Proceedings of the 13th Annual British Columbia Mine Reclamation Symposium in Vernon, BC, 1989.
The Technical and Research Committee on Reclamation

STRATEGIES FOR THE PREDICTION OF ACID MINE DRAINAGE

R.W. Lawrence[1], G.M. Ritcey[2], G.W. Poling[3]
and P.B. Marchant[1]

13th ANNUAL MINE RECLAMATION MEETING
Vernon, British Columbia

June 7-9, 1989

[1] Coastech Research, North Vancouver, B.C.
[2] CANMET, Energy Mines and Resources, Ottawa, Ont.
[3] Mining and Mineral Process Engineering, UBC, Vancouver, B.C.

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Richard W. Lawrence-'-, Gordon M. Ritcey[2], George W. Poling[3] and P.Brad Marchant[4]

[1]Vice President, Technical,
Coastech Research Inc
80 Niobe Street,
North Vancouver, B.C.

[2]Consultant,
CANMET
555 Booth
Street Ottawa,
Ontario

[3]Professor,
Dept. Mining and Mineral Process Engineering,
University of British Columbia,
Vancouver, B.C.

[4]President

Coastech Research Inc
80 Niobe Street
North Vancouver, B.C.

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ABSTRACT

A comprehensive 1 year study has been carried out to evaluate and compare methods to predict the formation of acid mine drainage (AMD) and to make recommendations on the methods most suitable for laboratory and field use. This paper presents the findings of this study and includes a brief description of methods evaluated, a summary of the test results, and a discussion on the ability of the methods to accurately predict field behaviour. A principal conclusion made from the results of the study is that accurate and confident prediction of AMD is not likely to be achieved in a single test. Factors affecting the choice of test procedures to be used for a given tailing or waste rock are discussed on the basis of simplicity, time, equipment, cost, ease of interpretation, and correlation with field data. In addition, approaches to be used in the selection of AMD prediction methods for site specific applications involving either land-based or sub-aqueous waste deposition are outlined.

INTRODUCTION

The disposal of mining and mineral processing wastes can have a significant environmental impact. Acid mine drainage (AMD) and associated heavy metal contamination in run-off and seepage water from waste rock and tailings containing the sulphide minerals pyrite and/or pyrrhotite is a common problem to mining operations throughout the world.

What can be done about this problem? AMD can be controlled by one of three approaches; treatment, control, or by prediction that allows preventative measures to be taken. The cost of treating waters is high, requiring the mining industry to spend many millions of dollars each year to meet stringent discharge limits. Effective control of acid formation by inhibition of the chemical and biological reactions contributing to the oxidation of pyrite has yet to be proven. The accurate prediction of AMD probably offers the most cost effective means of reducing the impact of AMD on the environment and on costs by allowing advance planning of sound waste management practices and maximum containment and effective treatment if AMD cannot be avoided.

For new mines and new developments in existing operations, the characterization of tailings and waste rock prior to production to predict if AMD will be generated is already required for permitting. Several AMD prediction techniques have been developed and are used in Canada and the United States by commercial laboratories, research organizations and regulatory authorities. In general, predictive techniques include static tests which examine the balance between acid producing and acid consuming components in a waste sample, and kinetic tests which attempt to predict AMD and drainage quality as a function of time. However, the ability of the various techniques to predict accurately actual field behaviour of mine wastes deposited either on land or in tailing ponds is often in doubt. Moreover, some techniques were developed for coal mines in the United States and might not be suitable for characterizing base metal or gold mine wastes produced in Canada.

A detailed and comprehensive study has been carried out for Supply and Services, Canada on behalf of Energy, Mines and Resources, Canada to evaluate AMD prediction procedures. This paper provides a summary of the results of the evaluation of ten AMD prediction methods for each of eight tailing and four waste rock samples from Canadian metalliferous mines. The paper also discusses the factors which might influence the choice of method for a particular waste type and its mode of deposition, and suggests a strategy for prediction to assist in the mining and waste management planning. For greater details of the methods evaluated and of the results and conclusions, the reader is referred to the study report (Lawrence et al, 1989) and to the individual references for each procedure.

METHODS AND PROCEDURES

TAILING AND WASTE ROCK SAMPLES

The tailing and waste rock samples used in the study were obtained by CANMET, Energy, Mines, and Resources, and shipped in early 1988 to Coastech for distribution to the participating laboratories. Tailing samples were air dried prior to testing. Waste rock samples were cone crushed to minus 6 mm for Humidity Cell tests, and rod milled to SO % minus 200 mesh or as otherwise prescribed for the remaining test procedures. Each tailing and waste rock sample was analyzed for sulphur species. A list of the tailing and waste rock samples together with their sulphur analyses are given in Table 1

Table 1. Tailing and Waste Rock Samples Used for AMD Prediction Tests

COMPANY / MINE	CODE	S(T) (%)	S(SO4) (%)	S(Sulphide) (%)
TAILING :				
Curragh - Yukon	CUT	24.95	0.14	24.21
Elliot Lake Quirke - Ont.	ELT	3.79	0.22	3.28
Equity Silver - B.C.	EST	3.40	0.06	3.11
Heath Steele - N.B.	HST	39.90	1.04	38.05
Key Lake - Sask.	KLT	4.68	4.21	0.39
Noranda Bell - B.C.	NBT	2.99	0.04	2.59
Waite Amulet -	WAT	13.00	0.24	12.74
Westmin - B.C.	WMT	22.90	0.36	22.13
WASTE ROCK :				
Curragh - Yukon	CUWR	8.66	0.03	8.19
Equity Silver - B.C.	ESWR	19.10	0.04	19.73
Heath Steele - N.B.	HSWR	6.12	0.03	5.89
INCO - Ont.	INWR	0.69	0.02	0.20

PREDICTION PROCEDURES

Ten prediction techniques were evaluated. Of these, four were static tests, four were kinetic tests, and two had the objective of providing information on the nature of either the pyrite or carbonate constituents of the waste materials. The ten procedures were as follows:

Static Tests:

B.C. Research Initial Test (Duncan and Bruynesteyn, 1979)

Acid Base Accounting (Sobek et al., 1978)

Alkaline Production Potential : S Ratio (Caruccio et al., 1981)

Net Acid Production Test (Albright, 1987; Lutwick, 1988; Lawrence et al, 1988)

Kinetic Tests:

B.C. Research Confirmation Test (Duncan and Bruynesteyn, 1979)

Humidity Cells (Sobek et al., 1978)

Shake Flasks (Halbert et al., 1983)

Soxhlet Extraction (Singleton and Lavkulich, 1978; Sullivan and Sobek, 1982)

Other Tests:

Hydrogen Peroxide Test (Finkleman and Giffin, 1986)

Manometric Carbonate Pressure Analysis (Evangelou et al., 1985)

In addition to the above tests, modifications to certain of the standard procedures were evaluated in an attempt to improve the methods or determine their limits of applicability.

Leachates from Humidity Cell, Shake Flask and Soxhlet Extraction Tests were analyzed for pH, redox potential, conductivity, acidity, alkalinity, sulphate and multi-element by ICP.

Comparison of the results of static test procedures was facilitated by using the standard convention of expressing the potential of a sample to generate or neutralize acid in terms of kg $CaCO_3$ equivalent per tonne of tailing or waste rock. For purposes of this paper, the difference between the neutralization potential (NP) and the acid potential (AP) is termed the Net Neutralization Potential (NET NP) , with negative values indicating a potential source of AMD.

FIELD DATA

Each mining company supplying tailing and waste rock samples were requested to supply information on the sample, its origin and AMD characteristics on site for comparison with the prediction data obtained in the laboratory.

RESULTS OF PREDICTION PROCEDURE EVALUATION

STATIC METHODS

A summary of the results of the static test procedures for the prediction of AMD is given in Table 2. For each static test procedure, a simple yes AMD/no AMD classification is given based on whether the value of the Net NP value derived from the test data is negative or positive. These classifications can be compared with the data obtained from the field survey which are also simply given in Table 2 as "yes or no".

The principal observations for each Static method are as follows:

Acid Base Accounting : provides an indication of AMD potential by balancing the stoichiometry of complete sulphur oxidation using, total sulphur assays to calculate acid potential, with the neutralization potential based on adding excess hydrochloric acid, boiling, and titrating excess acid with sodium hydroxide to an endpoint of pH 7. All tailing and waste rock samples were predicted to be potential sources of AMD. Three of the tailing samples, EST, KLT, and NBT, were not generating acid in the field. Of these, EST and KLT gave large negative NET

Table 2. Summary of the Results of Static Prediction Procedures

SAMPLE	ACID BASE ACCOUNT		MODIFIED * ACID BASE ACCOUNT		BC RESEARCH INITIAL TEST		ALKALINE PRODUCTION POTENTIAL		NET ACID PRODUCTION		FIELD
	NET NP	AMD ?	NET NP	AMD ?	NET NP	AMD ?	NET NP	AMD ?	NET NP	AMD ?	AMD ?
Tailing:											
CUT	-773.5	Yes	-750.2	Yes	-737.1	Yes	-775.8	Yes	-82.3	Yes	Yes
ELT	-119.0	Yes	-103.1	Yes	-94.4	Yes	-94.4	Yes	-20.6	Yes	Yes
EST	-68.3	Yes	-59.0	Yes	-76.3	Yes	-79.2	Yes	-7.2	Yes	No
HST	-1275.5	Yes	-1217.0	Yes	-1217.5	Yes	-1261.4	Yes	-69.2	Yes	Yes
KLT	-96.7	Yes	38.5	No	-44.7	Yes	-84.0	Yes	0.0	No	No
NBT	-6.4	Yes	6.1	No	5.0	No	-43.3	Yes	0.0	No	No
WAT	-409.2	Yes	-400.9	Yes	-396.8	Yes	-409.6	Yes	-41.2	Yes	Yes
WMT	-701.6	Yes	-677.3	Yes	-678.4	Yes	-698.6	Yes	-48.4	Yes	Yes
Waste Rock:											
CUWR	-175.6	Yes	-160.7	Yes	-226.5	Yes	-246.0	Yes	-9.6	Yes	Yes
ESWR	-596.6	Yes	-616.4	Yes	-573.7	Yes	-595.0	Yes	-84.9	Yes	Yes
HSWR	-178.7	Yes	-171.6	Yes	-157.9	Yes	-177.1	Yes	-7.3	Yes	Yes
INWR	-8.5	Yes	7.3	No	-7.2	Yes	-9.1	Yes	-6.8	Yes	Yes

Note: NET NP values are expressed as kg CaC03 equivalent. Positive values indicate an acid consuming material and negative values indicate the potential for acid generation

* Modified procedure uses ambient temperature/24 h digestion and sulphide sulphur analysis

NP values in the test. Samples NBT and INWR were barely acidic with NET NP values of -6.3 and -8.9 kg $CaCO_3$/t respectively. The standard Sobek et al (1978) method recommends that acid generation is indicated only if the NET NP is < -5 kg $CaC0_3$/t.

In a modified procedure in which AP is calculated based on sulphide sulphur analysis, and the acid digestion is carried out at room temperature, tailing samples KLT and NBT were classified as non-acid producing, as is the case in the field. One waste rock sample (INWR) was predicted to be non-acid generating (marginally) although AMD in the field was noted. For sample KLT, the rationale of using sulphide sulphur analysis is very evident since 90% of the total sulphur is present as gypsum formed in the acid leach process at Key Lake. Thus the assessment made by the standard procedure using a total sulphur analysis is clearly unrealistic for this sample.

BC Research Initial Test : this static test measures neutralization potential by direct sulphuric acid titration from the natural pH of a slurry of the waste material to an endpoint of pH 3.5. Two tailing samples, EST and KLT, were given AMD classifications opposite to that observed in the field. The erroneous classification of sample KLT as a potential source of AMD was again the result of using total sulphur analysis for the calculation of AP. Net NP values obtained using this sulphuric acid titration were very similar to those obtained using the hydrochloric acid digestion method of the Acid Base Account. The BC Research method is more time consuming and requires slightly more sophisticated equipment than Acid Base Accounting.

Alkaline Production Potential : values of NET NP derived from this less severe and shorter hydrochloric acid digestion procedure were similar to those obtained by Acid Base Accounting, although in some cases, NP values were significantly lower indicating only partial reaction of the contained carbonates. Using total sulphur assays for calculating AP, all samples were classified as potential sources of AMD.

Net Acid Production Test : entails the addition of hydrogen peroxide to the test sample to oxidize contained sulphides. The acid produced by the reaction is neutralized by carbonates in the sample and the net acidity, if any, remaining after reaction is determined by titration with sodium hydroxide to pH 8.3. This test correctly predicted all tailing and waste rock relative to the current field data with the exception of one tailing sample (EST) which all other static tests also incorrectly classified. For this sample, only weak NET AP was predicted unlike the high values obtained in the other tests. In the field, no AMD was reported. An advantage of this procedure is that sulphur assays are not required. This reduces the cost and time required for the test and makes it suitable for field use.

KINETIC METHODS

A summary of the results; of the kinetic test procedures for the prediction of AMD is given in Table 3. Field observations are also included in the table. The principal observations for each method are as follows:

BC Research Confirmation Test : provides an indication if sulphide-oxidizing bacteria can produce more acid from oxidation of sulphides in a waste sample than can be consumed by an equal weight of the sample. With the exception of tailing samples ELT and EST, the method identified all field AMD producers.

It is believed that, in general, the initial acidification of samples makes some results unrealistic. A modification of the procedure (Lawrence and Sadeghnobari, 1986) which compensates for the initial acid by the addition of base at the completion of oxidation equivalent to the initial acid addition, is seen to provide a reasonable improvement, although the opportunity to study the potential for the development of AMD in the higher pH ranges is still not possible.

Humidity Cells Test : designed to model the processes of geochemical weathering by subjecting a sample to alternate wetting, dying, and flushing cycles. The procedure correctly predicted field results on all 8 tailing samples and 3 out of 4 waste rock samples. The one incorrectly classified waste rock sample was shown not to generate AMD when it did (rarely) in the field. The test seems particularly well suited to the evaluation of waste materials, particularly waste rock, which are deposited on a land site where they would be alternately subjected to infiltration of water, drying and leaching sequences.

Shake Flask Test : similar in objectives to the humidity cell but maintains the waste sample in a saturated condition throughout the test. The shake flask test correctly predicted the behaviour of all 8 tailing samples, but was incorrect for 3 out of 4 waste rock samples which were indicated not to generate AMD when they did in fact in the field. The accurate prediction for tailing could be expected from this test which has a constant leaching action and might better model the behaviour of tailings which are often saturated and have low oxygen permeability. For the same reason, the test might not be well suited for waste rock which would be more likely to be subjected to alternate wetting, drying and flushing cycles as modelled better by humidity cells.

Soxhlet Extraction Tests : designed to simulate rapidly geochemical weathering using a special soxhlet apparatus. Although this test procedure can be seen as providing a less

Table 3. Summary of the Results of Kinetic Prediction Procedures

SAMPLE	BC RESEARCH CONFIRMATION TEST AMD ?	HUMIDITY CELLS AMD ?	SHAKE FLASKS AMD ?	SOXHLET EXTRACTION * AMD ?	FIELD AMD ?
Tailing:					
CUT	Yes, strong	Yes, moderate	Yes, at end of test	Yes, strong	Yes, after 15 years
ELT	No, v. marginal	Minor at end of test	Very low activity	Yes	Yes
EST	Yes, strong	No	No	No	No
HST	Yes, strong	Yes, strong	Yes, strong	Yes, strong	Yes
KLT	No	No	No	No	No
NBT	No	No	No	No	No
WAT	Yes, strong	Yes	Yes, moderate	Yes, strong	Yes
WMT	Yes, strong	Strong at end of test	Yes, moderate	Yes	Yes, after 1 year
Waste Rock:					
CUWR	Yes, strong	No	No	No	Yes, high Zn, SO4
ESWR	Yes, strong	Very low production	Low production	Yes, strong	Yes, after 6 months
HSWR	Yes, strong	V.minor at end of test	Extremely low activity	Yes, low production	Yes
INWR	Yes, marginal	V.minor at end of test	Extremely low activity	Yes, low production	Yes

* Soxhlet extraction tests using water

realistically modelled weathering environment than some other weathering tests such as humidity cells, the method using water as leachant was successful in predicting the field behaviour of all 8 tailing samples and 3 out of 4 of the waste rock samples in a much shorter time period. The method using acetic acid predicted all samples to be sources of AMD and it is believed that the results of this particular procedure is unrealistic.

OTHER TESTS

Hydrogen Peroxide Test : claimed to be able to estimate the pyrite content of a waste sample by comparing the rate of reaction of the sample with hydrogen peroxide, using pH and temperature as indicators of the rate, with the rates of reaction of standards of known pyrite content. However, the method lacked sensitivity and did not provide a realistic assessment of the pyrite contents of the test samples. The effect of the alkaline components of the samples on the direction and rates of reaction is also neglected. The results appear to be too inaccurate to be of real use.

Carbonate Pressure Analysis : method attempts to determine the rates of reaction of the carbonate species to be able to predict the effectiveness of neutralizing components in waste material. The results did not provide conclusive evidence of reliability in predicting the effectiveness of alkalinity production from a sample. The test procedure is considered to have potential as a supplemental test to be used with static tests or to aid in the interpretation of kinetic test data.

OVERALL EVALUATION AND COMPARISON

Table 4 provides an overview of the various static and kinetic test procedures for the prediction of AMD evaluated in this study on the basis of simplicity, time required, special equipment, cost, ease of interpretation, and correlation with the field data.

DISCUSSION AND CONCLUSIONS

This study shows that several of the static and/or kinetic procedures evaluated provided an accurate prediction of the field behaviour of many of the tailing and waste rock samples. However,

Table 4. Comparison of AMD Prediction Procedures

PREDICTION PROCEDURE	SIMPLICITY OF TEST	TIME REQUIRED	SPECIAL EQUIPMENT	$ COST PER SAMPLE	EASE OF INTERPRETATION	CORRELATION WITH FIELD DATA
STATIC TESTS :						
BC Research Initial Test	Yes	2 days *	No	75 - 200	Easy	1 tailing sample in error
Acid - Base Accounting	Yes	4 h *	No	50 - 130	Easy	3 tailing samples in error
Mod. Acid-Base Account	Yes	1 day *	No	50 - 130	Easy	1 tailing and 1 waste rock in error
APP : S Ratio Test	Yes	4 h *	No	50 - 130	Moderate	3 tailing samples in error
Net Acid Production Test	Yes	4 h	No	40 - 80	Easy	1 tailing sample in error
KINETIC TESTS :						
BC Research Confirmation	Moderate	3-4 weeks	Moderate	200 - 400	Moderate	2 tailing samples in error
Humidity Cell Test	Moderate	10+ weeks	Moderate	500 -1000	Moderate	1 waste rock sample in error
Shake Flask Test	Moderate	10+ weeks	Moderate	500 -1000	Moderate	Poor prediction for waste rock
Soxhlet Extraction Test	Moderate	3+ weeks	Yes	250 - 500	Moderate	1 waste rock sample in error
OTHER TESTS						
Hydrogen Peroxide Test	Yes	4 h *	No	80 - 120	Moderate	Poor estimate of pyrite content
Carbonate Pressure	No	4 h	Specialized	?	Specialized	Estimates of carbonate species inconclusive

Notes to Table :

1. In the Simplicity category, rating assumes test carried out by *a* trained laboratory technician or technologist

2. * In the Time Required category, time should be allowed for sulphur assay turnaround

3. In the Special Equipment category, rating assumes test carried out in a normally equipped chemical laboratory

4. In the Cost category, costs will vary from lab to lab, will depend on number of samples tested at same time, and on the number and cost of the sulphur species assays required. For kinetic tests, costs are based on a weekly sampling regime. Actual costs will depend on the number and frequency of leachate analyses performed including ICP multi-element analyses. Costs are estimates in $ Cdn as of March 1989.

the choice of one particular test procedure alone is not likely to provide *a* definitive assessment of whether a particular sample is going to produce AMD. It is more likely that a combination of two or more tests will provide a more confident assessment but even then, for some samples, prediction might be uncertain. The prediction of long term weathering characteristics of a tailing or waste rock will always have some uncertainty factor if the prediction test is carried out on a practical time scale in the laboratory.

Static methods of prediction have merit in providing a simple, rapid and low cost screening test to give *a* "first pass" indication of wastes that have the potential for AMD generation. In this study, the prediction of field behaviour on a yes/no basis was accurate for most of the methods, with approximately 80% accuracy. However, the predictions assume complete reaction of the sulphide and alkaline components of the rock and do not take into account the kinetics or equilibria of the acid generating and consuming reactions. The rate of release of alkalinity from a particular sample might not match the rate of acid production even though the sample might have a high positive net neutralization potential.

On the basis of cost and simplicity, the acid base account method might be preferred, although all methods gave similar results. The use of sulphide sulphur analyses to calculate AP values is recommended for better prediction. The Net Acid Production method provided prediction accuracy equal to the other static tests, but did not require sulphur species analyses for the assessment. This new method could therefore be carried out at a lower cost and would be suitable for field use. Further development and verification of this method is recommended.

The Humidity Cell and Shake Flask kinetic tests both appeared to be capable of accurately predicting AMD. The alternate wetting, drying and flushing cycles of the Humidity Cells appears to be preferable for the assessment of waste rock stored in an unsaturated condition on land, although the method also successfully predicted the field behaviour of all 8 tailing samples. Shake Flasks might be more suited for evaluating underwater storage of tailings and waste rock but not above-ground permeable wastes. This method was successful in predicting only 1 out of 4 waste samples of this type.

The Soxhlet Extraction Test using distilled water provided accurate prediction of all samples except one waste rock sample. Its advantage is that it provides a more rapid assessment and might be useful as a preliminary kinetic test for further screening of samples exhibiting AMD potential in static testing before carrying out more time demanding kinetic tests. However, the test requires more complex equipment than the other methods.

In this study, the BC Research Confirmation Test also provided good prediction of the occurrence of AMD in the field. This test has been popular in Canada for several years although now we consider that the initial acidification procedure used in the method provides an unrealistic condition. The method does not address the weathering characteristics in the approximate pH range of 7 down to 2. For some samples, the reactions taking place in this range might be critical in determining the formation of AMD. For the compilation of oxidation kinetics data and leachate quality information, tests such as the humidity cell, shake flask and soxhlet extraction are preferred.

Further work is required to develop and improve confidence in AMD prediction techniques and procedures. In particular there is a need to redress the lack of field verification for currently used prediction methods. An objective of a prediction scheme should be to consider the effects of variables such as hydrogeology, meteorology, geology, waste type, mine plan, disposal method, and reclamation plan. Figure 1 shows a suggested test strategy for integrating these factors to provide a systematic means of evaluating specific projects. In this way, a prediction procedure need not just simply be a yes/no test but can be selected with consideration to the above variables and be a valuable and essential tool to assist in determining the mining, waste management, and reclamation plans.

ACKNOWLEDGEMENTS

The authors of this paper wish to acknowledge the assistance, advice and support of Keith Ferguson, Environment Canada, throughout this study. We also wish to thank Frank Caruccio, University of South Carolina, for useful discussions. The financial support of Energy, Mines and Resources, Canada, through Supply and Services, Canada, Contract No. 23440-7-9178/01-SQ, is also gratefully acknowledged, c Her Majesty the Queen in Right of Canada (1989) as represented by the Minister of Energy, Mines and Resources.

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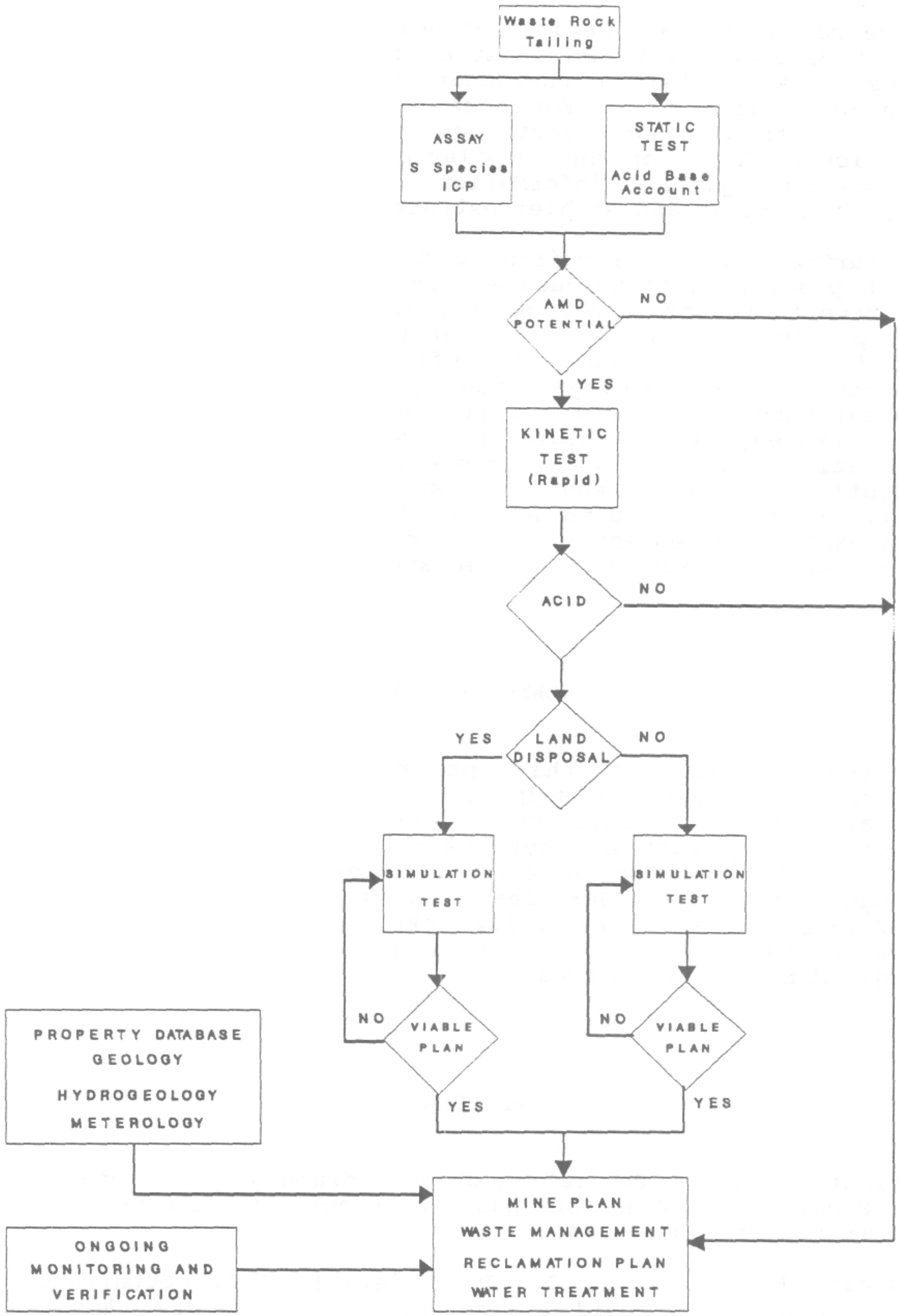

Fig. 1 Acid Mine Drainage Prediction Strategy

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