-91, Chair, Committee on courses of Instruction, Academic Senate, University of California at Berkeley

Editorial: Co-editor, Mineral Processing and Extractive Metallurgy Review (1990-present), Board of Review, Metall. Transactions B (1985-1990), Editorial Board, Hydrometallurgy (1986-present)

Professional Society Activities: TMS/SME Hydrometallurgy/Chem. Processing Committee (1986-1989) (1988-89 Chair), TMS Aqueous Processing Committee, (1988-present) (1989-90 Chair), TMS/EPD Programming Committee (1989-90, 1992-95 Chair), TMS/EPD Executive Committee (1989-present), TMS Copper, Nickel, Cobalt Committee (1989-present), TMS Education and Professional Affairs Committee (1989-present), TMS International Activities Committee (1991-92), TMS Reactive Metals Committee (1989-present), TMS Student Affairs Committee (1989-92)

**AWARDS**

Institution of Mining and Metallurgy; Bosworth Smith Trust Fund Award, 1981 Rio Tinto Zinc Corporation, Research Award, 1981/82

## RESEARCH INTERESTS

Aqueous chemistry in the processing and behavior of minerals and materials. Equilibrium, kinetics, mass transfer and mechanisms in aqueous, organic and solid systems. Leaching and transformation of minerals. Hydrolysis, precipitation and coprecipitation. Solvent extraction and organic phase reactions. Electrochemistry. Chemical thermodynamics. Applications in hydrometallurgy, materials science, environmental engineering and waste management, and earth sciences.

47 Publications in Journals, Conference Proceedings, etc, 22 Abstracts, Preprints, Invited Talks

**PATRICIA M. ERICKSON**  
U.S. Environmental Protection Agency  
Cincinnati, OH 45324

Patricia (Trish) Erickson is a chemist with the EPA's Office of Research & Development, Risk Reduction Engineering Lab. For the past 2 years she has managed research on characterization and remediation of RCRA and Superfund wastes. From 1980 to 1990 she was with the Bureau of Mines' Environmental Technology Group, conducting and managing research on acid mine drainage. The research program encompassed characterization of mine waste, mitigation of existing or predicted acid discharges, and water treatment. Ms. Erickson has contributed to more than 30 publications on mine waste and mine water.

B.A., SUNY College at Buffalo, Chemistry.

M.S., Pennsylvania State University, Analytical & Inorganic Chemistry.

**KEITH D. FERGUSON**  
Placer Dome, Inc.  
Vancouver, BC, CANADA

## EDUCATION

1977: Masters of Applied Science (Environmental Engineering) University of British Columbia

1975: Bachelor of Applied Science (Geological Engineering) University of British Columbia

## EXPERIENCE

- 1992-present: Senior Environmental Engineer, Placer Dome Inc. Responsible for studies and assessments of Acid Rock Drainage for large international mining corporation.
- 1982-1992: Manager/Head Mining and Metallurgy Program, Environment Canada. Responsible for managing the mining program in the Pacific and Yukon Region. Conducted reviews and assessments of new mine proposals in the region, inspected existing mining operations and negotiated environmental controls. Chaired the Prediction Committee of the Mine Environment Neutral Drainage Program, and Prediction and Prevention Committee of B.C. Acid Mine Drainage Task Force. Member of U.S. EPA Science Advisory Board reviewing amendments to RCRA and CERCLA legislation regarding mining wastes.
- 1979-1982: Project Engineer, Mining and Metallurgy Program, Environment Canada. Conducted reviews and assessments of environmental controls for new and existing mine projects.

- 1977-1979: Project Engineer, Municipal Program, Environment Canada. Conducted assessments of contamination of shellfish growing waters, sewage treatment plant operations, and of stormwater discharges to the Fraser River.
- 1976-1977: Research Assistant, Environmental Engineering Group, University of British Columbia. Conducted bench scale experiments to minimize the environmental impact of area used for airport runway de-icing.

## **PUBLICATIONS**

More than 25 publications in the environmental engineering field, including more than 15 on acid rock drainage prediction and abatement.

**RICHARD W. HAMMACK**  
U.S. Bureau of Mines  
Pittsburgh Research Center

Richard (Rick) Hammack received a B.S. in geology and a M.S. in geochemistry from West Virginia University. For the past 13 years, he has worked for the U.S. Bureau of Mines as an exploration geologist and as a research geochemist. Rick has spent 8 years evaluating the intrinsic reactivity of sedimentary and hydrothermal pyrite using evolved gas analysis, x-ray photoelectron spectroscopy, electron beam induced current microscopy, Mössbauer spectroscopy, and corrosion voltammetry. Much of this effort was directed towards the development of quick and simple methods for determining pyrite reactivity. Rick has also examined, on a microscopic scale, the effect of oxygen, humidity, chemolithotropic bacteria, and passivating agents on the oxidation of pyrite surfaces.

**RICHARD D. HUMPHREYS**  
California Water Resources Control Board  
Sacramento, CA 94244

Richard (Rick) D. Humphreys, P.G. (California Water Resources Control Board) is a geologist with more than ten years experience in hazardous waste management, water quality issues, and mine waste management. He has been with the Water Resources Control Board for six years as a technical consultant to the California Regional Water Quality Control Boards and as a developer of ground water monitoring regulations. Currently, he is developing mine waste management regulations that emphasize the proper management of acid-generating mine waste.

Prior to working for the State, Mr. Humphreys worked for several consulting firms that specialized in hazardous waste management and ground water cleanup. He also worked for the United States Geological Survey on sulfide geochemistry.



**KIM A. LAPAKKO**  
Minnesota Department of Natural Resources  
St. Paul, MN 55155-4045

Kim Lapakko is a Senior Engineer for the Division of Minerals at the Minnesota Department of Natural Resources. His work in non-coal mine waste management began at the University of Minnesota, the results of which are compiled in the Master's thesis "The Kinetics and Mechanisms of the Oxidative Dissolution of Metal Sulfide and Silicate Minerals Present in the Duluth Gabbro" (1980). Subsequent projects have encompassed five major areas of non-coal mine waste drainage impact assessment and mitigation: determination of background water quality; quantification of chemical release from mine waste and description of the subsequent chemical transport; mitigation of undesirable chemical release; prediction of mine waste drainage quality; and development of nonferrous mine waste regulations. His recent projects include:

1. evaluation of procedures for predicting acid mine drainage;
2. predictive testing on acid and trace metal release from wastes generated by gold mining;
3. predictive testing for sulfide-bearing waste management at a Minnesota mine;
4. developing an approach for integrating mine waste characterization and mine waste drainage quality prediction into a regulatory program for mine waste reclamation;
5. conducting laboratory column experiments and a pilot scale alkaline treatment system to neutralize acidic stockpile drainage;
6. laboratory experiments on the mitigation of waste rock acid generation by incorporation of alkaline solids;
7. compiling and analyzing laboratory and field drainage quality data for a cooperative project with the US Bureau of Mines, directed at developing a mathematical model for mine waste drainage quality prediction.

**ANDREW MacG. ROBERTSON**  
Steffen, Robertson and Kirsten, Inc.  
Vancouver, BC CANADA

Dr. Andrew (Andy) Robertson, P. Eng., a Principal of Steffen, Robertson and Kirsten (B.C.) Inc. is a civil engineer specializing in mine geotechnics and mine waste management. He has over 25 years of experience in the design of mine waste facilities, and has developed a particular interest and expertise in the field of acid rock drainage (ARD). Dr. Robertson has written and published twelve technical papers specifically on ARD.

Now an acknowledged expert in this field, Dr. Robertson has been involved in a large number of key ARD projects in Canada, the USA, Norway, Sweden, France, Germany, South Africa and other countries internationally. Dr. Robertson was the principal author for the development of the "Draft Acid Rock Drainage Technical Guide" for the British Columbia Task Force on ARD, and has lectured extensively in Canada, the USA, Sweden, the UK and South Africa on appropriate prediction, control and reclamation measures. He has provided specialist ARD review and mine decommissioning consulting services to a number of national authorities including the provincial governments of B.C., Saskatchewan and Ontario, and to Norway, Sweden,

South Africa, and the US Bureau of Mines. His consulting to the mining industry includes participation in ARD prediction and control studies and closure plan development for more than 30 base and precious metal and uranium mines internationally.

**GEORGE R. WATZLAF**  
U.S. Bureau of Mines  
Pittsburgh Research Center

Mr. Watzlaf received B.S. degrees in Secondary Physics Education and Mining Engineering, and a M.S. degree in Environmental Engineering from the University of Pittsburgh. He has worked for the Environmental Technology group as an Environmental Engineer at the United States Bureau of Mines' Pittsburgh Research Center for the past twelve years. Mr. Watzlaf has been involved in a variety of acid mine drainage (AMD) research projects. Much of his research has focused on factors that affect the rate of pyrite oxidation; particularly, pore gas oxygen concentration, iron-oxidizing bacteria, water saturation, and leaching frequency. He has also researched AMD treatment alternatives to remove manganese and the chemical stability of metals in AMD treatment sludges. He has recently become involved in researching the utility of limestone for treatment of mine drainage under anoxic conditions.

**WILLIAM W. WHITE, III**  
U.S. Bureau of Mines/SLRC  
Salt Lake City, UT 84108

**EDUCATION**

B.S. in Geology, 1967    University of Utah  
M.S. in Geology, 1973    University of Utah

**CAREER EXPERIENCE**

1979-1988:    Field Geologist/Project Leader - Mineral Resource Potential Evaluation of Federal Wilderness Study Areas, U.S. Bureau of Mines, Western Field Operations Center.

1988-1991:    Co-Researcher - Investigation of Enhanced Recovery Methods for Refractory Gold Ores, U.S. Bureau of Mines, Salt Lake Research Center.

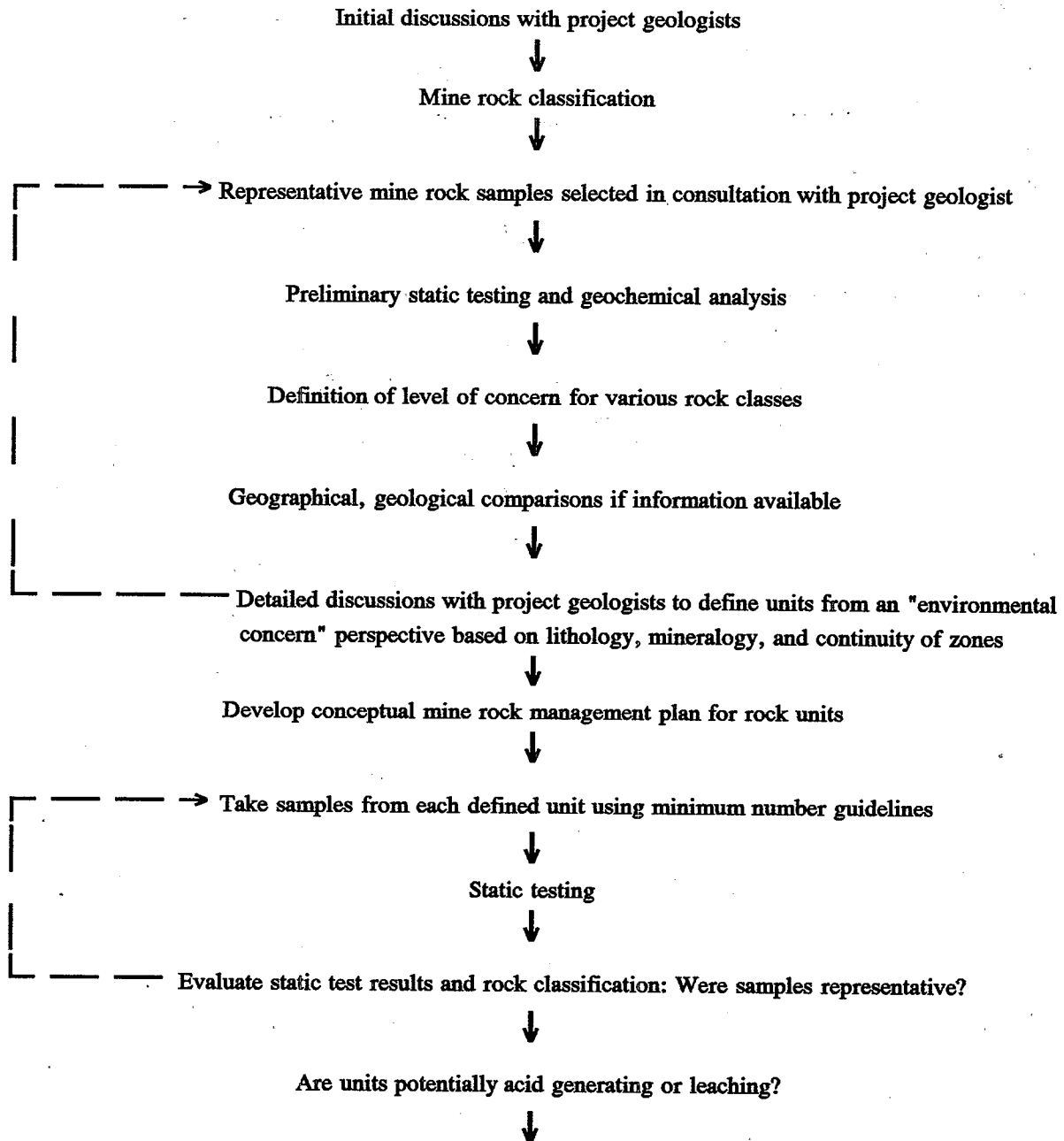
1991-Present:    Principal Investigator - Geochemical Predictive Modelling of Acid Mine Drainage from Waste Rock Produced by Metals Mines, U.S. Bureau of Mines, Salt Lake Research Center.

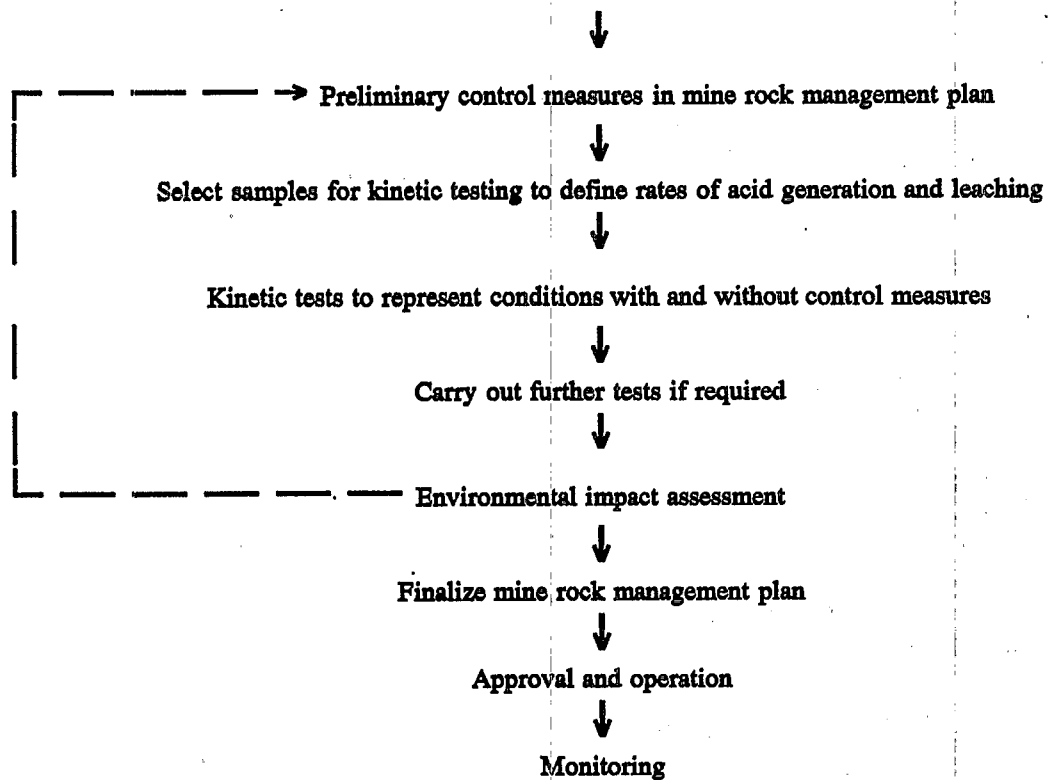
Member of AIME/SME

Registered Professional Geologist, State of Idaho

## APPENDIX C

### APPROACH TO EVALUATING POTENTIAL FOR ACID GENERATION AND METAL LEACHING<sup>9</sup>

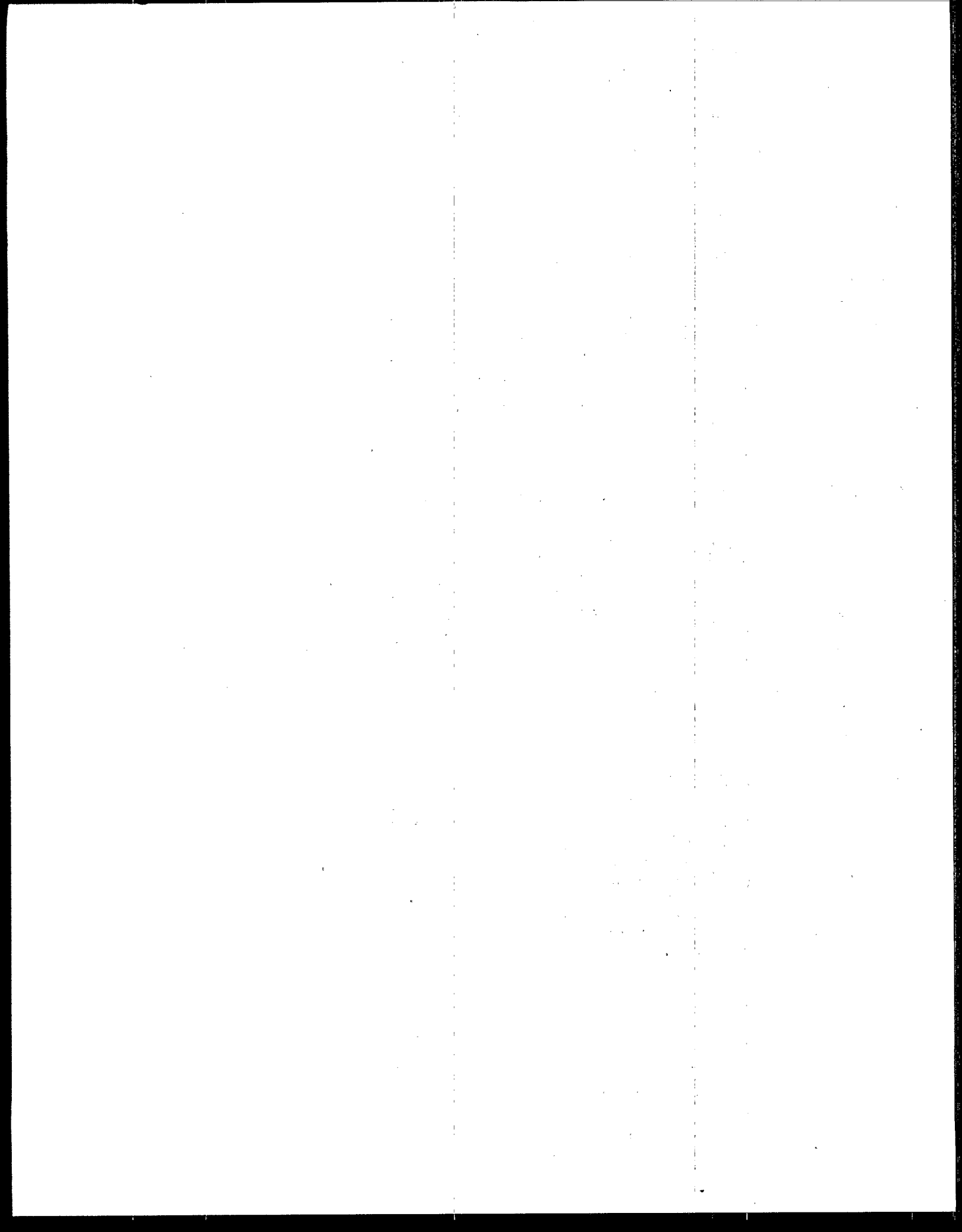


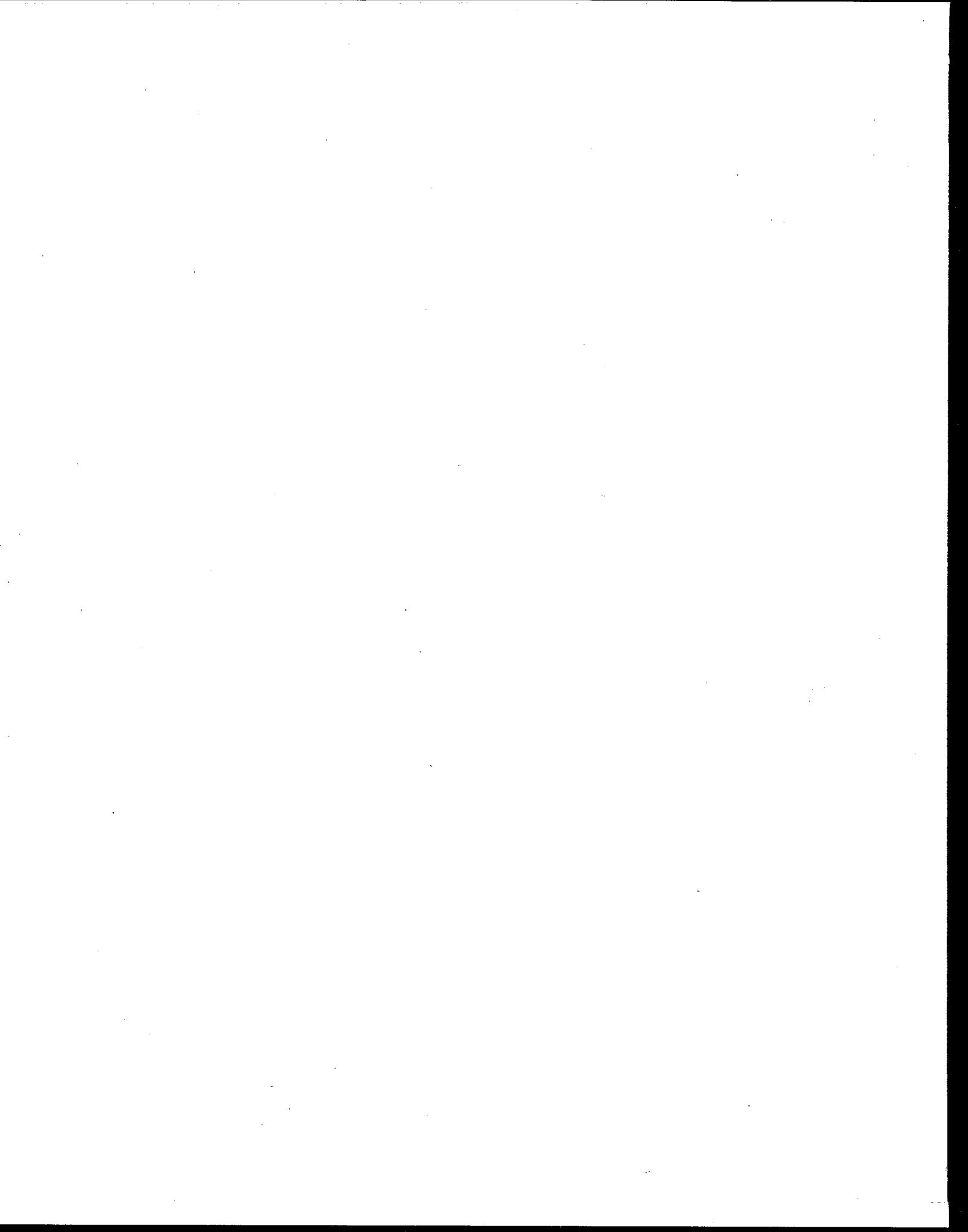


## APPENDIX D

### INFORMATION AND SAMPLE SOURCES<sup>9</sup>

	NEW MINE	OPERATING MINE	ABANDONED MINE
Mine Rock Classification	<ul style="list-style-type: none"> <li>● outcrop exposures</li> <li>● exploration drill samples, logs</li> <li>● exploration bulk sampling</li> <li>● geological sections</li> <li>● core assays</li> </ul>	<ul style="list-style-type: none"> <li>● outcrop and excavation exposures</li> <li>● drill core</li> <li>● production sampling</li> <li>● core assays</li> <li>● specific sampling from working areas and piles</li> </ul>	<ul style="list-style-type: none"> <li>● outcrop and excavations exposures</li> <li>● drill core</li> <li>● core assays</li> <li>● specific sampling from piles</li> </ul>
Mine Rock Distribution	<ul style="list-style-type: none"> <li>● mine planning</li> </ul>	<ul style="list-style-type: none"> <li>● mine planning</li> <li>● mine rock placement records</li> <li>● pit and underground plans and exposures</li> <li>● pile surveys</li> <li>● pile drilling and sampling</li> <li>● site personnel</li> </ul>	<ul style="list-style-type: none"> <li>● pit and underground exposures</li> <li>● existing records and plans</li> <li>● site personnel still available</li> <li>● pile surveys</li> <li>● pile drilling and sampling</li> </ul>
Acid Generation, Leaching Potential	<ul style="list-style-type: none"> <li>● static testing</li> <li>● short term leach extractions</li> <li>● mineralogy</li> <li>● site comparisons</li> </ul>	<ul style="list-style-type: none"> <li>● observation of old core</li> <li>● field sampling</li> <li>● static testing of distinct sub-units from working areas</li> <li>● static testing of pile samples</li> <li>● site observations - venting, staining</li> <li>● seep surveys</li> </ul>	<ul style="list-style-type: none"> <li>● observation of old core</li> <li>● field sampling</li> <li>● static testing of distinct units from working areas</li> <li>● static testing of dump samples</li> <li>● site observations - venting, staining</li> <li>● seep surveys</li> </ul>
Drainage Water Quality	<ul style="list-style-type: none"> <li>● kinetic testing</li> <li>● background water quality</li> </ul>	<ul style="list-style-type: none"> <li>● regular monitoring</li> <li>● seep surveys</li> <li>● kinetic testing</li> <li>● leach extraction</li> </ul>	<ul style="list-style-type: none"> <li>● monitoring records</li> <li>● seep surveys</li> <li>● kinetic testing</li> <li>● leach extraction</li> </ul>





United States  
Environmental Protection Agency  
Center for Environmental Research Information  
Cincinnati, OH 45268

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