Welcome Screen
Search
Report List

WORKSHOP ON MODELLING OF REACTIVE TAILINGS SPONSORED BY THE MEND PREDICTION COMMITTEE, FINAL REPORT

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August 1990

Welcome Screen | Search | Report List

WORKSHOP ON MODELLING OF REACTIVE TAILINGS

SPONSORED BY THE MEND PREDICTION COMMITTEE

FINAL REPORT

PRESENTED BY

KILBORN ENGINEERING (B.C.) LTD.

Suite 400 - 1380 Burrard Street
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Welcome Screen Search Report List

WORKSHOP ON MODELLING OF REACTIVE TAILINGS

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TABLE OF CONTENTS

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Welcome Screen Search Report List

ATELIER SUR LA SIMULATION PAR ORDINATEUR
DES CHARACTERISTIQUES DES RESIDUS REACTIFS,
PARRAINE PAR LE COMITE MEND

SOMMAIRE EXÉCUTIF

1.0 INTRODUCTION

La société Kilborn Engineering (B.C.) Ltd. (Kilborn) a été engagée par CANMET dans le bût d'organiser un atelier concernant la simulation par ordinateur des charactéristiques des rejets réactifs. L'atelier s'est tenu à Haliburton en Ontario du 23 au 24 mai 1990 sous la direction de monsieur Henry Steger de CANMET.

La participation était très diversifiée. Une liste des participants est ajoutée à ce rapport. En plus des délégués de CANMET, il y avait des participants des Etats-Unis, de la Suède et de l'Australie et des représentants de l'industrie, des bureaux d'études, des universités et de divers départements gouvernementaux.

Le programme de l'atelier est ajouté à ce rapport. Les présentations et les questions ont porté beaucoup sur un programme de simulation recherché et développé sous la direction de CANMET et capable, entre autre, de calculer la production d'acide sulphurique des rejets réactifs. Ce programme, appelé Programme d'Evaluation des Résidus Acides Réactifs (PERAR.RMC1), a fait l'objet de la première, de la troisième et de la onzième présentation. Ce programme est une adaptation du programme PERAR aux métaux communs. Il n'est pas encore disponible au public.

D'autres présentations ont exposé le point de vue des consultants des bureaux d'études, le point de vue de l'industrie et le point de vue du département de l'environnement canadien en ce qui concerne l'emploi de modèles. Les dernières présentations ont donné les perspectives suédoise, américaine et australienne.

De nombreuses discussions ont eu lieu en rapport avec les besoins de programmes pour ordinateurs afin de calculer les charactéristiques des rejets réactifs et leurs résultats.

Un compte rendu de chaque exposé et des questions et discussions est ajouté à ce rapport.

2.0 COMMENTAIRES D'OUVERTURE

Docteur Henry Steger de CANMET en tant que Directeur de de l'atelier, a souhaité la bienvenue aux participants.

Monsieur Keith Ferguson, de l'environnement du Canada, a indiqué que l'atelier est un pas important vers la préparation d'un modèle capable de simuler le débit d'acide des résidus réactifs. La mise au point d'un tel modèle est plus avancée que l'on ne pense, particulièrement avec le travail de CANMET effectué sur PERAR

Il a exprimé l'espoir que les participants seraient constructifs dans leur critique du programme PERAR et sans doute discuteront aussi d'autres genres de modèles.

Monsieur Ferguson a indiqué qu'il existe une réticence dans l'industrie contre l'emploi de modèles pour simuler les résidus réactif mais la présence à cette session de travail de nombreuses personnes très qualifiées permettrait de développer un modèle utile à la fois à l'industrie et au gouvernement.

3.0 PRÉSENTATIONS DIRECTEMENT EN RAPPORT AVEC PERAR

Le Programme d'Evaluation des Résidus Acides Réactifs adapté aux Résidus de Métaux Communs (PERAR.RMC1), est un modèle développé à partir du modèle utilisé pour les rejets d'uranium (PERAR). Il calcule l'acide généré par l'oxidation des minéraux sulfurés et permet de simuler les concentrations du zinc et du cuivre. Messieurs W.J. Snodgrass, K.A. Morin et B.E. Halbert ont parlé dans leur exposé de PERAR.RMC1.

3.1 Docteur W.J. Snodgrass de Beak Consultants a expliqué qu'un modèle doit être capable de produire des résultats utiles pour prendre des décisions concernant les rejets réactifs. Il a donné le contenu conceptuel du modèle et a exprimé son opinion en ce qui concerne ses faiblesses, ses limitations et ses possibilités futures.

Docteur Snodgrass a parlé des essais de validation et de calibrage du modèle.

Il a comparé le modèle à d'autres et a indiqué que PERAR.RMC1 adresse beaucoup plus de questions at aussi des questions qui sont plus complexes que les autre modèles. Pourtant, PERAR.RMC1 est plus compliqué à employer et plus difficile à comprendre pour un opérateur nouveau et peu expérimenté.

Une liste de onze (11) questions (problèmes) utilisées pour évaluer le débit d'acide et quels modèles peuvent aider à répondre est donnée à la page 2.7. RATAP.BMP peut répondre aux questions 1 à 5:

1. Temps pour oxyder tout le pyrite
2. Temps pour la formation d'acide pour l'aire de résidus
3. Débit d'acide de l'aire des résidus
4. Débit d'acide et de métaux lourds d'une aire de résidus
5. Estimation de l'incertitude de l'évacuation de la question 4, ci-haut.

RATAP.BMP a besoin de renseignements provenant des questions 6, 7 et 8 pour son usage:

6. Balance d'eau
7. Evacuation d'eau
8. Epaisseur et humidité du sol de la zone non-saturée.

D'autres questions peuvent être posées par d'autres codes:

9. Consolidation (basée sur la géotechnique)
10. Ordres d'équilibre
11. Options de contrôle.

3.2 Docteur K.A. Morin de Morwijk Enterprises Ltd. a présenté une critique du modèle PERAR.RMC1 basée exclusivement sur le rapport principal traîtant du sujet, d'autres rapports et le modèle n'étant pas disponibles. Il a proposé un programme de 5 étapes visant à améliorer le modèle et l'employer avec succès.

- Interrompre le développement (subventionné par le gouvernement) du modèle pendant quelques années.
- Livrer le modèle au secteur publique dès que possible, entre autres les futurs usagers, afin de déterminer l'acceptabilité et l'applicabilité de RATAP.
- Plusieurs années après la présentation de RATAP au public, faire un sondage avec les usagers afin de déterminer la meilleure façon d'améliorer RATAP pour le rendre plus précis et plus versatile.
- Présentement, décider si des améliorations subventionnées par le gouvernement devraient être entreprises.

Pendant la période de discussion, une question importante a été posée concernant la possibilité d'utiliser le modèle dans son état actuel. Une discussion a suivit indiquant que le modèle ne devrait pas être mis sur le marché sans être modifié, tout spécialement à le rendre plus facile à utiliser. Il est aussi important de noter que le modèle RATAP.BMT1 doit être calibré et validé à chaque site. C'est la raison principale pour laquelle le programme n'a pas encore été relâché. Dans les discussions qui ont suivi, on a mentionné que la calibration du modèle n'était pas pour changer les codes, mais en fait, était pour incorporer des renseignements spécifiques.

3.3 Monsieur B.E. Halbert de Senes Consultants Ltd. terminait les présentations ayant rapport au programme PERAR.RMC1 en donnant un aperçu du modèle et son calibrage et validation à Waite Alumet au Québec et à Nordic (Elliot Lake) et son application à Nordic.

Il est à noter que le modèle consiste de cinq modules qui peuvent être vérifiés indépendamment. Des simulations déterministes ou probabilistiques peuvent être effectuées. Une bonne concordance a été obtenue entre les résultats simulés et les valeurs réelles obtenues sur le terrain.

Durant la période de discussion, une question a été posée concernant le calibrage du modèle, à savoir s'il a été calibré suffisamment pour que l'on puisse employer le modèle avec confiance. Les recommendations du Docteur Morin ont été répétées et l'on s'est demandé ce qu'il faudrait faire avec PERAR.RMC1 et comment procéder. L'opinion générale a été qu'il est nécessaire de simplifier PERAR.RMC1 pour le rendre plus facile à utiliser avant de le distribuer.

4.0 POINT DE VUE DES INGENIEURS-CONSEILS

Messieurs K.D. Phinney, A.V. Bell et A.M. Robertson ont parlé dans leur exposé de leur expérience avec leurs modèles de simulation.

4.1 Monsieur K.D. Phinney de Monenco Consultants Ltd a expliqué que Monenco agit comme ingénieur-conseil auprès des sociétés minières et que son rôle est d'obtenir des permits, de faire des études environnementales, de désigner des emplacements de résidus d'usines ou de mines, etc...

Monsieur Phinney a indiqué que la simulation de rejets réactifs est limitée, en ce qui concerne les sites anciens, à l'évaluation de l'efficacité de diverses possibilités de réclamation et cela à partir d'observations faites sur le terrain.

En ce qui concerne les sites nouveaux, il est important que les entrées et sorties d'eaux soient calculées de façon précise. Monsieur Phinney a donné des exemples de sites situés au Nouveau Brunswick.

Monsieur Phinney a terminé son exposé avec quelques remarques au sujet de PERAR.RMC1. Il est d'opinion qu'il existe des modèles plus simples que PERAR.RMC1 pour calculer le débit d'acide des sites mais que PERAR.RMC1 sera utile pour étudier la possibilité de modifier la chimie des sites de résidus.

Durant la période de discussion, une question a été posée concernant les méthodes conservatrices employées par Monsieur K.D. Phinney. Les engénieurs sont souvent poussés à employer des moyens très conservateurs.

4.2 Monsieur A.V. Bell de Nolan, Davis & Associates a commencé son exposé en indiquant que les modèles devraient être de simples outils conçus de façon à donner des réponses à des questions spécifiques. Les modèles ne doivent pas être compliqués, mais doivent être faciles à utiliser. PERAR.RMC1 est un modèle très compliqué qui pourrait former une base pour comprendre des situations difficiles.

Il espérait que sa présentation résulterait en une discussion concernant l'emploi éventuel de PERAR.RMC1 ou d'autres modèles pour la simulation de charactéristiques de tas de résidus de mine et qu'elle donnerait des informations pour le calibrage ou le développement de modèles relatifs aux tas de résidus acidiques de mine. Les charactéristiques des résidus acidiques de mine diffèrent de plusieurs façons de celles des résidus réactifs, bien qu'il qu'il y ait des similarités en ce qui a traît à la production d'acide et l'effet que la décharge d'acide et les éléments qui ont été lessivés ont sur l'environnement.

Monsieur Bell a présenté des diapositives sur les tas de résidus de la mine de Heath Steele située au Nouveau Brunswick. Le programme expérimental consiste de l'évaluation de la performance de couvertures différentes et est arrangé en quatre phases. Les deux premières phases, c'est à dire, l'identification des tas à soumettre aux essais et l'installation d'instruments sont complétées. La troisième phase qui consiste à déterminer les charactéristiques des couvertures possibles est en cours d'exécution.

Monsieur Bell est d'opinion qu'il sera très difficile de développer un modèle capable de simuler la génération d'acide dans les tas de résidus de mine. Un tel modèle est pourtant très important.

4.3 Docteur A.M. Robertson de Steffen Robertson & Kirsten (B.C.) Inc. commençait son exposé aves ses commentaires sur le programme PERAR.RMC1.

Docteur Robertson a indiqué tout d'abord que PERAR.RMC1 devrait être distribué et essayé avant que l'on puisse en dire ou le juger d'avantage. Le modèle est bien fait en ce qui concerne les réactions, pourtant il ne s'occupe pas du mouvement de l'eau. Etant donné que l'on doit donner des réponses aujourd'hui il ne faut pas attendre mais le mettre à la disposition du public.

La présentation du Docteur Robertson était en rapport avec la simulation de la génération d'acide dans les résidus. A l'aide de diapositives, il a montré les conditions physiques réelles qui existent dans les sites à rejets, à Westmin, à Uravan. De nombreuses fissures et d'autres irrégularités laissent entrer l'oxygène et les différences en granulométrie de couche à couche occasionnent des variations énormes en teneur d'eau. Ainsi un modèle de simulation ne sera valide que s'il tient compte de cette complexité du site.

Docteur Robertson a aussi parlé de ses essais à Faro où une couverture spéciale, placée sur un tas de résidus de mine, permet de limiter l'entrée d'oxygêne.

Durant la période de discussion, une question a été posée relative à la disponibilité de données qui pourraient être employées par PERAR.RMC1. Docteur Robertson a indiqué qu'il possède des données et qu'il a déjà demandé il y a quelques mois d'avoir accès à PERAR.RMC1.

Docteur Robertson a fait des remarques sur l'entreposage dans les dépôts de rebut de roc, l'entreposage des sels acidiques à l'état sec et à l'état dissout. Les prédictions de l'environnement sous-terrain doivent tenir compte de cet entreposage et contrôleront nos mesures correctives. Un grand dépôt de rebut de roc a une grande capacité d'entroposage et cela peut prendre jusqu'à trois ans avant que quelque chose n'en ressorte. La simulation par ordinateur de la production d'acide doit être essayée en utilisant des modèles de canal à débit multiple lesquels donneront une variation stochastique de la production d'acide.

Docteur Robertson a décrit la consommation de chaux à la Mine Doyon. On croit que l'augmentation élevée de la consommation de chaux est causée par le nettoyage par pression et non par la production. L'entreposage d'acide est très important dans un dépôt de rebuts mais pas autant dans un site de résidus. La Mine Doyon a donc besoin de savoir ce que la consommation d'acide sera en 1991. Nous avons besoin de ces outils de prédiction. Ce ne sont pas tous les rebuts qui produisent de l'acide à la Mine Doyon, et nos modèles doivent reconnaître ce fait. Les barrages de résidus ont des bords, ce qui fait que la géométrie et les propriétés des matériaux font que les modèles doivent être divisés en sections.

5.0 POINT DE VUE DE L'AGENCE DE RÉGULATION

Monsieur K. Ferguson a exposé le point de vue des régulateurs vis-à-vis l'emploi de modèles de simulation de résidus réactifs. Il a d'abord indiqué que les régulateurs sont très sceptiques, ensuite il a fait un résumé de leurs besoins et des questions qu'ils posent. Il a donné son opinion en ce qui concerne les capacités de PERAR.RMC1 de répondre à ces besoins et à ces questions.

Monsieur Ferguson a montré des diapositives sur les résidus de Westmin et a indiqué que RATAP.BMT1 pourrait trouver une application à ce site.

Monsieur K. Ferguson a conclus que les régulateurs ont besoin de modèles afin de simuler la qualité de l'eau. Il a terminé en exprimant l'opinion que l'utilisation de PERAR.RMC1 donnerait des données utiles aux régulateurs.

Durant la période de discussion, une question a été posée relative à la validation et au calibrage de RATAP.BMT1.

6.0 POINT DE VUE DE L'INDUSTRIE MINIERE

Docteur E. Yanful a expliqué le point de vue de l'industrie minière relatif à l'emploi de modèles de simulation de résidus réactifs. Il a d'abord indiqué que les besoins de l'industrie sont semblables aux besoins des régulateurs; de plus, le modèle doit être capable de vérifier la validité d'une certaine technologie.

Les sociétés minières sont confrontées au problème de disposer de leurs résidus d'une façon qui est, d'un côté, acceptable du point de vue de l'environnment et de l'autre côté, économique. Leur bût principal est de survivre et de faire un profit de leurs opérations.

Docteur Yanful a expliqué que le bût principal du modèle est de simuler la génération de l'acide des résidus mais le modèle doit aussi être capable de déterminer l'efficacité des mesures de contrôle.

Docteur Yanful a conclus que les besoins de l'industrie minière en matière de simulation sont grands et que le bon modèle doit être employé dans la bonne situation.

Durant la période de discussion, une question a été posée à savoir si l'industrie minière considère PERAR.RMC1 utile et capable de répondre à ses besoins. Docteur Yanful a répondu que PERAR.RMC1 devrait être utilisé parce que le modèle est considéré comme très utile. Il est pourtant d'avis que le programme n'a pas été validé suffisamment et qu'il faudrait l'essayer d'avantage.

7.0 PRÉSENTATIONS DONNANT LE POINT DE VUE DE LA DÉLÉGATION ÉTRANGÈRE.

Monsieur Björn Sodermark et Mademoiselle Marie Collin de la Suède, Docteur Kirk Nordstrom des Etats-Unis et Docteur A.I.M. Ritchie de l'Australie ont présenté leurs points de vue respectifs.

7.1 Monsieur Björn Sodermark de l'Agence Suédoise de Protection de l'Environnement a parlé des traveaux commencé en Suède il y a une dizaine d'années en matière d'identification et de classification des résidus réactifs. En ce qui concerne les mesures de suppression, la solution recommendée est d'installer une couverture laquelle est durable et demande peu d'entretien.

La prochaine étape consiste à développer un modèle capable de déterminer la façon de construire une couverture efficace. Monsieur Sodermark doutait qu'il existerait jamais un programme compréhensif capable de simuler la production d'acide de résidus réactifs pour tous les systèmes et il pensait très qualifiées, tandis que maintenant on se dirige de plus en plus vers l'emploi de consultants et ces firmes n'ont souvent pas la compétence.

Docteur Nordstrom a insisté qu'il faudrait plus de collaboration entre les rechercheurs, le gouvernement et l'industrie, et que, d'autre part, if faudrait tenir compte plus de la géochimie et employer les modèles géochimiques existants.

Profeseseur Nordstrom a donné un bref aperçu des modèles géochimiques employés aux Etats-Unis. Il a parlé de Riverton, au Wyoming, où l'étude consistait à comparer les données obtenues au terrain avec les résultats de simulation géochimique et hydrologique. Il a expliqué les résultats des investigations effectuées à Butte, au Montana et doutait d'une des conclusions de l'étude, laquelle semblait indiquer qu'il faudrait quelques vingt mille années pour que les contaminants puissent descendre dans les eaux sousterraines.

Il a aussi parlé des travaux effectués à Whitewood Creek au Dakota du Sud où le programme MINTEQ a été employé et où les valeurs mesurées ressemblent aux valeurs calculées. Docteur Nordstrom a décrit les investigations qui sont en cours à Pinal Creek en Arizona où le mouvement d'acide provenant d'un ancien réservoir pose un danger pour l'eau potable de la ville de Phoenix.

7.3 Docteur A.I.M. Ritchie de l'organisation australienne de sciences et technologie nucléaires a commencé sa présentation avec ses commentaires sur PERAR.RMC1 et a exprimé sa conviction que le modèle sera un outil important à l'usage des régulateurs et des opérateurs dans leur évaluation des différents systèmes de contrôle. Il a ensuite donné, en forme chronologique, une description des travaux effectués à Ansto en connection avec la production et l'utilisation de modèles.

Le modèle a progressé d'un simple modèle homogène où l'oxygène est transmise par diffusion à travers les pores jusqu'au modèle ajusté où l'oxygène est aussi transmise par diffusion dans la zône de réaction. Finalement, le modèle a été corrigé en tenant compte du fait que l'oxygène était aussi tansmise par convection. Il a ensuite donné quelques résultats de l'utilisation du modèle.

8.0 DISCUSSION FINALE ET RÉCAPITULATION

Monsieur K. Ferguson a annoncé que le comité MEND a décidé de recommender à CANMET que le programme PERAR.RCM1 soit distribué. En effet, le consensus des personnes faisant partie du groupe de travail était qu'elles veulent utiliser le modèle. Le modèle devrait être modifié de façon à le rendre plus accessible à l'usager et la documentation devrait également être améliorée.

Docteur Henry Steger a ajourné l'atelier et a remercié chacun de sa participation. Il a remercié Mademoiselle Mary Paddon de Kilborn Engineering (B.C.) Ltd. pour son excellent travail d'organisation.

Finalement monsieur Steger a demandé s'il ne faudrait pas continuer à se rencontrer dans le futur à des réunions semblables et a demandé aux participants d'y réfléchir.

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

EXECUTIVE SUMMARY

1.0 INTRODUCTION

Kilborn Engineering (B.C.) Ltd. (Kilborn) was commissioned by CANMET to organize a Workshop on the modelling of reactive tailings. The Workshop was held in Haliburton, Ontario, May 23 - 24, 1990, under the chairmanship of Dr. Henry Steger of CANMET. The Workshop was sponsored by the MEND Prediction Committee.

The diversified participation consisted of representatives of CANMET, delegates from the United States, Sweden and Australia and representatives of the mining industry, the consulting community, universities and various government departments. The Workshop roster is presented in the Introduction Section of the Main Report.

The presentations and discussions concentrated on a simulation model studied and developed under the direction of CANMET and capable of calculating the generation of sulphuric acid from reactive tailings. The first, third and eleventh presentation dealt with this program called Reactive Acid Tailings Assessment Program, (RATAP.BMT1). The program is an adaptation of the program RATAP to base metal tailings. The model is not yet available to the public.

Other presentations provided a consulting engineering perspective, the industry perspective and the point of view of the regulatory agencies with regard to the use of models. Finally, representatives of the United States, Sweden and Australia presented their thoughts. Numerous discussions took place related to the use of programmed models capable of calculating the characteristics of reactive tailings and their impact on the environment.

The report includes a summary of each presentation and the associated question and answer period.

2.0 OPENING REMARKS

As chairman, Dr. Henry Steger of CANMET welcomed everyone to the Workshop. Mr. Keith Ferguson of Environment Canada then indicated that the Workshop is an important step towards the preparation of a model capable of simulating the reactive tailings acid flux. The finalization of such a model is more advanced than is generally known, especially with CANMET's work on RATAP.

He hoped that the participants would be constructive in their critique of RATAP as well as discuss other models. He indicated that there is industry resistance against the use of models to characterize reactive tailings, but the presence at this Workshop of a large number of highly qualified people would contribute to the development of a useful model for both industry and government.

3.0 PRESENTATIONS DIRECTLY INVOLVED WITH RATAP

The Reactive Acid Tailings Assessment Program, adapted to base metal tailings, (RATAP.BMT1), is developed from the model used for sulphidic uranium tailings, (RATAP). The model calculates the amount of acid caused by oxidization of the sulphide minerals and, in addition, calculates the concentration of zinc and copper. In their respective presentations, Messrs. W.J. Snodgrass, K.A. Morin and B.E. Halbert dealt with RATAP.BMT1.

3.1 Dr. W.J. Snodgrass of Beak Consultants explained that a model must be capable of producing useful results so that one can make decisions with respect to reactive tailings. He explained the conceptual content of the model and provided his opinion on its weaknesses, limitations and future possibilities.

Dr. W.J. Snodgrass spoke about the validation and calibration of the model. He compared RATAP.BMT1 to other existing models and indicated that RATAP.BMT1 addressed questions more complicated than other models. However because of its complexity, RATAP.BMT1 is more difficult to use and to understand by the new or unexperienced operator.

A list of eleven questions (problem statements) used for assessing acidic drainage and which models can help answer is given on page 2.7. RATAP.BMP can address Questions 1 through 5:

1. Time to oxidize all pyrite
2. Time of acid generation for tailings area
3. Acid flux from a tailings area
4. Flux of acidity and heavy metals from a tailings area
5. Estimate of uncertainty of flux of above point 4.

RATAP.BMP needs some information from Questions 6, 7 and 8 for its use.

6. Water balance
7. Groundwater flow
8. Thickness and soil moisture of unsaturated zone.

Other questions can be addressed by other codes:

9. Consolidation (geotechnical based)
10. Equilibrium sequences
11. Control options.

3.2 Dr. K.A. Morin of Morwijk Enterprises Ltd. presented a critique of the RATAP.BMT1 model based exclusively on the main report because other reports and the model were not available. He recommended a five step program to improve the model:

- Halt (government-sponsored) model development for several years.
- Initiate detailed field and laboratory studies for comparison with RATAP simulations and for expanding current in-field

knowledge of acid drainage from tailings impoundments.

- Release the model as soon as possible to the public domain, that is, to the intended users, to allow an extensive determination of RATAP's acceptability and applicability.
- Several years after release of RATAP, conduct a survey of users to determine where RATAP can best be improved to make it more accurate and more widely applicable.
- At that point in time, determine whether government-sponsored improvements should be undertaken.

During the discussion period, a question related to the possibility of using the model in its present form was asked. A discussion followed which seemed to indicate that the model should not be released without modifications, especially with regard to making it more user-friendly. It is also important to note that the model RATAP.BMT1 must be calibrated and validated for each specific site. This is the main reason why the program has not yet been released. It was brought out in subsequent discussions that calibration of the model is not a model coding change but is, in fact, incorporating site specific data.

3.3 Mr. B.E. Halbert of Senes Consultants Ltd. ended the presentations devoted to the program RATAP.BMT1. He gave an overview of the model content, its calibration and validation at Waite Amulet in Quebec and at Nordic (Elliot Lake), and its application at Nordic.

The model consists of five modules which can be verified independently. Deterministic or probabilistic simulations can be carried out. A good resemblance was achieved between the predicted values and field observations.

During the discussion period, a question was asked related to the calibration of the model and if such calibrations had been carried out sufficiently to have confidence in the utilization of the model and its results. The recommendations summarized by Dr. K.A. Morin were repeated and the question was asked what to do with RATAP.BMT1 and how to proceed? Generally, the consensus of opinion was that RATAP.BMT1 should be made more user-friendly.

4.0 ENGINEERING AND CONSULTING COMPANIES PERSPECTIVE

In their respective presentations, Messrs. K.D. Phinney, A.V. Bell and A.M. Robertson related their experience with the use of simulation models.

4.1 Mr. K.D. Phinney of Monenco Consultants Ltd. explained that Monenco acts as a consulting engineer to various mining companies. Its role is to obtain permits, to carry out feasibility studies, to design tailings disposal areas, etc.

With regard to old sites, Mr. K.D. Phinney indicated that the use of a model is limited to evaluating the efficiency of various reclamation possibilities and using field measurements. With regard to new sites, it is important that the water balance be carefully calculated. Mr. K.D. Phinney gave examples of sites situated in New Brunswick.

Mr. K.D. Phinney closed his presentation with his remarks related to RATAP.BMT1. It was his opinion that there are simpler models than RATAP.BMT1 to calculate the acid flux from sites but felt that RATAP.BMT1 will be useful to study the possible modification of tailing sites chemistry.

During the discussion period, a question was asked related to the conservative methods used by Mr. K.D. Phinney. Engineers are often forced to use very conservative methods.

4.2 Mr. A.V. Bell from Nolan, Davis & Associates began his presentation by indicating that models should be simple tools designed to give answers to specific questions. Models should be user-friendly. RATAP.BMT1 is a very complicated model that could form the basis for understanding complicated situations.

He hoped that his presentation would promote some discussion on the application of RATAP.BMT1 or other models to acid waste rock and further would provide some input to the modelling community for any requirements they might have for the calibration or development of models relative to acid waste rock situations. The characteristics of acid waste rock differ in many ways from those of reactive tailings, although there are of course similarities relative to the acid generation chemistry and the impact that acid runoff and leachates have on the environment.

His slide presentation was in connection with the waste rock piles of Heath Steele situated in New Brunswick. The experimental program involves evaluation of the performance of different covers and is arranged in four phases. The two first phases, the identification of the piles to be used for the tests and the installation of monitoring equipment, are completed. The third phase is underway and consists of determining the characteristics of potential covers.

He is of the opinion that it will be difficult to develop a model capable of simulating acid generation in waste rock. Such a model is nevertheless very important.

4.3 Dr. A.M. Robertson from Steffen Robertson & Kirsten (B.C.) Inc. started his presentation with his comments on RATAP.BMT1. Dr. A.M. Robertson indicated that RATAP.BMT1 must be released and tested before we can comment further on it. The model addresses the reactions very well, but not the flow path. Because we have to give answers today, we must not wait and must release RATAP.BMT1. We will do better with the model than without.

The presentation of Dr. A.M. Robertson dealt with the modelling of acid generation in tailings. He showed slides of the physical conditions which exist in tailings sites at Westmin and at Uravan. Numerous cracks and other irregularities are responsible for the entry of oxygen and the change in size distribution from layer to layer results in randomly located perched water tables. A model will only be valid if it takes these complex site conditions into account.

Dr. A.M. Robertson also reported on his tests at Faro. A special cover put onto a waste pile limits the entry of oxygen.

During the discussion period, a question was asked related to the availability of data which could be used by RATAP.BMT1. Dr. A.M. Robertson indicated that he has some data and that he had asked some months ago to have access to RATAP.BMT1.

Dr. Robertson reflected on the storage in waste rock dumps, the storage of acid salts in the dry state and dissolved state. Predictions in the downstream environment must take into account this storage and it will control our remediation measures. A large waste rock dump has a large storage capacity and it can take up to three years before anything comes out of it. Modelling of acid generation must be attempted using multi-flow channel models which will give a stochastic variation of the acid generation.

Dr. Robertson described Mines Doyon's lime consumption. The steep increase in lime consumption is believed to be caused by flushing, not by generation. Storage of acid is very important in a waste dump, not so much in a tailings site. So, Mines Doyon needs to know what the acid consumption will be in 1991, we need these predictive tools. Not all waste is producing acid at Mines Doyon and our models must recognize this. Tailings dams have edges, thus the geometry and the materials properties dictate that the models be broken up into sections.

5.0 REGULATORY AGENCY PERSPECTIVE

Mr. Keith Ferguson presented the perspective of the regulatory agencies with regard to tailings modelling. He first indicated that regulators are very sceptical towards models and then made a summary of their needs and the questions they usually ask. He gave his opinion with regard to the capabilities of RATAP.BMT1 to satisfy the needs and to answer the questions.

Mr. K. Ferguson showed slides of the tailings at Westmin and indicated that RATAP.BMT1 could find an application at this site.

Mr. K. Ferguson concluded that the regulators have a need for the use of models to predict water quality and expressed the opinion that the use of RATAP.BMT1 will provide useful information to the regulators.

During the discussion period, a question was asked related to the validation and calibration of RATAP.BMT1.

6.0 MINING INDUSTRY PERSPECTIVE

Dr. E. Yanful explained the mining industry perspective with regard to the use of models to simulate reactive tailings. First, he indicated that the needs of the mining industry are similar to the needs of the regulators; but in addition, the models must be able to verify the validity of a certain technology.

Mining companies are faced with the problem of disposal of their mine wastes not only in an environmentally acceptable manner but also in an economical manner. The main aim of the companies is to stay in business and to make a profit.

Dr. E. Yanful explained that the principal use of the model is to calculate the generation of acid from reactive tailings, but the model must also be capable of determining the efficiency of control options.

Dr. E. Yanful concluded that the mining industry has many modelling needs and that the right model must be used in the right situation.

During the discussion period, a question was asked as to whether the mining industry considers RATAP.BMT1 useful and capable to satisfy its needs. Dr. Yanful replied that RATAP.BMT1 must be used because the model is considered to be very useful. However, he was of the opinion that the model has not been sufficiently validated and that it must be tested more rigorously.

7.0 PRESENTATIONS FROM FOREIGN DELEGATES

Mr. Björn Sodermark and Ms Marie Collin from Sweden, Dr. Kirk Nordstrom from the United States and Dr. A.I.M. Ritchie from Australia described respectively their countries perspective.

7.1 Mr. Björn Sodermark of the Swedish Environmental Protection Agency explained that work started in Sweden ten years ago on the identification and classification of reactive tailings deposits. With regard to abatement measures, the preferred solution was the installation of a cover because this method is long lasting and requires little maintenance.

The next step involved the development of a model capable of determining how to build an efficient cover. He expressed doubts if ever there will be a comprehensive program that can be fully trusted to calculate the final acid flux from reactive tailings for all systems and assumed that it may not be necessary because each problem is site specific.

Mr. Björn Sodermark then presented the results of a case study in Sweden to determine the best cover, both from a technical and economical aspect.

In Sweden, the government must provide the extra funding for the installation of covers for top priority projects. Because of the high cost of the abatement measures, Sweden is now acquiring a better understanding and developing more complete models.

Thereafter, Ms Marie Collin from Kemakta Konsult AB gave a brief summary of her work carried out in Sweden with models for the calculation of the effectiveness of covers. She explained the content of her model and described some examples of calculations carried out with the model.

During the discussion period, Ms. Marie Collin indicated that it was her opinion that the temperature module incorporated in RATAP.BMT1 was incorrect. Dr. J.M. Scharer replied that the module has since been changed completely and takes into account the concerns of Ms Collin.

7.2 Dr. Kirk Nordstrom of the U.S. Geological Survey explained that in the U.S.A., one is primarily looking at old sites and that it is estimated that there are some 55 billion tonnes of reactive tailings, most of them from copper and uranium mining.

Is there an acid problem? and must one act and how? are the questions that must have answers. The two remedial measures considered are source control and effluent control.

Dr. Kirk Nordstrom gave a brief summary of the investigations and treatments carried out over the last years. He explained that during the 60's and 70's the work was carried out by federal agencies, research institutes and universities who were very qualified. In the 80's, the trend is to engage a consultant and such firms often do not have the proper expertise.

Dr. Kirk Nordstrom stressed the need for closer collaboration between researchers, government and industry. He would like to see more use made or more effective use made of the existing geochemical models, thus taking more geochemistry into account.

Dr. Kirk Nordstrom gave a brief summary of the geochemical models used in the United States. He explained the studies carried out at Riverton, Wyoming where field results were compared to results obtained with geochemical and hydrological models. He explained the results of investigations carried out at Butte, Montana and expressed his doubts about one of the conclusions of the study which seemed to indicate that it would take 20,000 years for significant contaminants to move down into the groundwater.

He also touched on the work carried out at Whitewood Creek, South Dakota where the model MINTEQ was used and gave a good resemblance to the measured values. Dr. Kirk Nordstrom described the investigations being undertaken at Pinal Creek, Arizona, where a plume of acid from an old storage reservoir poses a threat to the Phoenix aquifer.

7.3 Dr. A.I.M. Ritchie from the Australian Nuclear Science & Technology Organization (ANSTO) began his presentation with his comments on RATAP.BMT1. He expressed his conviction that the model will be an important tool for regulators and operators to evaluate different control options. Then he gave, chronologically, a description of the work carried out at ANSTO related to the production and utilization of models.

The model has progressed from a simple homogeneous model, where the oxygen is transmitted by diffusion through the pore spaces, to an adjusted model, which takes into account the transmission of oxygen through diffusion into the reaction zone. Finally, the model has been corrected taking into account the fact that the oxygen is also transmitted by convection. He then gave some results of the utilization of the model.

8.0 FINAL DISCUSSION AND SUMMATION

Mr. K. Ferguson announced that the MEND Prediction Committee has decided to recommend to CANMET that the program RATAP.BMT1 be released for public use. It was indeed the consensus of the participants of this Workshop that they want to use the model. The model should be modified to make it more user-friendly and the documentation should be improved.

Dr. Henry Steger adjourned the Workshop and expressed his thanks to everybody for their participation. He thanked Ms Mary Paddon of Kilborn Engineering (B.C.) Ltd. for her excellent organization of the Workshop. Finally, Dr. Henry Steger wondered if one should not continue to meet in the future and asked the participants to think about it.

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

INTRODUCTION

Kilborn Engineering (B.C.) Ltd. was requested by CANMET under the sponsorship of the MEND Prediction Committee to organize and report the findings of a Workshop on the modelling of reactive tailings. The Workshop was to provide a forum encouraging the interchange of ideas and discussion on the modelling of reactive tailings. Participants were encouraged to provide:

- their perspective of modelling
- the differences in conceptual approaches to modelling
- future requirements for component models and linkages thereto
- their evaluation of the suitability of the model RATAP.BMT for modelling reactive tailings vis-a-vis other available models.

RATAP.BMT (Reactive Acid Tailings Assessment Program to Base Metal Tailings) is a modelling program developed by CANMET to assess acid flux from base metal tailings. Two research reports on the program appear in Appendix D and form the basis of the Workshop discussion.

Members and associates from the MEND Prediction Committee were requested to attend along with six sub-consultants chosen through a selection process for their experience and capability in modelling. Presentations were solicited from the sub-consultants who were primarily researchers and engineering consultants; from a Canadian mining industry representative; from a Canadian regulatory agency representative; and from the United States, Sweden and Australia delegates.

This report is the annotated minutes of those presentations, Section B 1 through 11 and Section C. Following these introductory remarks is the Agenda for the MEND Workshop and the names and addresses of the attendees.

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MODELLING OF REACTIVE TAILINGS WORKSHOP
MAY 23 - 24, 1990
WIGAMOG INN, HALIBURTON, ONTARIO
SPONSORED BY THE MEND PREDICTION COMMITTEE

AGENDA

Tuesday, May 22, 1990

All day	Check - in at your leisure
18:00	No host bar and dinner. Please join us if you have already checked in.

Wednesday, May 23, 1990

08:00 to 09:00	Breakfast in the Dining Room
09:00 to 09:15	Welcome - Keith Ferguson Introductions
09:15 to 09:45	First Presentation - W.J. Snodgrass, Beak Consultants
09:45 to 10:00	Question and Discussion Period
10:00 to 10:30	Second Presentation - Monenco, Keith Phinney
10:30 to 10:45	Question and Discussion Period
10:45 to 11:00	Coffee Break
11:00 to 11:30	Third Presentation - Morwijk Enterprises, Kevin Morin
11:30 to 11:45	Question and Discussion Period
11:45 to 13:15	Lunch
13:15 to 13:45	Fourth Presentation - Nolan, Davis & Associates, Alan Bell
13:45 to 14:00	Question and Discussion Period
14:00 to 14:30	Fifth Presentation - SRK, Andy Robertson
14:30 to 14:45	Question and Discussion Period
14:45 to 15:00	Coffee Break
15:00 to 15:30	Sixth Presentation - Environment Canada, Keith Ferguson
15:30 to 15:45	Question and Discussion Period

15:45 to 16:00	Seventh Presentation - Industry Perspective - Ernest Yanful
16:00 to 16:15	Question and Discussion Period
16:15 to 17:15	General Discussion and Questions
18:00	No Host Bar and Dinner

Thursday, May 24, 1990

08:00 to 09:00	Breakfast
09:00 to 09:30	Eight Presentation - Swedish Perspective, Marie Collin
09:30 to 09:45	Question and Discussion Period
09:45 to 10:15	Ninth Presentation - American Perspective, Kirk Nordstrom
10:15 to 10:30	Question and Discussion Period
10:30 to 10:45	Coffee
10:45 to 11:15	Tenth Presentation - Australian Perspective, Ian Ritchie
11:15 to 11:45	Question and Discussion Period
11:45 to 13:15	Lunch
13:15 to 13:45	Eleventh Presentation - Senes Consultants, Bruce Halbert
13:45 to 14:00	Question and Discussion Period
14:45 to 15:00	Coffee Break
15:00 to 17:00	Discussion and Summation
18:00	No host bar and dinner

Friday, May 25, 1990

Please check out by 11:00.

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MEND WORKSHOP ROSTER

VERSION IV - MAY 25, 1990

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* Denotes member of MEND Prediction Committee

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

INTRODUCTION TO THE MINUTES

Dr. Henry Steger, CANMET, introduced himself to the participants as Chairman of the Workshop and passed the meeting to Mr. Keith Ferguson, Environment Canada and Chairman of the MEND Prediction Committee.

Mr. Ferguson in his welcoming address stressed the importance of mathematical modelling of reactive tailings and indicated that this programming is further advanced than one might realize, especially with the work done by CANMET on RATAP. He further indicated that there is resistance in the industry to tailings modelling, but stressed that a lot of good people were participating today and that a useful tailings model can be developed.

With these comments in mind, the floor was passed to Dr. W.J. Snodgrass of Beak Consultants Limited for his comments on modelling in general and RATAP in particular.

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

BEAK CONSULTANTS LIMITED - DR. W.J. SNODGRASS

The presentation focussed on the RATAP model, especially its adaptation for prediction of acid generation from base metal mine tailings, (RATAP.BMT1). Please refer to:

1. Adaptation of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings, Main Report, in Appendix Tab D.
2. Hand-out by Dr. W.J. Snodgrass: Concepts used in RATAP.BMT computer model found at the end of these minutes.

In his opening remarks, Dr. W.J. Snodgrass indicated that he was very much involved with the development of RATAP and thus well qualified to speak about its concepts. He listed the objectives of his presentation:

1. To outline some of the concepts of the model
2. To present his opinion of the weaknesses, limitations and future directions for the model, because understanding what the model does or does not do is the key point for this Workshop.

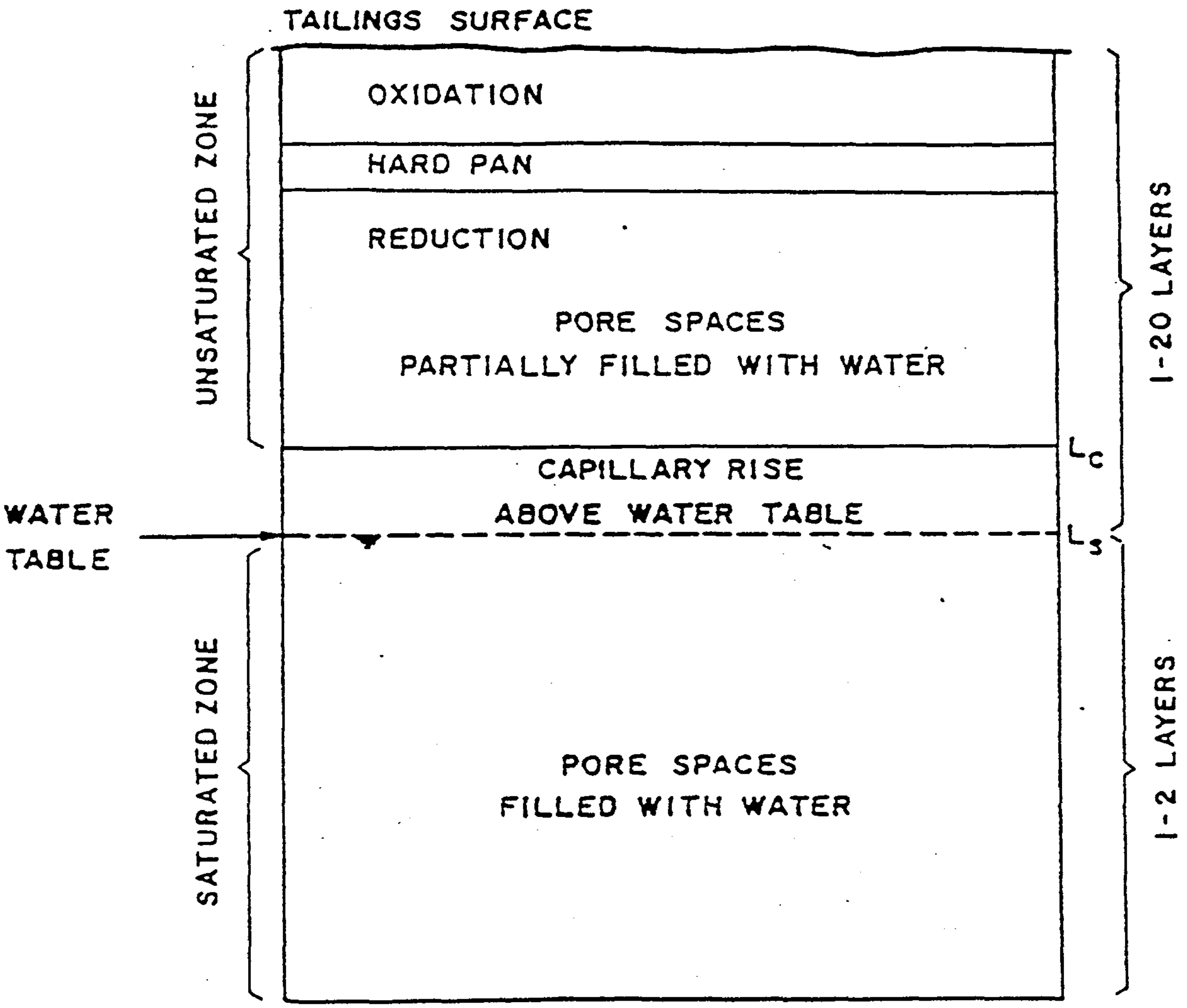
He summarized his view, and that of his colleagues, of the objectives of modelling:

1. To provide a useful predictive basis for making decisions concerning tailings management alternatives; and/or
2. To describe mathematically the most important interactions involving chemical interactions and migrating groundwater.

He indicated that the hand-out discusses the model framework and also summarizes the seven steps useful in approaching the modelling process. Please refer to paragraph 2.1.2, page 2.2 of the hand-out. Dr. Snodgrass stressed that RATAP's assumptions (pyrite oxidization, moisture model, etc.) and limitations are difficult to define. Some limitations can be defined by checking the validity

FIGURE 2.1

CONCEPT ADOPTED
FOR MODELLING OF TAILINGS



of the model and by determining the predictive abilities of the different components of the model, example the sub-model for moisture.

Dr. Snodgrass further classified the environmental models into research models, application models and management models; and listed a few available in the literature. All models describe geochemistry, but some do it only from an equilibrium point of view. RATAP uses a probabilistic approach. Dr. Snodgrass gave examples of programs using probabilistic code (UTAP, etc.).

Dr. Snodgrass had a few comments on the philosophical approach of model building, starting simple and increasing its level of complexity, indicating that with RATAP the start was made at an intermediate level of complexity. He gave an overview of a few of the simple concepts in RATAP. RATAP basically is orientated towards assessing the source term, ie. tailings.

Figure 2.1 of the hand-out shows the concept adopted for modelling of tailings, consisting of an unsaturated zone and a saturated zone. The various layers of the unsaturated zone were described and are determined by field measurements or from other knowledge or more complex physical models.

A discussion (Dr. Ian Ritchie) resulted regarding the field measurements to determine the depth of the layers and if RATAP determined any of these positions.

Dr. J.M. Scharer: Hardpan and the oxidation zone are calculated in RATAP. The key question is the depth to the fully water-filled zone. There are formulations for estimating the moisture content with depth. One of the limitations to RATAP is formulae for predicting soil moisture content variations.

Continuing his description with the RATAP concept, Dr. Snodgrass indicated that RATAP uses a box model approach on a layer by layer basis, computing the oxygen concentration of the air, the chemical concentration of the pore water and the variation of the minerals in the different areas.

The elements considered include:

- Ca, K, Na, Al, Fe
- sulphate, hydroxides, silicate, carbonate
- various trace elements such as Cu, Zn, As.

Several validation checks were included with the model:

- solution concentrations vertically
- calculation of oxygen
- residual concentration of pyrite.

Several conclusions come out of RATAP and out of the Australian and American literature. One major conclusion is that the oxygen diffusion rate is the factor which controls oxidization and thus determines acid flux.

Dr. Snodgrass listed on page 2.13 of his hand-out a list of processes that RATAP.BMP considers: kinetics, oxygen diffusion, shrinkage, etc. and asked the question how simple or how complicated a model must be to successfully answer questions? He further compared RATAP.BMP with other acid drainage models, (example, Jaynes, Ritchie, etc.) and referred to work by Snodgrass et al. regarding the total flux of oxygen with time as a function of the gas diffusion coefficient (see Figure 3 of hand-out).

The work with the models shows that there is a marked decrease in acid flux over time. The hand-out lists a comparison of capabilities of the various models (Table 2.1).

Dr. Snodgrass further described five determinants of code selection:

- question(s) you ask (see page 2.7, etc. of hand-out)
- environment of concern (tailings area?, waste rock?, pit?)
- complexity of the question (acid flux?, metals?, hardpan formation?, temperature?)
- source factors (tailings area?, waste rock?)
- background of the user (user friendly?, programmer friendly?)

RATAP is concerned only with the source term. Other models are needed to simulate effects further down the environment.

A list of eleven questions (problem statements) used for assessing acidic drainage which models can help answer is given on page 2.7. RATAP.BMP can address Questions 1 through 5:

1. Time to oxidize all pyrite
2. Time of acid generation for tailings area
3. Acid flux from a tailings area
4. Flux of acidity and heavy metals from a tailings area
5. Estimate of uncertainty of flux of above point 4.

RATAP.BMP needs some information from Questions 6, 7 and 8 for its use.

6. Water balance
7. Groundwater flow
8. Thickness and soil moisture of unsaturated zone.

Other questions can be addressed by other codes:

9. Consolidation (geotechnical based)
10. Equilibrium sequences
11. Control options.

Dr. Snodgrass presented a short extract of a videotape of acid mine drainage with points of view by industry, government and public.

Comment on videotape
by Dr. Kirk Nordstrom: The film was done very well but did not address the quantitative aspect of the problem and what will be done about it.

QUESTION AND ANSWER PERIOD:

Mr. Ferguson:	Does RATAP address any control options?
Dr. Snodgrass/Dr. Scharer:	It does not address control options per se but these can be built into RATAP: it is flexible enough, and can be done very easily. The initial conditions of the boxes can be varied at will; for example, the effectiveness of $CaCO_3$, the effectiveness of a cover, the effectiveness of moisture content can be built in. The soil moisture model is a reasonable model, but it lacks the sophistication of some other existing models.
Mr. Ferguson:	A side by side comparison of the effectiveness of various control measures should be one of the major uses of a model, but I heard you saying that the model should be used 'judiciously'. Please explain.
Dr. Nicholson:	We looking at a model that is built with certain constructs in mind, the control options built in can be looked at.
Dr. Nordstrom:	We need to understand the systems as much as possible and then determine what type of control might work better.
Dr. Nicholson:	Agrees, he considers the control options as a second stage after investigation of the basic processes.

Dr. Snodgrass: He reiterated the basic objectives of the model and indicated that the first main objective is understanding the system, what are the most important processes? Oxygen diffusion is one of them.

Mr. Ferguson: What is it what we want the model to do? We should ask the question again once we have heard from other speakers.

* * * * * *

CONCEPTS USED IN

RATAP.BMT

COMPUTER MODEL

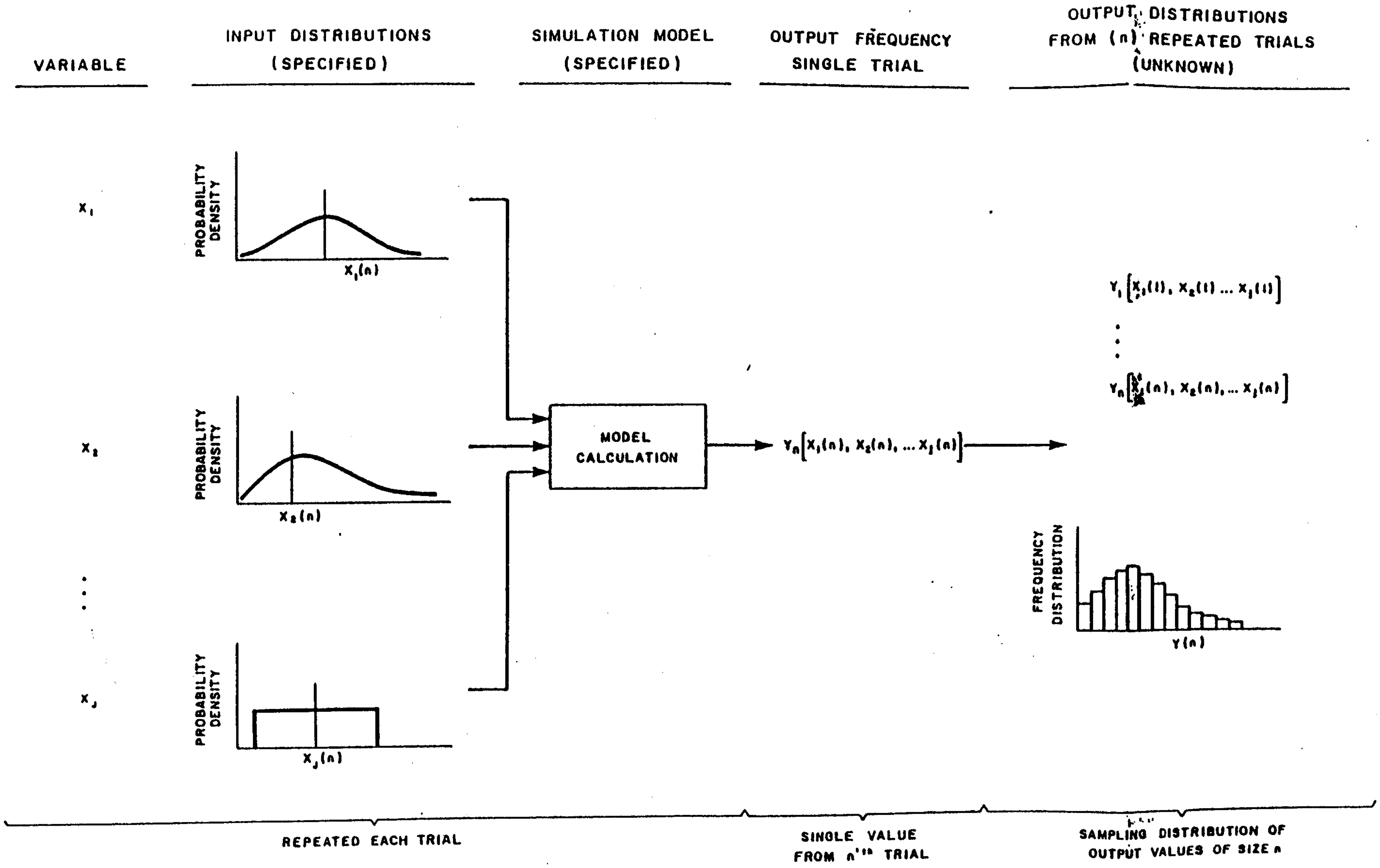
MODELLING OBJECTIVES

1) TO PROVIDE A USEFUL PREDICTIVE BASIS FOR MAKING DECISIONS CONCERNING TAILINGS MANAGEMENT ALTERNATIVES; AND/OR

2) TO DESCRIBE MATHEMATICALLY THE MOST IMPORTANT INTERACTIONS INVOLVING CHEMICAL INTERACTIONS AND MIGRATING GROUNDWATER

FIGURE 11

CONCEPT OF PROBABILISTIC ANALYSIS



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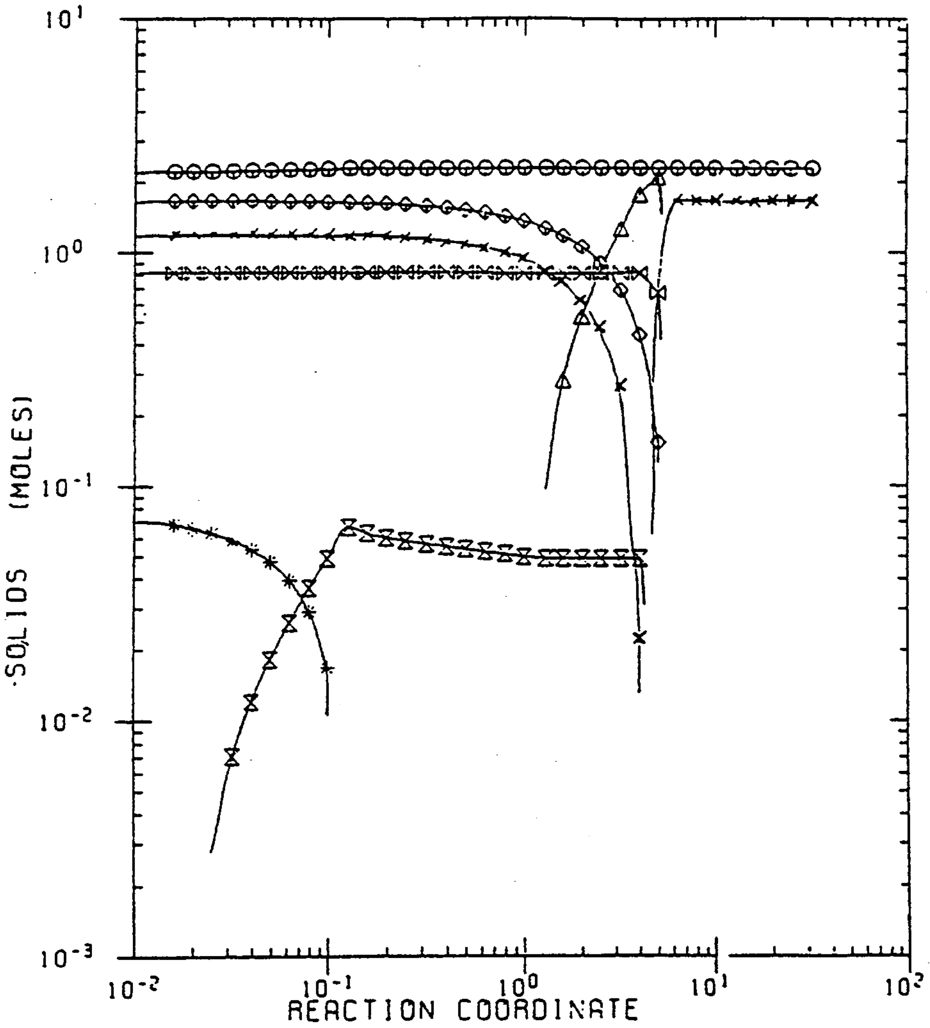

Figure 2a. The abundances of solids as a function of the reaction coordinate oxygen, for the full mineral assemblage. (symbols: ○ = $CaSO_4 \cdot 2H_2O$; × = FeOOH(α); Δ = $FeSO_4 \cdot 7H_2O$; ∗ = $CaCO_3$(s); ◊ = FeS_2 (pyrite); ⋈ = $Al(OH)_3$ (gibbsite); ⧗ = $FeCO_3$(s).)

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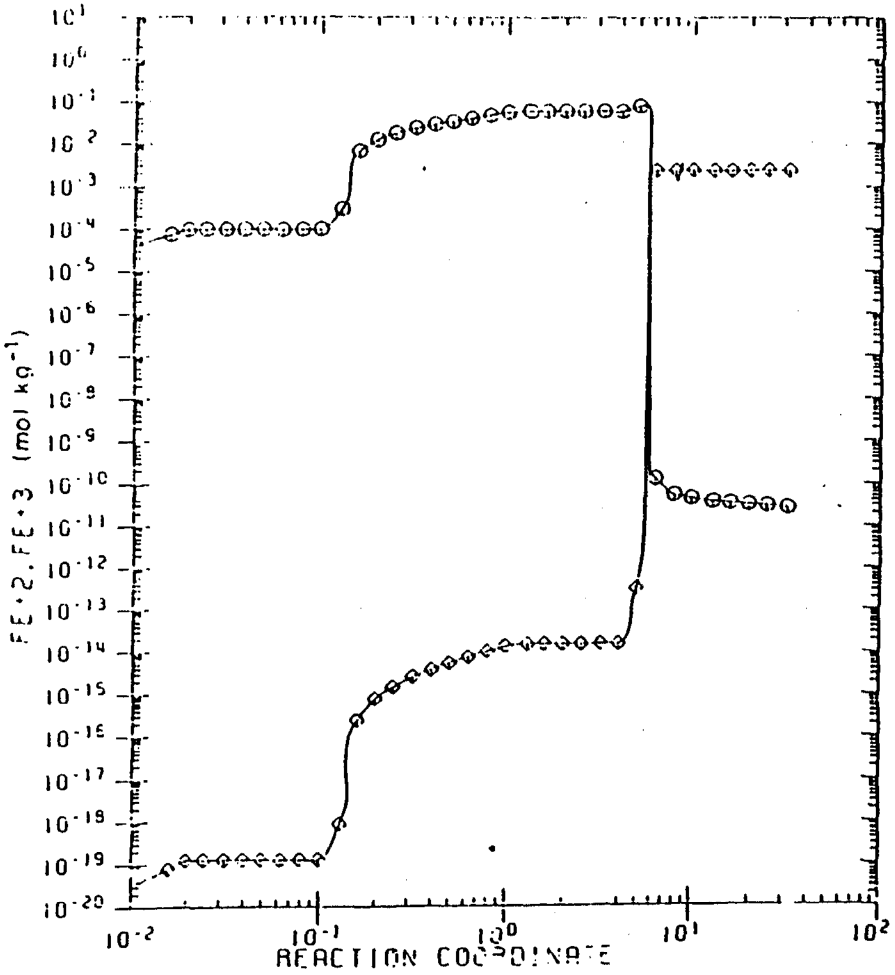

Figure 2c. The concentration of Fe^{2+} (0–) and Fe^{3+} (◊ –) as a function of the reaction coordinate oxygen, for the full mineral assemblage.

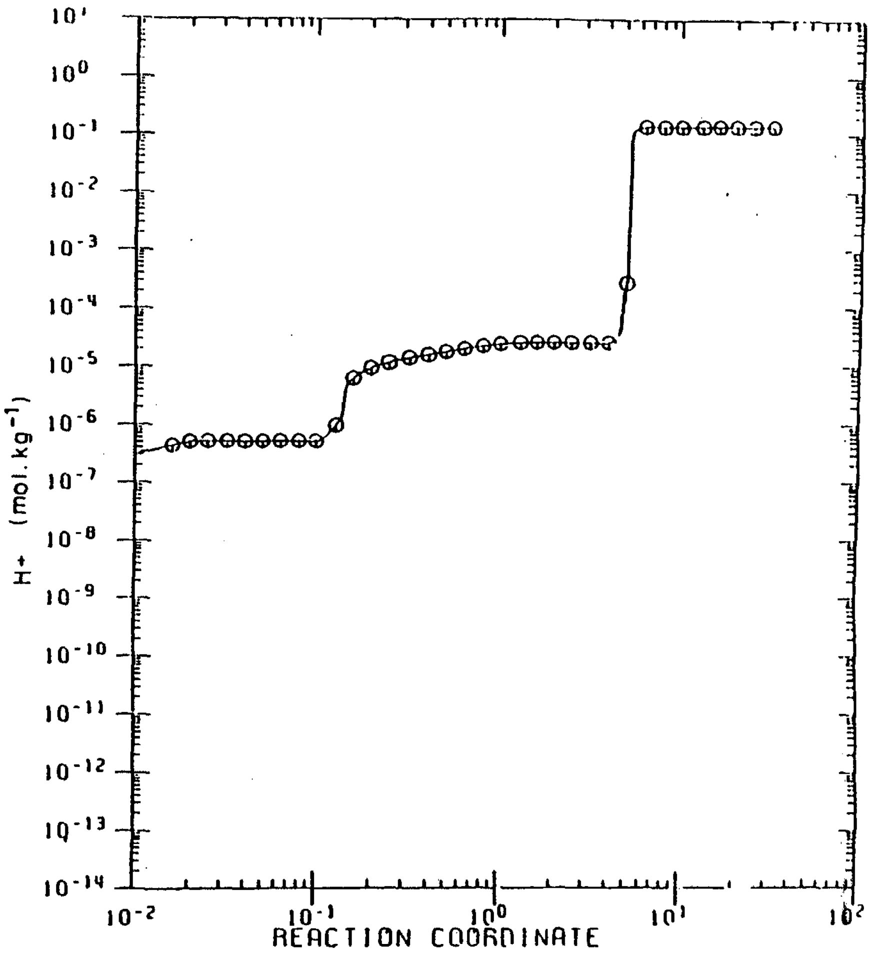

Figure 2b. H^+ concentration as a function of the reaction coordinate
gen, for the full mineral assemblage.

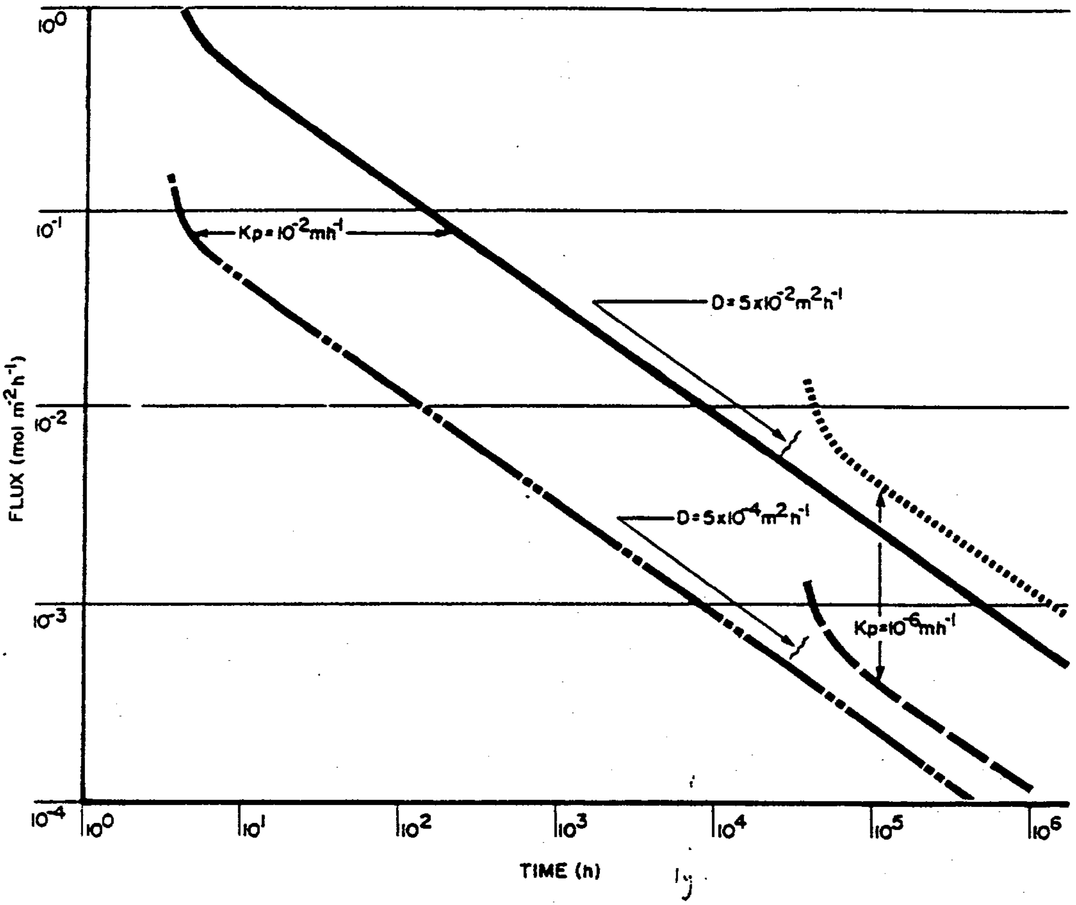

Figure 3. Total flux of oxygen with time.

TABLE 2.1: COMPARISON OF CAPABILITIES OF SEVERAL MODELS

Component	Jaynes et al.	Harries & Ritchie	Nicholson et al., 1986	RATAP
Sulphide Mineralization	pyrite in shale blocks	Sulphide in blocks of rock	Pyrite particles	Pyrite, phyrrohite, chalcopyrite particles
Sulphide Particle Size Distribution	No	No/Yes	No	Yes
Sulphide Mineral Oxidation Kinetics	Biological chemical	Implicit as boundary condition	First order coefficient	Biological, chemical
Diffusion Control (in each box)	Constant vertical implicit into shale	Constant vertical (air) Water in porous rock	Calculated from moisture content	Calculated from moisture content
Pore Water Chemistry	Yes	No	No	Yes
Neutralization	Semi-empirical	-	-	Thermodynamic/ kinetic
Mass Balance on Sulphide	Yes	Yes	Yes	Yes
Mass Balance Other Minerals	No	No	No	Yes
Effectiveness of Management Options	-	-	-	Yes
Uncertainty Analysis	No	No	No	Yes

2.0 MODELLING OBJECTIVES

The development of a model to answer questions concerning acidic drainage from mine tailings is dependent upon the objectives of the investigator. Different questions asked about the same tailings system will necessitate the use of different models. The background of the professional using the models will also influence the selection of a model.

This section presents a framework for evaluating deterministic quantitative models which describe acidic drainage from tailings. These models have the following objectives:

(1) to provide a useful predictive basis for making decisions concerning tailings management alternatives; and/or

(2) to describe mathematically the most important interactions involving chemical interactions and migrating groundwater.

After presentation of the framework, the alternate questions that may be of concern to an investigator concerned with acidic drainage are presented. Finally, the objective and problems for which RATAP is appropriate, are critiqued and compared to a few other available models which evaluate similar questions.

2.1 Framework for Evaluating One's Confidence in Calculations Made by a Model

2.1.1 Introduction

A model is an abstraction of reality that describes, in either qualitative or quantitative terms, a certain set of the complex interrelationships of the system being studied. A quantitative model is described herein as being either empirical or deterministic. An empirical quantitative model involves a statistical relationship between two or more variables. A deterministic quantitative model is based upon physio-chemical principles such as the law of conservation of mass.

In any given situation, the costs of management procedures to ameliorate environmental impacts can be determined with relative ease and accuracy. However, the results or benefits of such procedures can only be predicted with assurance if quantitative models, capable of predicting the response of the tailings to a given management strategy, are available.

The utility of such models for assessing the effects of tailings management alternatives on acidic fluxes is determined by the degree to which the models adequately abstract the coupled nature of hydrogeology and chemistry and are readily understood and applied by a particular use.

2.1.2 Framework Used In This Study

A variety of frameworks have been presented in the literature for evaluating the utility of a model, its capabilities and limitations.

Various investigators have presented their approach to the modelling process (e.g., Orlob, 1975). We find it most useful to use the following seven steps.

1. problem definition and objective formulation,
2. system abstraction and discretization (conceptual model, physical and chemical boxes),
3. model construction,
4. mathematical solution,
5. model calibration,
6. model validation, and

7. model prediction.

A model is constructed to fulfill certain objectives. Different objectives necessitate different spatial and temporal scales. For example, one's objective may be to develop a model capable of predicting how long into the future, acidic fluxes from a tailings pile will be a problem. Alternatively, one's objectives may be to predict the seasonal change in pH in tailings pore water at a specific depth in the tailings pile. The former objective involves a time scale of years to decades while the latter involves a time scale of weeks. The spatial scale of the former objective is the thickness of the tailings mass while the spatial of the latter objective is 1 m or less. If one is particularly concerned with predicting the pH variation at the oxidation front, the spatial scale may be 0.01 to 0.1 m.

These examples illustrate particular points about the terminology: spatial scale, temporal scale. These "scales" represent the size of the "time block" or the "distance block" over which significant changes occur. They also become the size of the "time block" or of the "size block" (spatial scale) which is used for organizing the model.

System abstraction and discretization is the physical, biological and chemical representation of the tailings deposit.The system boundaries are selected based on field data which describe the physical, biological and chemical characteristics of the system and from data which describe the flows of mass or energy into and out of the system. Selection of the system boundaries is made to be consistent with the model objectives. A box (e.g., a layer of the unsaturated zone) is considered as one of a spatially distributed set of entities each of which has the capacity to store mass or energy; the total number of boxes describes the physical structure of the entire system. A box is chosen such that flows of mass or energy occur between interconnected boxes, but such that spatial variations of mass or energy within the box are small. Thus, the tailings mass is divided into volumes (boxes) which are each sufficiently homogenous such that physical, chemical or biological detail necessary for the realization of a model's objectives is not lost. In the RATAP model, the boxes consist of a number of layers, one lying above the other; for example, for 20 layers in the unsaturated zone and 2 layers in the saturated zone, the total number of boxes is 22.

A box is subdivided into compartments, each describing a different biological or chemical entity deemed to be important to fulfill the model's objective(s). Thus, each compartment describes a different form of mass or energy found within a box (e.g., iron concentration in the porewater, mass of mineral phases such as goethite, pyrite, air temperature, orthophosphate, detrital); compartments within a box describe all of the forms of mass or energy stored within that box. Physical, biological and chemical flows of mass or energy may occur between interconnected compartments.

As Okubo (1971) notes, "the box model treats mixing 'averaged' over each box and attempts to see changes only as between boxes. The mixing processes at the interfaces of the boxes are parametrically disguised as exchange - or transfer-rate constants with the dimensions of (t^{-1})." Okubo also notes that other investigators have found the well-mixed assumption unnecessary for successful box model application, and have related the box transfer-rate coefficients to advective and eddy diffusivity processes described in 1-D and 2-D transport models.

Construction of a model involves four basic steps:

1. identifying the physical, biological and chemical processes and the corresponding laws governing the rates of mass flow between compartments and/or boxes (e.g., pyrite oxidation, oxygen diffusion; gypsum precipitation or dissolution);

2. listing the assumptions made, including simplifications of physical laws;

3. constructing systems of mathematical equations which describe the behaviour of the system. The system of equations is constructed by writing a statement of

conservation of momentum, energy or mass for each compartment in each box. For example, the rate of change of mass equals the difference between the rate of mass input and the rate of mass output; and

4. evaluating the boundary conditions.

The mathematical solution involves using an analytical solution or numerical solution for the system of equations to obtain the predictions made by the model. If computer techniques are used, the mathematical solution also involves code verification. Code verification is the process used to show that the mathematical equations have been properly coded in the computer language.

Model calibration consists of selecting a set of coefficient values from field measurements and/or literature values such that the model output duplicates a set of *in situ* measurements of some known system. The coefficients are constants describing empirical relations where fundamental laws are unavailable. Their uniqueness is partially a function of the spatial and temporal structure of the model. Selection of values for coefficients for which field measurements have not been made is usually done by varying the coefficient values over the range of reported literature values until satisfactory agreement is reached between model predictions and environmental observations. Coefficient values obtained from field measurements may also be varied if the modeler decides that a measurement does not describe conditions throughout a compartment. Alternatively coefficient values may be determined using an optimization method which minimizes the difference between model predictions and observations.

Model validation consists of using the calibrated model to predict one or more sets of system conditions independent of the first set. If the validation is acceptable, then the model may be used, with confidence, to make predictions for purposes described in the model objectives. If the validation is not acceptable, then the model should not be used to make predictions where one requires much confidence in the predictions. If the validation is not acceptable, it may be necessary to modify the model with respect to its assumptions (step 2 above), or mathematical basis (step 3 above). Model predictions may be used with confidence for those objectives for which model is validated. It may still be necessary to use the model either for research purposes (to determine the most important factors in the model) or for extrapolation purposes. Its use in such an application should be made carefully, as one's confidence in the results may be fair to poor.

For model validation, several tests are possible. The first (least severe and insufficient) test is to compare the model structure--compartments and intercompartment mass flows--with the real world to determine that functional responses are reasonable and that all major factors are included. A second test involves comparing model predictions and environmental observations for one tailings pile for one time period (e.g., for a month or year) equal to or longer than the time scale of the model's objectives. A third (more severe) test involves two possibilities: (i) a comparison between model predictions and environmental observations for several tailings piles and/or (ii) a comparison between model predictions and observations from one tailings system for a time period equal to several time scales. A fourth test involves comparison between model predictions and observations for several time scales on one tailings system and for one time scale on several tailings systems. The standard used to determine the adequacy of agreement between model predictions and observations may be either qualitative (e.g., judgment, of reasonableness) or quantitative (e.g., use of an appropriate statistics and lack of fit test). To the present time, most model validation efforts have been qualitative.

2.2 Proper Formulation of Problem Statements

The above description of a framework indicates that the proper formulation of the problem statement and the expectations of the user are two key aspects of the analyses of acidic drainage. The problem statement may be a "problem definition", on a statement of "modelling objectives". It must be a clear, concise, articulation of the objectives of the investigator. It should be written in a precise manner, but in sufficient detail to be unambiguous to the lay reader.

If the investigator can only describe, in fuzzy terms, his expectations of what he wants out of an investigation, this is not sufficient for a problem statement for a modelling investigation. These expectations must be defined more precisely in order that the proper model be selected.

Listed below are a series of problem statements currently in use for assessing acidic drainage and a few comments upon model selection.

1. How much time is required to oxidize all pyrite in a tailings area?

   The problem statement would require that the model adequately describe the major factor controlling the rate of acid generation. Since several models (see Section 2.5) indicate that the acid generation flux over time is mainly controlled by oxygen flux into the tailings, a model which considers a constant pyrite oxidation rate coefficient and pore gas diffusion of oxygen may be adequate.

   From knowledge of the acid flux over time, the time to consume most of the pyrite can be calculated.

2. How long will acid generation be a problem for a tailings area?

   This problem statement needs to be further referred before one can attempt to address it. It can mean any of the following:

   i) how much time is required to oxidize most of the sulphide minerals in the unsaturated zone? (This is similar to question 1 above)

ii) how much time is required before the acid generation flux decreases by one order of magnitude or two orders of magnitude to cause a substantially different geochemical regime than at present?

iii) how much time is required before the acid flux reaches a specific level (e.g., x mol acid/m^2/yr.) which the environment can accept. (This question is addressed below under question 3).

For the second interpretation (ii) given above, the same variables used for question 1 would be required.

3. What is the acid flux from a tailings area?

The model objectives would require that it adequately model all hydrochemical and biological variables which control acid formation.

This would include:
- pyrite oxidation kinetics;
- soil moisture and cover control upon oxygen penetration;
- water pathways and associated water flow rates;
- quantity of acid generated from pyrite oxidation, and its subsequent input into aqueous pathways.

With these specifications, the acidity calculations would represent an upper limit because they would not include neutralization reactions. Neutralization reactions between tailings or soil grains, and acidic pore water reduce the acidity because of the effective alkaline buffer generated from the solid phase.

4. What is the flux of acidity and toxic heavy metals from a tailings area?

This problem statement would require that the model have similar capabilities to that described above for question 3 but that the model be able to evaluate solid phase dissolution processes in addition. The relevant precipitation-dissolution processes would include (i) interactions with limestone added in a cover, in the tailings, or in downstream receiving waters, and (ii) modifications to speciation of metals such as aluminum and iron in the pore water as the acidic water percolates through aluminosilicate and other minerals.

Modifications to the speciation of iron due to its hydrolyses causes a significant change in the acidity of waters formed by pyrite oxidation. These modifications are influenced in a significant way, by chemical precipitation processes between minerals and pore water and by ion-exchange processes. These pore-water, mineral-phase interactions may be controlled by equilibrium processes (e.g., as defined by a solubility product) or by kinetic processes (e.g., the mineral may dissolve very slowly - not allowing the pore water to attain equilibrium with it).

5. What is the Uncertainty in Estimates of Fluxes of Acidity and Metals from a Tailings Area?

This problem statement requires that the model have the ability to calculate (predict) the potential range of acidity fluxes emanating from the tailings. The range of acidity can be estimated using one of two approaches. A black box approach based upon observed data may be used. Alternatively, modelling tools can be used to relate the flux estimates to environmental variability, the heteorgeneity of tailings, and the uncertainty in values of the models parameter.

A statistical treatment of observed data provides some estimates of uncertainty but it is specific to the observed existing conditions of the tailings site. It does not allow any extrapolation to other conditions which may be encountered in the future or at other planned sites.

Methods which allow estimates of uncertainty based upon the model itself include sensitivity analyses, first order error analyses, adjoint methods, error propogation methods, and Monte Carlo simulation. All methods suffer from one or more limitations. Sensitivity analyses generally involves evaluating the effects of specific model parameters, physical processes or tailings properties. First order error analyses and error propogation methods require additional mathematical analyses for their application and are difficult to apply in a complex, non-linear problem. Monte Carlo simulations gives a global overview of uncertainty; it requires additional computer coding and hence is an overhead to model simulation.

6. What is the water balance for a tailings area?

This problem statement requires that the main hydrological pathways influencing water movement through a tailings area be evaluated.

Two different types of models may be evaluated, dependent upon the pathways of concern: a watershed based hydrology model or a groundwater based hydrology model. A watershed based hydrology model can be used to describe the major interactions between air and the earth; these include rainfall, runoff, infiltration, evaporation, and evapotranspiration. The level of complexity of the watershed model can range from a water budget approach to rainfall-runoff models. The rainfall-runoff models may only consider rainfall, surface runoff and infiltration and not describe groundwater processes; hence, they are oriented mainly towards event runoff modelling. More complex watershed models (e.g., HSPF) may describe infiltration, interflow, and deep groundwater movement for calculating the base flow in surface streams.

A groundwater based model may be used to describe the major hydrological fluxes through the ground and tailings system. Such models generally treat air-ground processes and groundwater contributions to surface water as a boundary condition.

7. What is the magnitude and direction of groundwater flow through the tailings?

This question would require use of a 1-D, 2-D or 3-D, non-steady-state or steady-state, hydrologic groundwater model to estimate flow direction and magnitude.

8. What is the thickness of the unsaturated zone and its soil moisture profile?

This questions would require use of a 1-D non steady-state or steady-state unsaturated zone model. It may include the hysteric effect of wetting and draining.

9. How much consolidation will occur over time?

This question requires use of a model which describes the effects of tailings solids weight upon forcing porewater upward or downward, the vertical permeability of the tailings, and the degree of deformation as consolidation occurs.

10. What equilibrium sequences of minerals occur during the acidification process?

This question requires use of a reaction pathway code type of model. It provides the conceptual basis for predicting what heavy metals might be transported from the tailings as acidification occurs. Uncertainties in the calculated equilibrium sequence occur due to uncertainties in the basic thermodynamic data used in the calculations.

The actual sequence of minerals, which are observed in nature, may differ significantly from the calculated sequence for two reasons:

i) fomation of metastable solid phases, and
ii) kinetic factors.

The kinetics of mineral precipitation and dissolution are one major area requiring inclusion in reaction path codes to develop truly predictive tools.

11. What is the effectiveness of control options?

This question will be dependent upon the control option being considered.

A cover which is composed of depyritized tailings can be evaluated with a model similar to that used to answer questions 3 or question 4 above

A cover which attempts to minimize oxygen penetration could also be described with the model used question 3 or question 4.

Stream neutralization of acidic runoff would require a model which describes river/lake water flow, the buffering provided by the neutralizing agent and the natural background buffering in the stream before impact of acidic drainage, and the acidity of seepage from the tailings area. In such streams, the background buffering can generally be described by the bicarbonate system. As well, buffering provided by such neutralization agents as lime and limestone can also be described mathematically using the bicarbonate system. Contributions to electroneutrality provided by organic acids in streams draining bogs and by aluminum in streams draining from igneous bedrock areas, may also be important in certain streams.

2.3 Modelling Philosophy

The philosophical approach used by this team of investigators is to start simple and to increase the complexity of the model as required.

2.4 Questions Addressed by RATAP.BMP

RATAP.BMP was formulated to answer questions 1, 2, 3, 4 and 5 above.

RATAP.BMP considers the following processes:

- sulphide mineral oxidation kinetics as a function of water temperature, oxygen concentration, mass of pyrite etc.
- oxygen pore-gas diffusivity and its control upon the oxygen flux into the tailings.
- shrinkage of sulphide mineral grains as they oxidize.
- depth-dependent characteristics.
- temperature variations due to oxidation of phyrrotite, pyrite, chalopyrite, and sphaelerite.
- moisture variations with depth in the unsaturated zone.
- equilibrium and kinetic reactions between pore water and relevant minerals.
- pore water transport of metals including aluminum, iron, calcium, magnesium, potassium, silica, copper, zinc, and of anions including arsenic, sulphate, and carbonate.

2.5 Comparison of RATAP.BMP to Other Acidic Drainage Models

Other models in the literature include those of the Rogowski group (e.g., Jaynes, et al., 1984a, b)) and of the Ritchie group (e.g., Davis and Ritchie, 1986; Davis et al., 1986). The questions addressed by RATAP.BTP have been defined and coded independently of these other modelling efforts. This has resulted in some similarities and some significant differences between the varios modelling efforts.

1. Models for Acid Mine Drainage

Jaynes et al. (1984a, b) evaluated acidity fluxes from spoils associated with coal strip mines. Pyrite dynamics are based upon the total time required to oxidize all pyrite within a box in the discretized vertical profiles (one-dimensional).

'The rate of pyrite oxidation is assumed to be controlled by both first-order reaction kinetics and the combined diffusion rates of the products and reactants to the reaction site within shale blocks. Both oxygen and ferric iron may serve as the oxidant. Ferric iron concentrations are controlled by iron complexation and precipitation reactions that are assumed to be rapid and completely reversible. Ferric iron is assumed to be produced by both direct chemical oxidation of ferrous iron and oxidation of ferrous iron by autotrophic bacteria. Environmental factors which affect the bacterial "activity" are oxygen concentration, temperature, and solution pH. Fluctuations in the bacterial "activity" caused by changes in their environment are considered to be rapid so that their "activity" is always at its maximum. Pyrite oxidation and bacterial "activity" are linked through their modification of a shared environment.'

'Oxygen is the ultimate electron acceptor for pyrite oxidation and is considered to be supplied to the profile by gaseous diffusion, from the surface first through the large pore spaces between the shale blocks then into the blocks to reach the reactive pyrite surfaces. Diffusion of oxygen in the blocks is implicit in the model. Sources for hydrogen ion include pyrite oxidation, iron complexation and precipitation reactions. Sinks for hydrogen ion include ferrous iron oxidation, hydrolysis of the rock matrix, and exchange reactions. These last two sink reactions are lumped together as one reaction in the model and given a pH dependence in the form of a simple empirical reaction. Carbonate neutralization reactions are not considered explicitly at this time. Hydrogen ion, ferrous and ferric iron and ferric complexes, sulfate and bisulfate, and solution "acidity" are leached from the spill profile by a constant water flux.'

The major differences between the model of Jaynes et al., (1984) work and RATAP.BMT include the following mechanisms considered by RATAP:

- carbonate mineral interactions;
- mass balance on the various mineral phases;
- explicit inclusion of all relevant pore water cations and anions and use of the electroneutrality equation to calculate pH, rather than use of an empirical relationship of Jaynes et al. for calculating pH; and
- uncertainty analyses.

Similar to the findings of RATAP, Jaynes et al. (1984) found that:

- oxidation of pyrite is primarily controlled by the oxygen diffusion rate of all the factors which could potentially control pyrite oxidation.

The findings of RATAP, differ from those of Jaynes et al., (1984). The following is one example. RATAP calculates that kinetics are an important control upon acidic fluxes for an initial period of time before oxygen diffusion control becomes important over the long-term. Jaynes et al. results do not indicate that kinetic controls are important for any substantial period of time although they assert that autotrophic activity can greatly increase the rate where oxygen is not limiting

2. Models for Acid Fluxes From Tailings

The work of Ritchie's group is a landmark in the sulphidic mine waste literature which parallels the development of RATAP.

Their main objective was to calculate the acidic flux from tailings. They used the work of Jaynes et al., (1984) as a basis for developing a simplified treatment of the problem. They assume that the 'oxidation rate is limited by the rate that oxygen is supplied to oxidation sites within the particles comprising the wastes. Oxygen supply is assumed to be controlled diffusion through the pore space of the wastes followed by diffusion into a moving reaction front within the particles. An approximation is made which incorporates the effect of reaction of pyrite into the boundary conditions. A further approximation involving a pseudo steady-state simplification is made that allows an analytical solution to be formulated.' The results predicted by this analytical solution are compared with the calculations of an earlier simpler model (Harries & Ritchie, 1983). The chemistry of the pore water is ignored.

In further work, two additional refinements were considered. 'In the first, the limiting approximations were examined by developing a numerical solution to the set of equations for oxidation in pyrite mine wastes under natural conditions. The numerical solution allows one to examine oxidation at the moving front within the blocks comprising the wastes. Properties predicted by the numerical solution were compared with results predicted by an approximate analytical solution.'

In the second refinement, 'the assumption of just one initial size for pyritic blocks was relaxed to take proper account of the range of particle sizes in the wastes. Comparison of the simpler model with the more realistic model (i.e., incorporating the sulphide mineral psd.) shows that for practical purposes the simpler model is good enough to assess the magnitude and longevity of the environmental impact of pollutant generation in the wastes. It is, however, essential to include the particle size distribution to obtain accurate estimates of the heat source distribution profile and to a lesser extent the oxygen concentration profile, two parameters that can be measured and used to assess the applicability of the model to the real field situation.'

In an extension of this work (Bennett et al., 1989) the convection and diffusion of oxygen into heaps was examined. 'Both downward oxygen transport through the surface and to horizontal movement in through the side were modelled. Measured values of pyrite oxidation were used to evaluate kinetics. The results show that for time scales smaller than about two years, diffusion is always an important oxygen supply process. For air permeabilities less than about 10^{-10} m^2 thermal convection is never a significant air transport mechanism at these early times but it is significant at permeabilities exceeding 10^{-10} m^2. For time scales longer than 2 years after establishing the heap, and at permeabilities less than about 10^{-10} m^2, thermal convection can become significant depending on the magnitude of other parameters such as heap size and pyrite content.'

Similar to the findings of RATAP, oxygen diffusion is a dominant process controlling pyrite oxidation. However, their formalism does not allow one to assess the relative of importance of kinetics versus diffusion upon controlling oxygen fluxes into the heap as readily as RATAP.

2.6 Summary of Modelling Approaches

An overview of the different components addressed by each of these models is summarized in Table 2.1. In general, the models from the left column to the right most column represent a gradation from simple questions to more complex questions. The models which address more complex questions are required to assess the limitations of the models asking less complex questions.

In terms of deciding whether a more complex model is required, the work of Ritchie's group indicates that for some questions, more complicated treatments (e.g., considering the psd of sulphide mineral blocks) do not give significantly different answers that simpler treatments (e.g., uniform sized pyrite minerals). However, a systematic evaluation of all possible simplifications are required before one can decide that a particular degree of detail is <u>not</u> required in a model.

To assist the MENDS committee in their evaluation of models, a systematic listing of simplifications for RATAP could be made. Then a comparison of RATAP's calculations with and without these simplifications could be made to determine whether particular modificiations/simplifications are in order to the model.

Using the work of Ritchie's group and the RATAP.BMP as a base, the following summary can be made.

The work of Ritchie's group present an oxygen transport-control approach to model construction and testing. It involves defining the problem, assessing important mechanisms, and then making the appropriate modelling assumptions upon which the code formalism and model predictions are based. As ever, as more questions are raised about the modelling assumptions, more complex models must be formulated to address these questions concerning the appropriateness of the original model. In the case of the more complex questions, Ritchie's work indicates that the original models were essentially "good enough" for the relatively simple questions being asked, but that the models required significant modification when the questions being asked, changed.

In reflection of questions addressed by the RATAP.BMT code, it addresses a larger number of questions and questions which are more complex than those addressed either by the work of Ritchie's group or by Jaynes' work. It permits evaluation of the limitations of the modelling work of these two respective investigators. RATAP.BMP permits evaluation of many additional questions which are beyond the scope of the questions evaluated by these investigators. But RATAP.BMP requires a more informed user and is harder for a novice user to obtain an understanding of the main processes controlling acidification reactions and the resultant transport of metals and anions.

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

MONENCO CONSULTANTS LIMITED - MR. K.D. PHINNEY, P.ENG.

This presentation dealt with the consulting engineer's perspective on the modelling of reactive tailings. Please refer to:

- Presentation to MEND Workshop (May 23-24, 1990) on the Modelling of Reactive Tailings by K.D. Phinney, P.Eng., Monenco Consultants Limited found at the end of these minutes.

In his opening remarks, Mr. Phinney indicated that they regard the 'problem' as fairly simple and that their whole emphasis is orientated towards examining the effectiveness of control procedures. Monenco's perspective is from the role of consulting engineers to mining companies. Consulting engineers perform the following functions:

- obtaining permits
- environmental assessments
- design of tailings disposal areas
- reclamation of existing sites
- design and/or operation of waste treatment systems
- the close-out of existing sites and
- hopefully, the successful close-out of new sites.

He wondered if we were working in a vacuum and why more mining companies representatives were not involved?

Mr. Phinney indicated that Monenco is able to model to the extent necessary to be satisfied of the direction to take and the rate of success. His remarks follow his hand-out well; therefore, the minutes will be brief and only highlight important aspects and useful questions.

The presentation consisted of three parts:

- Reactive tailings and the need for acid generation modelling with respect to existing and future tailings deposits,
- General comments on RATAP.BMT,
- Discussion of a couple of case studies.

Reactive tailings and the need for acid generation modelling

With respect to existing tailings deposits, the modelling is limited to the evaluation of the expected effectiveness of potential reclamation schemes. Direct measurements are possible because the deposit exists. The modelling is very easy, and is based simply on limitations due to the rate of transport of oxygen across the surface. Advective transport, diffusion and breathing or venting is taken into account.

Dr. Ritchie asked a question regarding the breathing or venting and how this was done.

Mr. Phinney replied that they take into account the weather, the conditions in the area, and make the assumption that the increased pressure increases the level of oxygen within the substance that is modelled. Thus, with respect to existing tailings sites, measurements are taken of what is occurring and then modelling is used to determine what the expected effectiveness of various control methods might be.

Mr. Phinney illustrated this with a case of a former strip mine (waste rock) in New Brunswick. Please refer to page 3, Figure 1 and Table 1 of his hand-out.

Questions resulted regarding the oxygen flux and the oxygen concentration of the waste pile (Dr. Ritchie, Dr. Scharer) and a general discussion followed regarding 'over-engineering' (Dr. Yanful, Dr. Robertson).

Mr. Phinney replied that the whole site is acid generating and this is based on site measurements. The amount of oxygen required is back-calculated. No information on the oxygen content of the waste pile is assembled as this is not in the scope of work. The waste rock is very porous and the assumption is made that no neutralization by materials takes place inside the pile. The costs are based on the worst case acid generation scenario. Mining companies are prepared to spend that money if they are confident that the selected option will be successful, they are prepared to spend the right amount of money, not necessary the optimum amount. There is no storage in the system, so it is a stationary system.

A discussion followed between Dr. Robertson and Mr. Phinney regarding Faro, which is acid generating but with no current acid flux, and the possible answer for long term covers.

Mr. Phinney continued his presentation with the case of the future sites. Please refer to page 3 and 4 of his hand-out. The water balance must be carefully modelled, but the need for modelling the acid generation process within reactive tailings during the operating phase of the mine is not attempted nor is needed. His emphasis with respect to future sites is to ensure that he has a firm handle on the water balance and has looked at the residual total acidity with respect to the final reclamation plan.

An example was presented of the future tailings disposal site of the East West Caribou Project in northeastern New Brunswick. The disposal site consists of a 100 ha flooded area. Modelling was used to estimate the rate of total acid generation with respect to the flooded tailings in order to determine if the effects on the receiving side will be acceptable.

At present, at the request of the regulatory agencies, tests are being carried out with flooded and exposed pilot tailings deposits in order to confirm the results of the modelling.

Comments on RATAP

Mr. Phinney said that he knew about UTAP, but had not heard about RATAP before this meeting. At first he thought that the purpose of the model was to calculate total fluxes of acidity and indicated that a simpler model can be used to achieve this; but indicated, as was brought up today, that it has also other useful purposes. From his point of view, he summarized the three useful purposes of a model:

- a convenient format to account for all the factors which are descriptive of the process
- a format which can be used to fit, measure data, leading to an expression which can then be applied to other similar or new cases
- a method that can be used to quantitatively predict the behaviour of a process using a minimum of field information.

He was not sure where RATAP fits in, probably with purpose one. It is a very impressive compilation of most of the factors which affect acid generation, and suggested not to be disappointed if it does not give quantitative answers in all cases.

He always regarded the process of acid generation within tailings and waste rock as simple, but very complex because of the heterogeneity of sites and a myriad of environmental factors. He expressed the opinion that it is very difficult to develop an all inclusive model that will describe future and even existing situations without a lot of field measurements.

The propagation of error analysis must be done on the RATAP model. He wondered if part of it is not done using the probabilistic approach. It would be interesting to see what the range of values would be for Figures 3.2 and 4.2 (previous presentation of Dr. Snodgrass). He wondered what the limits of such a model are when one has to estimate, use information from the literature, assume so many of the various parameters that go into the model. What does it mean in the end, what do the estimates give us?

In his concluding remarks, Mr. Phinney indicated that from his point of view, such estimates are not essential to the successful management of long term reclamation of tailings deposits. However, the RATAP model may have a very useful application as a means of investigating the feasibility of modifying the chemistry of sites, form in situ seals and study other inhibitors to acid generation.

QUESTION AND ANSWER PERIOD:

Dr. Robertson:	He repeated the question already raised during the presentation with regard to the example of the Faro tailings pond, which is strongly acid generating but has no current acid flux due to storage and neutralization. Monenco's technique could thus not be used to predict long term solutions.
Mr. Phinney:	Monenco's approach would be to assume that the impoundment would generate acid 'forever' and would try to determine the ultimate capacity of the pond to neutralize the acid. One needs to know more about the hydrology and the hydrogeology than one needs to know about the chemistry.
Dr. Robertson:	He indicated that the chemistry is important and that we do need this type of complex model.
Mr. Sodermark:	He commented that he liked the simple practical oxygen flux approach, which is exactly like the approach they had in Sweden. We must use the knowledge we have today to make abatement measures but we have to improve our knowledge all the time. We need complex models to try to optimize our abatement measures. In the meantime, we have to do a lot of 'over-engineering', that is the way we have gone in Sweden.
Mr. Phinney:	He added that independent of the modelling results you still are responsible for what happens if the results are wrong. This does not mean that modelling is not useful, but the modelling results alone will not do it. The sites are so complex and different although the mechanisms are simple.
Dr. Scharer:	The acid flux will start when the $CaCO_3$ is consumed and this gives a problem with Monenco's worst case approach. The RATAP model gives a realistic scenario, it will simulate a realistic

acid flux. That is where RATAP becomes useful, it will tell when there is going to be a problem.

Mr. Phinney: One needs to plan for the future but the controls must be put into place today if one expects a problem in the future.

Dr. Nicholson: He clarified that it is not the purpose of the current models to indicate to a mining company, with any degree of confidence, what their treatment costs will be in the next 20 years. However, the models can tell what the trends in acid flux are over time, and this is important.

Dr. Snodgrass: Is the acid flux at the receiving end or at the water table separating the unsaturated zone from the saturated zone or out of the tailings? RATAP will help answer some of the questions in a simple way, why is there no acid flux, rate of acid generation potential, influence of neutralizing potential, etc. He does not disagree with Mr. Phinney's practical approach.

Mr. Phinney: The acid flux is at the receiving end. RATAP is not complex but the tailings dump is complex.

Mr. Kresta: He indicated that a model is a very important tool to evaluate the best approach but one must be certain that one can make claims based on the model. The mining company must have the capability of restoring the site to a situation acceptable to the population. These conditions are site specific.

Mr. Barr: The liability varies and is site specific, the long term cost should not be carried by the taxpayer.

Mr. Bell: Modelling is extremely useful because it will help us to understand the system better. In support of Mr. Phinney's conservative approach, he commented that conservatism is something that exists and will probably increase in the future because of public participation. A lot of forces push engineers towards conservatism.

* * * * * *

PRESENTATION TO

MEND WORKSHOP (May 23-24, 1990)

on the

MODELLING OF REACTIVE TAILINGS

K.D. Phinney, P.Eng.
(Monenco Consultants Limited)

1.0 INTRODUCTION

We are pleased to provide our perspective on the modelling of reactive tailings. Our perspective derives from our role as consulting engineers involved in the planning of new mine developments and the reclamation of existing and abandoned minesites. In this regard, we have developed and routinely apply in-house models which enable the prediction of acidity. However, within this context, our use of models is limited to estimations of acidity as a function of control and reclamation procedures. We have a high degree of confidence in these models, due mainly to the fact that our specific needs for modelling enable the parameters to be limited to those which can be accurately defined.

From our perspective, we do not foresee the need to use more generalized models, such as RATAP.BMT for the planning of new mines or the close-out of existing sites. The following sections will hopefully provide some rationale for this view and possibly help to orient the direction of further model development efforts.

Welcome Screen Search Report List

2.0 REACTIVE TAILINGS AND THE NEED FOR ACID GENERATION MODELLING

The need for acid generation modelling can be considered with respect to two situations:

1. existing tailings deposits, and
2. future tailings deposits.

Existing tailings deposits are those that have resulted from previous or ongoing milling operations. Future tailings deposits are those that will occur as the result of new mines.

2.1 Existing Tailings Deposits

Our modelling of existing tailings deposits is limited to the evaluation of the expected effectiveness of potential reclamation schemes. The existence of the deposit enables direct measurement to determine the status of the deposit with respect to acid generation. This information, combined with an evaluation of surface and groundwater hydrology, enables a complete description and "interpretation" of the acid generating system.

Modelling becomes necessary to assess the expected effectiveness of potential reclamation schemes. Thus, we routinely model the effects on acid generation of flooding and earthen covers, based on the ability of these "covers" to limit the rate of oxygen transfer into the tailings. This type of modelling is relatively straightforward and depends primarily on a careful definition of those factors which will affect the rate at which oxygen can be transported into the tailings.

The results of this modelling include a set of "worse-case" acidity fluxes, ranging from those for the existing deposit to those for various reclamation schemes. This information can then be combined with other engineering considerations to determine the expected costs and effectiveness of the potential reclamation methods.

Our use of modelling for existing situations is possibly best illustrated by reclamation investigations for a 120 ha former strip mine site in New Brunswick. This site generates 10-20 t/d of acid (as $CaCO_3$) due to pyrite oxidation and has resulted in water treatment operations at a rate of 450-900 m^3/h on a year-round basis. The system was described by the completion of chemical, hydrological and hydrogeological studies. Modelling was then used to determine the expected effectiveness, based on residual acidity fluxes, of various types of covers (Table 1).

2.2 Future Tailings Deposits

In our view, the management of reactive tailings for future mine developments will not depend on, nor necessarily be enhanced by, the application of generalized acid generation models such as RATAP.BMT. We expect that our use of models will continue to emphasize the assessment of effectiveness of reclamation schemes and estimations of residual acidity for environmental assessment purposes.

The fact that tailings from a particular ore deposit will be reactive can readily be established from the "history" of the area, acid generation tests on samples of ore during drillings and bulk sampling programs, and from acid generation tests on samples of tailings during bench and pilot milling programs. We would not replace these direct measurements by predictions based solely on modelling.

The present and no doubt future regulatory climate dictates, at least in our experience, that future tailings sites must be stabilized within a short period of time following cessation of mining. Hence, predictions of the long-term behaviour of "exposed" tailings is of little interest to the regulatory agencies. The behaviour of the site after reclamation is of paramount interest. Hence, our modelling of acid generation is directed towards this interest.

Whereas we carefully model the reclaimed tailings disposal site, we do not attempt nor need to model the acid generation process within reactive tailings during the operating phase of a mine. Only the water balance must be carefully modelled to ensure acceptable management of the tailings disposal area during the operating phase. Acid fluxes for exposed tailings during the operating phase are based on the results of acid generation tests. Inaccuracies in the estimate of acid fluxes will result only in decreases or increases in the quantity of neutralizing agents, which in any case are normally quite small compared to overall operational demands for milling and minewater treatment. Inaccuracies in the water balance, however, can have disastrous results due to hydraulic limitations in treatment equipment or the tailings disposal area itself.

Our use of models for future tailings disposal sites is illustrated by the East West Caribou project in northeastern New Brunswick. This 2500 tpd base metal mine, which started-up in 1988, involved the development of an approximately 100 ha disposal area for reactive tailings. Modelling was used to support the application to the regulatory agencies for allowance of reclamation by complete flooding of the tailings. At present, "pilot" flooded and exposed tailings deposits are being created at the request of the regulatory agencies, in essence, to confirm the results of our modelling.

2.3 RATAP.BMT - Some Comments

The RATAP.BMT model as described in the March 1988 report is an impressive compilation of many of the factors which influence the acid generation process within sulphide tailings. However, the non-homogeneity of tailings and the processes within them, and the myriad of micro- and macroenvironmental factors which influence the acid generation process may not favour the development of an all-inclusive model capable of quantitative predictions of acid fluxes and other parameters. An analysis of the "propagation of error" for the model would likely indicate severe limitations for quantitative predictions, even for the assumption that the model accurately reflects the mechanism of acid generation. In any case, from our perspective, such estimates are not essential for the successful management and long-term reclamation of tailings deposits. The model may have more application as a means of predicting or "following" the chemistry of existing tailings deposits for which reclamation measures are not planned due to economic or technical limitations.

We believe that less generalized models, developed on the basis of rate limiting factors, such as oxygen transport, will have more accurate application to "real" tailings disposal situations.

TABLE 1

Fire Road Site - Effectiveness of Barriers

Item	Relative Rate of Acid Generation (After Reclamation)
No reclamation (present situation)	1.0
Water cover (100 cm)	0.02
Porous soil (100 cm)	1.0
Silt or clay cover (unsaturated) (100 cm)	0.3
Clay cover (saturated) (100 cm)	0.02

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

MORWIJK ENTERPRISES LTD. - DR. KEVIN MORIN

The presentation dealt with comments on the adaptation of the reactive acid tailings assessment program to base metal tailings, RATAP.BMT1. Please refer to:

> Comments on: Adaptation of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings by Kevin A. Morin, (May 27, 1990) found at the end of these minutes.

Dr. Morin indicated that his comments are based on the Main Report, Adaptation of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings. He had not received a copy of the model and thus had not been able to test it; also he had not received any other reports on RATAP.

Modelling is part of a strategy for delineating the processes involved in an environmental system, and the strategy should include:

- field studies
- laboratory testing
- theoretical applications
- modelling.

The report does not indicate who is going to be the end user of RATAP, what is the intent of the model? It could be used for research investigations, consulting assessments, industry monitoring, regulatory inquiries, criminal prosecutions. It is necessary to know the end user. He stressed that his comments are oriented towards the weaknesses of RATAP.BMT1, not the strong points.

Dr. Morin indicated that each model is composed of three basic types of routines:

Type 1:	Complex routines based on established field studies, laboratory testwork and/or theory
Type 2:	Complex routines based on arbitrary assumptions derived from field studies, laboratory testwork and/or theory
Type 3:	Simplistic routines based on simplifications of field studies, laboratory testwork and/or theory.

He then compared the modules of RATAP.BMT1 with the above classification summarizing them as follows:

Type 1:	most of the acid generation modules
Type 2:	tailing cover module:

From the report, Dr. Morin understood that the tailings cover is either there or is not there, and that it cannot be added along the way. This represents a weakness of the model since it cannot simulate existing tailings (when there is already acid generation) when a cover is added.

Dr. Ritchie asked for a response and Dr. Scharer indicated that there is no problem because the initial conditions can be set.

Aqueous Speciation Module:

- ferrous iron sulphate is not included
- the sulphate balance might not be accurate.

Dr. Scharer replied that the pH is not very much affected by this, but that ferrous iron sulphate is included in the sulphate balance.

Trace Metal Module:

- Copper is not included.

Dr. Scharer commented that this was corrected in RATAP.BMT2. Mr. Halbert commented that the geochemistry of copper and zinc are some of the areas of greatest uncertainty, and a discussion followed with Dr. Scharer related to the concentrations of copper hydroxide and copper carbonate in solution. Dr. Snodgrass requested to press on.

Type 3: Tailings Temperature Module:
The model does not account for increases along the sides of the tailings areas.

Water Content Model:
The basic objective of the model is to predict acid flux, that is acid generation and movement of the water. The model assumes a constant water content on a month by month basis for 100 years, and this assumption might make the predictions unreliable.

Dr. Nicholson queried Dr. Morin's understanding of model validity when a simple assumption is made in one of its modules. Dr. Morin replied that if the water movement is complex, then RATAP may not be appropriate; but if the water movement is simple, then RATAP can answer complex questions.

Solute Transport Module:
Dr. Morin criticized this module. There is very little documentation and no complex equations are included as is the case with other modules, only two sentences.

Dr. Snodgrass explained that in the past year the developers of RATAP have looked at the effect of variable flow rates.

Dr. Ritchie asked Dr. Morin if he believes the water model should be a 3D model. Dr. Morin replied that a 2D model would be better rather than a 1D one, not necessarily a 3D one, but suggested to use the model first and then make changes after a survey is made of what people think.

Dr. Morin continued by explaining his understanding of the water movement and compared this with the Jaynes model. Dr. Nicholson explained that the Jaynes model deals with waste rock piles, spoils, and the physical situation dictated the concept used.

Dr. Morin continued his criticism with other selected issues:

- stochastic probability distributions, it would be better to have the results expressed between confidence levels
- assumptions of homogeneity
- equation 2.0 which equates the lateral area is not balanced.

A discussion resulted with regard to the assumptions of homogeneity. Dr. Ritchie indicated that the sites are very homogeneous in large blocks. Based on the knowledge of the hydrogeology of the site, the tailings can be split up in several blocks and modelled separately. Mr. Halbert said that this approach is possible and was carried out at Nordic.

Dr. Morin continued his review of RATAP.BMT1 with the problems related to calibration of the model at Waite Amulet:

- the physical system included a perched water table
- poor sulphide data
- pH was poorly predicted. (error up to 1.3 pH units)

A general discussion resulted regarding data one can expect to receive from tailing areas. The data was poor and the validation should not be based on such a situation:

- oxygen was predicted to decrease to zero whereas measurements indicated that not all oxygen was consumed
- predicted acid fluxes were hypothetical only and not based on filed data.

A general discussion resulted regarding the error in oxygen measurements.

Dr. Morin concluded his criticism of RATAP.BMT1 by indicating that the basic objective of RATAP, which is predicting acid flux, may not be met due to limitations such as water movement. He, therefore, proposed the following recommendations:

1. Stop the development of the model for several years
2. Conduct field work and laboratory studies for comparison to the model

3. Release the model at the same time to the public in order to determine its acceptability and its applicability .
4. After several years, conduct a survey to determine the usefulness of the model
5. Then improve on the model.

QUESTION AND ANSWER PERIOD:

Dr. Nicholson:	Dr. Nicholson started the question and discussion period by stating that he agrees that it would be nice to see what Dr. Morin indicated, but the RATAP model is actually only a research model. It is not in the shape nor format that can be used right off the shelf by a consultant or a mine manager. In any case, the model has its limitations and will only answer certain questions.
Mr. Ferguson:	Is RATAP.BMT a better tool than the other tools we are using and should it be used?
Dr. Nicholson:	Yes, but he stressed that it is not the only tool one should be using; the model should not be sent out to an unexpecting public. The users must be well aware of the problems and limitations and of the assumptions built into the model or required as input. The users must be taught how to use the model.
Mr. Davé:	Industry will use the model with unsophisticated operators, thus the model must be in a user friendly shape for the average engineer.
Dr. Steger:	How closely must we be able to model what we see in the field and do we prefer field data over modelling results?

Dr. Morin:

- the pH should be between plus or minus .5 units
- the acid flux should be within a factor of 2
- the water quality should be accurate. Dr. Morin indicated that he is a hydrogeologist and thus biased towards water movement. Emphasize the field site more, this is more important than modelling.

Mr. Davé: Is the model ready right now? Can it be used?

Dr. Nicholson: The model is not complete.

Mr. Phinney: Mr. Phinney disagreed and expressed the opinion that the model is there right now and can be used and tested. The model contains many of the factors that affect acid generation and certain modules can be useful for some, other ones for others. He thought that it is naive to assume that one can develop a generalized tailings reactivity model that would apply to all tailings situations.

Mr. Halbert: The model has to be adopted to each specific site and this is the main reason why RATAP has not been released. We do not want people to say that it does not work.

Dr. Nicholson: He indicated that development will accelerate if the model is released, but research is needed to calibrate and validate the model.

Dr. Steger: He said that part of the reasons for this meeting is to find out if RATAP.BMT is an acceptable model, if the development is proceeding in the right direction and if there is a use for it.

Dr. Nicholson: He indicated that one cannot be responsible for what the user does with the model.

Dr. Yanful: Dr. Yanful contributed by saying that industry depends on research and is willing to help in the development of models and to take advantage of tools that are available to improve its options.

Ms Erickson: She thought that there is not enough information to properly validate and evaluate the model and a copy would be required for use at some sites. What other calibration exercises have been carried out?

Mr. Davé: At Waite Amulet, we had only one hole with a complete set of data.

Dr. Steger: He indicated that another set of data would be required if some money is available.

Mr. Townsend: Mr. Townsend stated that development depends on research.

* * * * * *

COMMENTS ON:

Adaptation of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings

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May 27, 1990

GENERAL COMMENTS

Modelling can be viewed as part of an interactive strategy for defining an environmental system. The strategy should include field studies, laboratory testwork, adaptation of theory, and modelling.

An enhanced emphasis on any portion of the aforementioned strategy, such as modelling, leads to an imbalance. For example, enhanced emphasis on field studies will provide data which may be too complex or extensive for interpretation and simulation. Enhanced emphasis on modelling, for example, may provide simulations which are too complex to be applied to, or detected, in the field.

In some ways, the RATAP model has suffered from enhanced emphasis. The most obvious demonstration of this is the stochastic capability of the model. The probability distributions for such parameters as porosity and hydraulic conductivity have not been defined in most field studies and yet these distributions are critical to accurate stochastic simulations. Even the creators of RATAP implicitly recognize this limitation because they do not call for measurements of distributions in their recommendations for further field work in the RATAP.BMT1 report.

In contrast to the enhanced emphasis, RATAP.BMT1 suffers from some problems that render its simulations simplistic and restrictive at best. This can be seen by viewing any model as composed of 3 basic types of routines:

1. Complex routines based on established field studies, laboratory testwork, and/or theory.
2. Complex routines based on arbitrary assumptions derived from field studies, laboratory testwork, and/or theory.
3. Simplistic routines based on simplifications of field studies, laboratory testwork, and/or theory.

If a model is composed of the first type only, it is applicable to relevant field sites and laboratory experiments. If only the second type of routine is present, accuracy of the model's simulations can be arbitrary. With the third routine, the simulations will be simplistic at best.

The scenario is more complex whenever two or more types of routines appear in a model. As explained in the Specific Comments below, RATAP appears to have all three basic types of routines, which could render the RATAP simulations arbitrary and simplistic at best. While there are indeed some modules in RATAP that belong to the first, competent category of routines, these <u>best</u> routines are not the determining factor in the quality of the simulations. The weakest modules determine the highest quality of the simulations.

Welcome Screen Search Report List

Another problem with RATAP is more general in nature. A model can be used for a number of purposes by various types of users. For example, a model such as RATAP could potentially be used for research investigations, consulting assessments, industry self-monitoring, regulatory inquiries, and criminal prosecutions. Each of these purposes has unique requirements. RATAP appears to be intended for research investigations based on documentation and existing applications to date. However, the Government of Canada has likely been contibuting funds to RATAP development in order to use the model for regulatory purposes. The appropriate purposes and the intended users should be specified.

RATAP has been under development for several years and the modellers have only applied RATAP to a few locations at a few tailings areas. This effort is not sufficient to determine the general applicability of the model. Consequently, RATAP should be released so that it can be used by researchers around the world to determine whether it is generally applicable and where it can be best improved. Specific recommendations are:

- Halt (government-sponsored) model development for several years.

- Initiate detailed field and laboratory studies for comparison with RATAP simulations and for expanding current in-field knowledge of acid drainage from tailings impoundments.

- Release the model as soon as possible to the public domain, that is, to the intended users, to allow an extensive determination of RATAP's acceptability and applicability.

- Several years after release of RATAP, conduct a survey of users to determine where RATAP can best be improved to make it more accurate and more widely applicable.

- At that point in time, determine whether government-sponsored improvements should be undertaken.

SPECIFIC COMMENTS

These comments specifically address the report entitled, "Adaptation of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings Main Report" (15SQ-2344-7-9208). The main body of this report without appendices was provided for review by Kilborn Engineering (B.C.) Ltd. as part of this contract.

p.2-2, bottom: Only 8 iterations are allowed on pH, temperature, and oxygen. In the tests, this was found to be sufficient, but occasions may arise where more iterations would be necessary. The model should calculate an error factor during iterations and, at least, report the error in the output.

p.2-3 & 2-4, Section 2.2.1: This is a simplification of carbonate behavior in groundwater systems that may incorrectly predict pH in the range at which most copper and zinc would precipitate from solution. Further testing of the implications of the simplification are necessary.

p.2-4: Because initial Ca is calculated from gypsum solubility, this indicates that no $CaCO_3$ is dissolving at Time 0 and, thus, that neutral-pH conditions are assumed at initial times. This assumption is not discussed in the report, but is important because simulations of existing acidic tailings must then begin at some time in the past before net acidity developed.

p.2-6, "Water Content": The water content is said to remain "at steady state from month to month". In other words, it does not change during the 10- to 100-year simulations. Water tables in tailings impoundments are known to fluctuate by up to meters seasonally. Consequently, this simplification results in significant errors in the calculation of acidic fluxes, which is reportedly the primary objective of the model. Therefore, one can conclude that the model has failed to meet its primary objective.

p.2-6 & 2-7, Section 2.2.3: It is not clear if a tailings cover can be placed during a simulation so that pre-cover conditions can develop before the cover appears. If not, the model cannot accurately simulate existing sites following cover. If the cover can appear during a simulation, the assumption of constant water content (previous comment) is not valid.

p.2-8, Section 2.3.2: Although research has shown that some acid generation occurs at impoundment dams, Equation 2.7 does not account for lateral conduction. The "dx" used in the equation is actually oriented vertically. This implicit treatment of a tailings impoundment as homogeneous is incorrect as acid generation in some impoundments is known to occur in localized areas, such as at dams where lateral movement is significant.

p.2-9, Equation 2.10: Dimensional analysis of this equation incorrectly indicates:

$$\text{mol}\cdot\text{m}^{-2}_{\text{tails}}\cdot\text{mth}^{-1} = \text{mol}\cdot\text{m}^{-2}_{\text{sulfide surf}}\cdot\text{mth}^{-1}$$

This may have introduced errors of orders of magnitude on the biological rate into simulations.

p.2-10, Equation 2.11: The other stated factors of nitrogen [N] and inhibitors [I] are missing from this equation and thus appear to be arbitrarily dismissed.

p.2-19 & 2-20, Section 2.6.2: The factor of p_p is introduced without explanation.

Section 2.7: Nearly the entire section is dedicated to geochemical reactions which affect non-conservative aqueous species. The critical issue of water advection is only described in 2 sentences on p.2-22. The sentences state that plug flow only occurs: vertically in the unsaturated zone and laterally in the saturated zone. These assumptions as well as that of constant water content over decades dramatically highlight the restrictive and idealistic treatment of water movement by the model.

In light of the restrictive and idealistic assumptions on water movement, the simulations of acidic fluxes by the model can only be considered restrictive and idealistic. Consequently, the intense effort placed in the calculation of acid generation and metal levels will be rendered inappropriate in some unknown number of cases by the simplistic treatment of water movement.

p.2-23, Equation 2.41: Under the explanation of "f_2, f_3", what are "2+ and 3+ sericite species"?

p.2-24, Equations 2.43 and 2.44: These equations are "based on laboratory data" of unspecified quality and unreferenced environmental conditions. As a result, the validity of the iron system and the associated acidity system in the model rests on this ambiguous "laboratory data".

p.2-26 & 2-27, Equations 2.48 to 2.51: In chemically reducing acid-drainage systems, a major aqueous complex is $FeSO_4^0$ because the major cations and anions often include ferrous iron and sulfate, respectively. Because this complex is not in the model, accurate simulations cannot be assured for iron, sulfate, and acidity.

Also, Equation 2.51 assumes that all SO_4 complexes are negligible relative to SO_4^{2-} and HSO_4^-. This is incorrect in many cases of subsurface acid drainage.

Welcome Screen Search Report List

Furthermore, manuals for models such as PHREEQE have explained that pH cannot be accurately calculated from electroneutrality because of round-off errors and because H^+ can be derived from the vast "storage" in H_2O. There is no mention of these problems in the report, leading to a conclusion that either the resolutions were overlooked in the report or the model may not accurately predict pH (see comment for p.3-6).

p. 2-28, Section 2.9: The first assumption means that Cu and Zn play no role in the calculation of pH (Equation 2.48). As a result, concentrations of Cu and Zn must be <u>significantly</u> less than 10 mmoles/L and 0.001 mmoles/L (approx. 0.05 mg/L) at pH 2 and 6, respectively. This is unlikely, invlidating the assumption.

Sections 2.9.1 to 2.9.4: The assumptions of mineralogy in various ranges of pH appear to be arbitrary and are not justified in the report by any references to field or laboratory data. Consequently, the invokation of these assumptions may introduce signficant errors into simulations.

p.2-30: Equations 2.54 and 2.56 are not dimensionally balanced.

p.2-32, Equation 2.64: The factor CUCOP is undefined.

p.2-34, Equation 2.73: What is the meaning of "BULKD = the dry solids below solids density of the box"?

Table 3.4: There is reportedly a perched water table at a depth of 1.4 m at WA-20. This invalidates the physical assumptions of the model. The fact that the perched water table coincides with lower pyrite (Figure 3.2) around a depth of 1.15-1.55 m and similarly depressed pyrrhotite may have geochemical implications which were ignored in the interpretation.

Figure 3.2 and 3.3 & p.3-5: The matches to the irregular data are <u>not</u> good and just reflect the average (unoxidized) value placed as input into the model. The slope of the predicted lines at the oxidation fronts could be significantly sharper or shallower and still be called "good" relative to the Figures, and corresponding "areas under curves" would also not change significantly. Consequently, there has been no true calibration performed in this report.

p.3-6 & Figure 3.4: Because pH is a log scale and a difference of 1 pH unit can represent a major difference in water chemistry, the match is in fact <u>poor</u> and <u>not</u> "in reasonable agreement".

Figure 3.5: Measured data show that oxygen consumption decreases with depth so that oxygen concentrations become stable. On the other hand, the model predicts oxygen consumption

continues until all oxygen is depleted. This is obviously incorrect and overestimates the amount of acid generation in the simple one-dimensional system.

Figures 4.1 and 4.2: These are hypothetical results with no measured data on either acidity concetrations or water movement for confirmation. Also, there are no other predictions provided, such as for copper and sulfate.

p.5-1: Because the basic objective is to simulate and predict acid flux, accurate simulations are required for <u>both</u> acid generation and water movement. The model fails to consider the complexity of water movement so that the simulations will be idealistic at best, in spite of the intense effort to calculate acid generation.

p.5-2: The predicted data did <u>not</u> provide an acceptable match to the field data, as explained above.

p.5-3: I agree with the recommendation for further field studies. However, a critical capability of the model is its stochastic capabilities and yet there are no recommendations from the modellers on collecting information on probability distributions. This suggests that either the probability distributions thought to be well defined or the probability distributions are not important for simulations.

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

NOLAN, DAVIS & ASSOCIATES - MR. ALAN BELL

This presentation dealt with waste rock, particularly the Heath Steele waste rock belonging to Brunswick Mining & Smelting Corp. in New Brunswick. Notes prepared by Mr. Bell are attached at the end of these minutes as is a copy of a paper related to the acid waste rock field trials at Heath Steele, New Brunswick. Please refer to:

- MEND RATAP.BMT Workshop. Comments/Presentation by Allan V. Bell, P.Eng. Nolan, Davis & Associates, Halifax, Nova Scotia
- An Update on the Acid Waste Rock Field Trials at Heath Steele, New Brunswick. Allan V. Bell, P.Eng., et al. Paper presented to: Acid Mine Drainage Conference, GAC-MAC Annual Meeting, Vancouver, B.C., May 16-18, 1990.

Mr. Bell indicated that modelling means different things to different people. Models do not have to be complicated to be useful, but must be user friendly. Models are simply tools designed to answer specific questions, but will probably not be useful if they ask more questions than they answer. Complicated models like RATAP provide a base to understand very difficult situations.

Mr. Bell commenced with a slide presentation on Heath Steele. He hoped that his presentation would promote some discussions on the application of RATAP.BMT or other models to acid waste rock and would provide further input to the modelling community on any requirements they might have relative to using the Heath Steel Project for the calibration or development of models relative to acid waste rock situations.

Mr. Bell indicated that it is well known how to minimize the generation of acid mine drainage, how to control it and how to treat it. What is not well established is how to prevent it. The Heath Steele site is ideally cited for the assessment of acid waste rock.

Welcome Screen Search Report List

The project was arranged in four phases:

1. identification of piles to be used for the project
2. installation of monitoring equipment
3. determination of characteristics of potential covers
4. overall objective of installation of covers.

During Phase 1 four piles were identified. One pile was moved and re-installed on an impermeable liner because the bed rock was porous. During Phase 2, each of the four piles was outfitted with six instrument clusters per pile. Each cluster consisted of a piezometer surrounded by gas sampling points. Adjacent to these, and within one metre, temperature probes were installed in a separate hole. Phase 3 is not completed yet.

With the aid of his slides, Mr. Bell summarized the results obtained with the different piles: temperature profiles, oxygen distribution, seasonal variations. Since the Phase 3 is delayed, there will be more time to study the piles and gather more information. Only six months of data was collected from one pile and this is not sufficient to study the seasonal variations. The results are best described in Section 5.0 of the paper referred to at the end of these minutes.

The piles have temperature and oxygen characteristics which are representative of wastes undergoing active sulphide oxidization. Generally, the temperature gradient with depth is relatively uniform, but the longitudinal profile of oxygen levels is less uniform. The pile installed on the impermeable cover enables them to measure the water quality. Next year, three of the four piles will be outfitted with a cover.

Mr. Bell concluded his presentation by commenting on the applicability of modelling to waste rock. He thought that modelling of waste rock might be easier because there is no water table, but the presence of a wide range of variability in mineralogy and size distribution would make it more difficult. It is very important and considered to be a high priority to be able to predict acid generation. An understanding of the performance of covers is needed. It is difficult to develop such a model and it will take considerable time before such a model will come into being.

QUESTION AND ANSWER PERIOD:

Mr. Davé: The piles are already highly oxidized? Also is there any water mounting into the piezometers? Discussions about oxygen entry.

Mr. Bell: The piles were created in the 1950's. The piles, except the one pile that was moved, were built on highly fractured bedrock and we see no evidence of groundwater mounting within the piles. The pile that was moved to a liner enables us to collect background water quality data, the acidity is high, up to 30,000 mg/l, pH of 2.0. A lot of precipitation is required before water comes out of the pile and it comes out as a slug.

A discussion resulted regarding oxygen entry into the piles.

Dr. Ritchie: Dr. Ritchie explained that oxygen entry into piles is primarily as a result of diffusion from the surface and convection from the edges. He asked the question if it is possible to determine the air permeability with the instruments installed in the piles.

Mr. Bell: He indicated that he does not know, but as Dr. Ritchie indicated, air could be blown in and so the gas permeability could be measured.

Dr. Ritchie: He wondered if there is a lower limit of permeability at which convection does not occur, and it might be that one could design the dumps in such a way to stop the convective process.

Dr. Scharer: Is there was any evidence of thermal convection since the temperature inside the pile was at least 30 degrees higher than the ambient temperature?

Mr. Bell: There is definitely visual evidence.

Dr. Ritchie: Dr. Ritchie also commented on Dr. Scharer's question. Is it an important phenomenon and from an engineering standpoint what can be done about it?

* * * * * *

MEND RATAP.BMT WORKSHOP
Comments/Presentation
by

Alan V. Bell, P. Eng.
Nolan, Davis & Associates
Halifax, Nova Scotia

Introduction:

My role today is to introduce the issue of acid waste rock into the discussion relative to the applicability of RATAP.BMT to the prediction of waste rock pile behaviour and impact. I propose to do this by presenting a recently prepared paper on the Heath Steele Waste Rock Study which is appended to these notes. The objective of the Heath Steele study is to gather performance data for various covers applied to highly acid generating waste rock piles. At this time we have completed the second phase of the project in which we have instrumented four piles and characterized background conditions in the piles. The methodology used and the results to date are presented in the paper.

Waste Rock vs. Tailings

The characteristics of acid waste rock differ in many ways from those of reactive tailings, although there are of course similarities relative to the acid generation chemistry and the impact that acid runoff and leachates have on the environment. Some of these differences are summarized in Table 1. The key aspects from the standpoint of modelling and prediction are the extreme variation in mineralogy and physical properties (particle size, void ratio, diffusivity, etc.) that occur in waste dumps as compared to tailings, and I'm not suggesting that tailings are typically homogeneous: in fact, we are now very much aware of the variation that occurs in many tailings systems due to the interdeposition of slimes and sands, changes in mineralogy of the ore etc. However the variation in physical characteristics within a typical waste pile can be even more extreme due to factors such as the following:

Welcome Screen Search Report List

TABLE 1

Comparison of Acid Mine Drainage Factors In Waste Dumps and Tailings Impoundments

A. ACID GENERATION	WASTE DUMPS	TAILINGS IMPOUNDMENTS
i) Sulphide source	- Variable in concentration and location - Conditions may vary from sulphide rich to basic over short distances	- Conditions uniform often with very high sulphide content
ii) pH variation	- Highly variable conditions over short distances	- Fairly uniform conditions with a few major horizontal zones
iii) Initiation of Rapid Oxidation	- Usually starts immediately after first wastes are placed (in "trigger" spots)	- Usually starts after tailings placement ceases
iv) Oxygen Entry	- Enters freely along highly conductive flow paths at base of dump and large open void spaces. ‘Chimney and ‘lung’ effects.	- Restricted by water in the tailings void spaces and the lower conductivity of the partially saturated void spaces
v) Seepage	- Seepage rapid along preferential flow paths	- Seepage slow and uniform
vi) AMD Releases	- Large infiltration resulting in large seepage from toe and and to groundwater - Rapid release following generation, sometimes with both neutralized and acid AMD seeps.	- Large early surface AMD run-off - Lower infiltration - Gradual transition in seeps from process water, to neutralized AMD, to AMD.

Source: Robertson, 1988

- material dumped is often not from a single source throughout the life of the dump.

- the method of dump construction greatly influences its physical properties, for example end dumping results in the larger rock pieces being segregated at the bottom of the pile thus creating a highly permeable zone for air convection into the pile.

- depending on the weathering characteristics of the rock and the degree of traffic on the surface of the dump, relatively high degrees of compaction can occur, again greatly influencing the diffusion characteristics of the pile.

- Acid generation in waste piles is influenced significantly by dump geometry and climatic conditions.

- Results of the Heath Steele project to date show that the air transport mechanisms into the four dumps being monitored are apparently quite different, seeming to favour diffusion from the surface in one case, to predominately convection and weather related advection processes in others.

Obviously it will be extremely difficult to develop and verify a single generic model to describe and predict the behaviour of such systems.

Modelling Priorities for Waste Rock

The RATAP model currently appears to be primarily a research oriented tool rather than a system suited to general application for predictive purposes by industry and regulators. This in no way distracts from its value to gaining collective knowledge and understanding of acid generation and transport mechanisms within reactive tailings systems. It would however appear that its development and validation to the point where it is a user friendly tool for general distribution and application still requires time and resources.

The model should be released for general application by the industry with a view to encouraging comments and suggestions for improvement. To continue the development of RATAP to the point where it is generally applicable to acid waste rock will obviously require a significant effort and expenditure. While there is little doubt that such an approach would catalze an increase in our understanding of the geochemistry and physical transport mechanisms occurring in waste dumps, one must question whether the application of RATAP is the most cost effective means of achieving this objective.

Given a limited availability of funding, the short and intermediate term needs for acid waste to work research would appear, from the practioners viewpoint, to be as follows:

1. Improve our collective understanding of gas transfer mechanisms within waste rock piles through instrumentation of piles in manner similar to that described for Heath Steele. The information base that will result from this case will not only improve our basic understanding but can also lead to the development of guidelines relative to preferred construction practices for future piles.

2. Develop further understanding and design criteria for covers and seals for waste rock piles. This should be based on monitoring the performance of covers relative to temperature, gas and characteristics in the pile, and on the development and practical application of diffusion models for cover alternatives such as the work described by Marie Collin.

3. Continuation of the development and application of standard sampling and acid generation prediction methodologies for waste rock particularity with respect to the mine planning/predevelopment phase.

4. Monitoring of acid waste rock dump impacts including leachate plume dispersion to aid in the understanding of such impacts and to allow the calibration/validation of available ground and surface water contaminant transport models.

An Update on the Acid Waste Rock Field Trials
At Heath Steele Mines, New Brunswick

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Paper Presented to:
Acid Mine Drainage Conference, GAC-MAC Annual Meeting
Vancouver, British Columbia
May 16-18, 1990

ABSTRACT

The paper describes an experimental program to evaluate the performance of alternate covers for existing acid waste rock piles currently in progress at Heath Steele Mines in New Brunswick, including the selection of experimental piles, installation of instrumentation, definition of background conditions, and design of covers to be installed and monitored as the final phase.

1.0 INTRODUCTION

The Heath Steele Mine site provides a unique opportunity to evaluate management techniques for acid waste rock under practical field conditions. The mine is located approximately 50 km northwest of Newcastle, New Brunswick, and about 60 km southwest of Bathurst, within the drainage basin of the Northwest Mirimachi River (see Figure 1).

The Heath Steele property was developed in the late 1950s before the implications of acid drainage were fully appreciated. Highly pyritic waste rock was therefore used in the construction of haul roads and other infrastructure, and the site contains in excess of 20 acid-generating waste rock piles which pose a challenge to currently available reclamation technology.

A recent study on acid waste rock management at Canadian base-metal mines (Nolan, Davis, 1987 and Bell, 1988) identified the need for field performance data on waste rock pile covers and other management systems. The Heath Steele waste rock study is designed to address this need, as well as to aid in the development of practical reclamation measures for mine sites in Northeastern New Brunswick where the combination of massive sulphide ore bodies and the sensitivity of local salmon resources to acid and metal toxicity pose an especially difficult challenge to mine reclamation.

2.0 PROJECT DESIGN

During the fall of 1986, a proposal was submitted to various federal and provincial agencies to use several of the waste rock piles at the Heath Steele mine site to develop and test strategies for the long-term management of acid generating waste rock. A four phase program was developed, and on December 16, 1988, an agreement to fund the initial three phases was signed by the New Brunswick Department of Natural Resources and Energy, the New Brunswick Department of Commerce and Technology, and Brunswick Mining and Smelting Corporation.

The four phases of the overall project are as follows:

Phase I	Selection of four piles to be used for specific field trials.
Phase II	Installation of monitoring equipment to define the characteristics and background data for the four piles identified in Phase I.
Phase III	Column tests to evaluate the performance characteristics of potential covers.
Phase IV	Application of covers and performance monitoring under field conditions.

Phase I was completed in the summer of 1988. Phase II was essentially completed in the spring of 1990 and it is the results of this phase that are described in this paper. Phase III is still ongoing with consideration being given to homogeneous soil covers, zoned soil covers and soil/membrane composite systems. It is hoped that the selected covers will be applied as a function of Phase IV in 1991 with performance monitoring continuing for several years thereafter. Total funding for the first three phases is $312,000.

The initial selection of the four piles to be monitored in Phase II and potentially covered in Phase IV was made by ranking the many piles at the site according to the following selection criteria:

- Size and shape
- Ability to segregate from other wastes or interferences
- Type and gradation of material
- Ease of monitoring
- Availability of background data

Prior to committing to the expense of installing monitoring equipment, the candidate piles were subjected to a field characterization to determine the following:

- Vertical profile through centre of each pile into bedrock
- Composition/mineralogy of material
- Acid producing/consuming ratio
- Geophysical characteristics
- Topography

Following this investigation, four piles, identified as 18A, 18B, 17 and 7/12 were confirmed as being suitable for instrumentation. Their characteristics are described in Table 1. They all consist of pyritic, acid-generating material and range in size from 3,000 tonnes to 236,000 tonnes.

It was decided that the waste rock piles should be monitored over a period of at least one year to adequately characterize the background conditions, and thereby enable the performance of the covers to be fully evaluated relative to seasonal variations. The parameters that best reflect the dynamics of waste rock acid generation were considered to be pore gas oxygen levels, the temperature profile within the pile, and the characteristics of any pore water and/or leachate associated with the pile. The instrumentation and monitoring of the study piles were therefore designed to assess these characteristics.

3.0 SITE PREPARATION

Site preparation consisted of re-contouring each of the waste rock piles to maximum side slopes of approximately 3:1 (H:V). Each pile was also isolated from the influence of any neighbouring topographical or other local features. The objective was to provide side slopes that could easily accommodate equipment required for placement of the covers in Phase IV of the study. The more uniform shape resulting from re-contouring of the waste rock piles would also reduce any shape-induced effects on the monitoring results.

Investigations in Phase I indicated that the bedrock near the surface is highly fractured and therefore of relatively high permeability. Mounding of pore water within the piles is, therefore, highly unlikely. Consequently, monitoring of pore water quality and determination of a water balance for the existing piles was impractical. Ditches were constructed around the piles to minimize the inflow of surface water and to collect any surface runoff once the piles have been covered in Phase IV.

After re-contouring the piles, the installation of instrumentation in Piles 18A, 18B and 17 was commenced using an air track percussion machine to drill 150 mm holes. There was some concern that the gas balance in the piles might be modified by this process. However, it was felt that equilibrium conditions would be rapidly re-established due to the high porosity and permeability of the piles. A total of six instrumentation stations were installed on each pile.

Waste rock Pile 7/12 was to be moved as part of an ongoing reclamation program at Heath Steele Mines. This provided a unique opportunity to place the pile on an impermeable liner and thereby provide for the collection of leachate before and after placement of the cover in Phase IV. Construction of the new base with an impermeable Fabrene membrane, relocation of the pile, and installation of instrumentation was completed in June 1989.

4.0 INSTRUMENTATION

The typical instrumentation cluster assembled at each sampling location consists of a piezometer installed to bedrock or about 5 metres depth, constructed of 38 mm diameter PVC tubing. A series of pore gas monitoring tubes were installed on the piezometer, and an adjacent series of temperature probes installed in a separate hole within one metre of the piezometer. Due to space limitations on Pile 7/12, both pore gas and temperature probes are mounted on the piezometer. A typical sampling station is shown in Figure 2. The specific details of the oxygen and temperature installations are as follows:

Pore Gas Instrumentation

The general instrument configuration for sampling pore gases is presented in Figure 3. Sampling ports were established at depths of approximately 1.0, 1.5, 2.0, 3.0, 4.0 and 5.0 metres by taping non-collapsing tubes of norprene rubber, a flexible, acid resistant material, to the PVC piezometer tube prior to installation in the drilled holes. Once in the hole, a layer of sand/gravel was placed around each sample point and the upper ends clamped at all times other than during sampling. The system was designed to use a low-volume portable oxygen analyzer (Teledyne 320A). When the instrument is connected and the tube clamp is released, the instrument draws air through the tubing to the sensors located within the analyzer. Because of the minimum volume of air extracted from the area around the sampling point, neighbouring gas sampling tubes were considered to be unaffected by this procedure.

Temperature Measurement

In order to monitor temperature profiles within each of the piles, type K thermocouples were installed at depths of approximately 0.3, 1.5 and 4.6 metres in a separate 150 mm hole which was backfilled with granular material to prevent "chimney" effects.

Welcome Screen Search Report List

The thermocouples were fabricated by the manufacturer to meet specific requirements for acid resistance and are specified as long-lasting for burial in contact with water. The K thermocouple is well-suited to operate within the temperature conditions expected at the site. Readings were made by attaching a hand-held thermocouple thermometer (Digi Sense Model BA 8528-40) to the surface, using colour-coded thermocouple plugs.

Other Instrumentation

On Pile 7/12, both seepage and surface runoff can be independently monitored for flow and quality. Automated water samplers (ISCO Model 2900 with water level sampler activator Model 1640) and automated water level recorders (Richards type) were installed at the outlet weirs. Collected water samples have been analyzed for the following parameters: pH, acidity, iron, copper, zinc and sulphate. Supplementary analyses for lead and total solids have been conducted. Also on Pile 17, the existence of a collection ditch at the downstream toe provides the means to monitor the quality of combined runoff and seepage, although the ditch also acts as a collector for other local drainage.

A weather station was installed at the site in the spring of 1989 to provide precipitation, temperature and evaporation data.

5.0 RESULTS AND DISCUSSIONS

Thirteen data sets have been collected for Piles 18A, 18B and 17. The data for these piles covers a full range of seasons but does not provide for an evaluation of water or contaminant balances due to the problems associated with the location of the piles on fractured bedrock. For Pile 7/12, it will be possible to determine contaminant loadings, but to date only six months of data have been collected. This is insufficient to fully assess seasonable variations. Monitoring will be continued on a monthly basis in 1990 to remedy this short-coming.

The full set of data for each pile has been presented in the Phase II draft report issued in April 1990 (NOlan, Davis, 1990). It is too voluminous to include here but a typical data set for Pile 18A, the smallest pile, is presented as an example. The raw data for temperature and oxygen concentration are shown in Tables 2 and 3.

The longitudinal plot of temperature data for December (Figure 4) clearly indicates a relatively uniform temperature gradient with depth throughout the pile, with bottom temperatures of approximately 12°C compared to surface temperatures of -14°C. Similar gradients were observed in the pile during the other winter months.

The seasonal variation in temperature within the pile (Figure 5) shows the temperature at the bottom of the pile warming in response to increased summer surface temperatures to the point where the gradient is reversed from May through October. During the August 1989 sampling period, the bottom of the pile was recorded as having a temperature of 17.3°C compared to a surface temperature of 32°C.

The longitudinal profile of oxygen levels for November 1989 (Figure 6) indicates a far less uniform distribution than for the temperature data, but in general, oxygen levels are depleted towards the bottom of the pile. It is not clear whether the low values shown at Station 2 reflect a local low due to a zone of low permeability or a local region of particularly active pyrite oxidation. Similar irregularities have been observed at the Rum Jungle and Mount Washington sites as described in Section 6.

Seasonal variations in oxygen levels (Figure 7) show that the depletion of oxygen at depth is observed year-round, although concentrations are considerably higher in late winter and spring than during the fall. At Station 3, the variation at 3.7 m depth (i.e. the bottom of the pile) is from 13 percent in May to a low of 0.5 percent in October. The change in oxygen concentration at depth appears to follow a reasonably regular cycle evident in Figure 7. There would appear to be a correlation between the temperature and oxygen levels with the lowest oxygen levels associated with the highest temperatures.

Corresponding depth profiles for temperature and oxygen at Station 3 are shown in Figure 8 and confirm the general depletion of oxygen with depth, as well as the stabilizing effect of depth on temperature.

The fact that there is a temperature difference of 25°C between the surface and bottom of the pile over a depth of only 3.4 m, despite its obviously high porosity, would appear to provide strong evidence of the ongoing exothermic oxidation process within the pile. The temperature within the pile is still very much influenced by ambient air temperatures, and it appears from the pore gas data that the oxidation reaction is moderated as the pile temperature drops on a seasonal basis to a low in April. At this time, pore gas oxygen concentrations are at their highest.

Similar data sets were obtained for Piles 18B and 17. Pile 7/12 has been monitored for only six sampling periods todate. The oxygen data collected for Pile 17 show far less variation than for the other piles described and in many instances greater oxygen concentrations were found at depth than at the surface. An explanation for this phenomenon could be the fact that the surface of this pile consists of hard packed fine material and the primary route for the ingress of air to the interior of the pile may be from the sides. This condition may be the result of end dumping on the slope and the combination of weathering and compaction on the surface.

The oxygen profiles for Pile 7/12 also reflected a different pattern. Levels were initially very low at the bottom of the centre sampling station for the July and August sampling times but then increased rapidly to much higher values (14 to 17.6 percent) during the fall. A possible explanation might be that very high levels of oxidation existed immediately after moving the pile and were quickly consumed due to the availability of fresh reaction sites. As temperatures in the pile increased, thermal convection of air into the pile increased oxygen levels with time. A longer period of sampling is, therefore, required to determine stabilized temperature and pore gas data.

An assessment of the water quality data collected to date at Pile 7/12 indicates the following:

- New precipitation is initially adsorbed and therefore does not necessarily result in water leaving the waste rock pile.
- Concentrations of contaminants can be very high in both the surface drainage and underdrain. Acidity concentrations of over 30,000 mg/l are characteristic of the collected water.
- Concentrations of contaminants in the waters leaving the pile often increase with time following the precipitation event.
- Surface runoff from the pile may be as high as 30 percent during a storm event.
- Surface water is as contaminated as the underdrain flows.

6.0 COMPARATIVE REVIEW

The objective of this phase of the project is to define the background conditions in each of the four test piles so as to provide a basis for evaluating the performance of the covers to be installed in Phase IV. It is useful, however, to briefly review the findings to date and to compare the baseline conditions with those in other waste rock cover trials, such as those at Rum Jungle in Northern Australia and the Mount Washington Site in British Columbia.

The temperature characteristics of the four piles are generally similar in that each pile displays relatively uniform temperature gradients from the surface to the bottom of the pile, with the deeper piles generally showing higher temperatures at depth. Temperatures in Pile 7/12 are warmer for a given depth than the other three piles, but it has not yet been determined whether this is due to transient conditions of increased oxidation rates potentially associated with moving the pile. It is important that the data base be augmented to clarify this aspect.

The oxidation of pyrite to sulphuric acid and ferrous sulphate is exothermic and releases 1440 kJ per mol FeS_2 (Bennett et al., 1988). This release of heat results in elevated temperatures in pyritic waste rock dumps and explains the high temperatures measured in each of the waste piles. Similar results were obtained at Rum Jungle, but at Mount Washington temperatures were found to be relatively constant throughout the dump profile (Golder, 1989). In order to fully evaluate the effectiveness of the cover, it will be necessary to calculate the distribution of heat production in the piles using a heat transfer model similar to that applied at Rum Jungle, where this determination provided a very definitive demonstration of the effectiveness of the cover in curtailing oxidation in the pile as shown in Figure 9.

At the Heath Steele site, the temperature monitoring shows that the effect of seasonal temperature changes influences the temperatures at depth within the dumps, and it will be important to ensure that this effect is taken into account when making comparisons between pre- and post-cover conditions. At Rum Jungle, the ambient temperature was of influence only to about 6 m depth. At Mount Washington, pre-cover conditions were not monitored for a seasonal cycle, and this has caused problems in the early interpretation of the effectiveness of the cover.

The profiles of oxygen concentrations determined to date at the Heath Steele site are somewhat erratic. This may be due to local variations in the dump permeability, local differences in mineralogy, or a combination of the two. Similar irregularities were observed at Rum Jungle prior to placement of the cover as shown in Figure 10.

Significant seasonal variations in oxygen concentrations have been measured in the piles at the Heath Steele site. The lack of seasonal data at Mount Washington does not permit comparison with that project. At Rum Jungle, there do not appear to be such marked seasonal changes but the effect of diurnal atmospheric pressure changes on oxygen concentrations in the dump during the Australian wet season was quite marked and was well documented in that project (NTDME, 1986).

Harries and Ritchie, 1985, report that there are three mechanisms by which oxygen can be transported to reaction sites within a waste dump: diffusion, thermal convection, and advection driven by atmospheric pressure variations. Thermal convection causes the oxygen concentration to be higher at the base of the dump due to the effect of drawing in air through high porosity layers caused by segregation during dumping. Diffusion causes the oxygen concentration to decrease monotonically with depth, while advection can cause more uniform changes in concentration throughout the dump. Evidence of these three oxygen transfer mechanisms can be drawn from the data collected at Heath Steele. The instrumentation of oxygen levels within the four piles appears to be working well and, together with temperature data, will provide an effective means of monitoring the performance of the covers to be placed in Phase IV.

Welcome Screen | Search | Report List

7.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were made as a result of the Phase II work:

- The project has achieved the objective of defining pre-cover background conditions in Piles 18A, 18B and 17. Further monitoring is required on Pile 7/12 to achieve a full seasonal cycle and to allow any short-term effects of moving the pile to be delineated.

- Since it is now expected that placement of the covers will not occur prior to the 1991 construction season, it is recommended that monthly monitoring of all piles should be continued through June 1991.

- All instrumentation is functioning according to expectations and is thought to reflect the conditions in each pile with reasonable accuracy. The existing instrumentation should continue to serve the needs of the project if properly maintained and protected during the placement of the covers.

- All four piles appear to have temperature, oxygen and, in the case of Piles 17 and 7/12, water quality characteristics representative of wastes undergoing active sulphide oxidation reactions and are, therefore, suitable candidates for the placement and evaluation of covers.

- It is recommended that cover placement on Pile 7/12 be given priority for Phase IV due to the ability to determine contaminant loadings for that pile.

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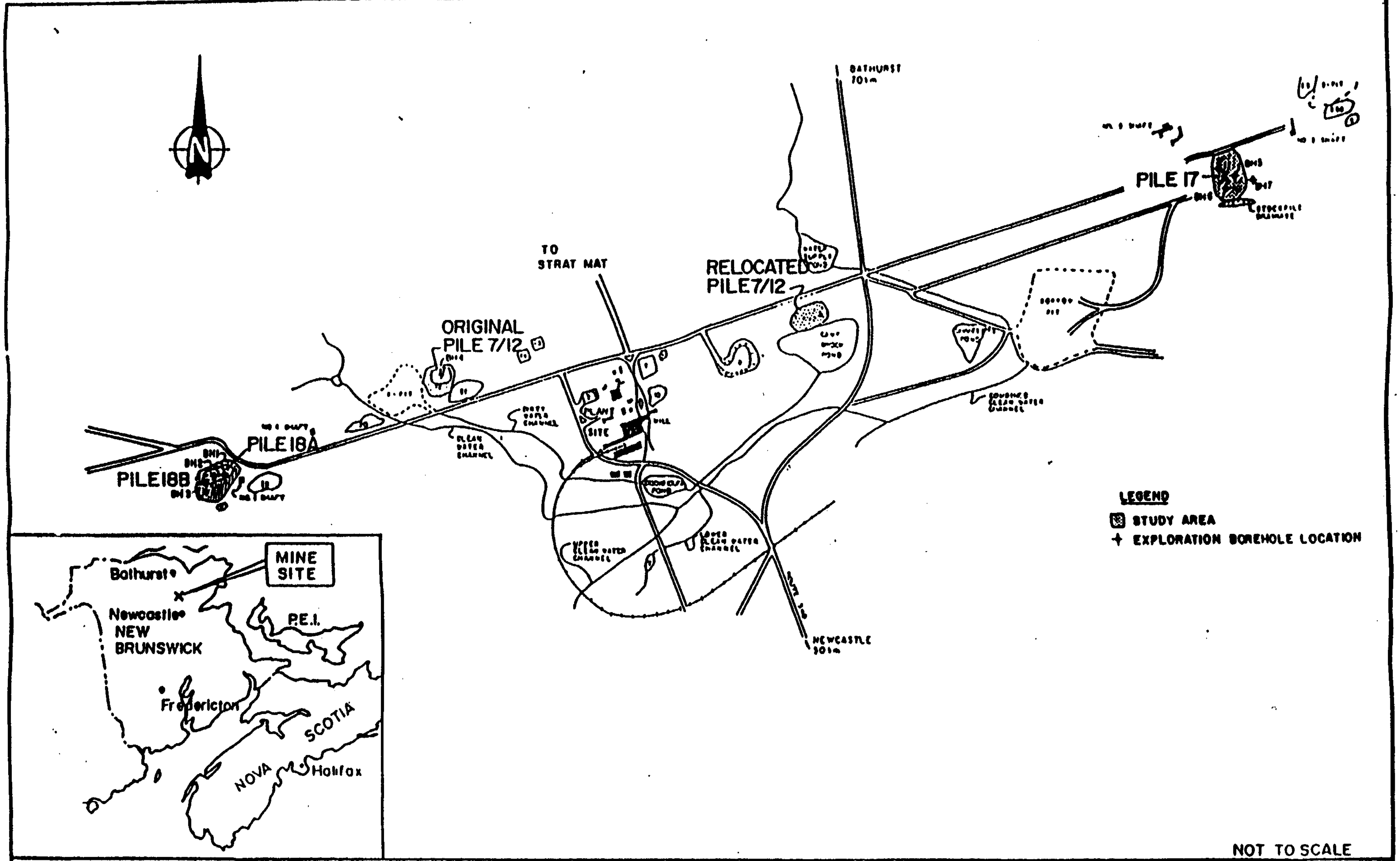

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FIGURE 1

WASTE ROCK DISPOSAL SITES LOCATION MAP
HEATH STEELE MINES

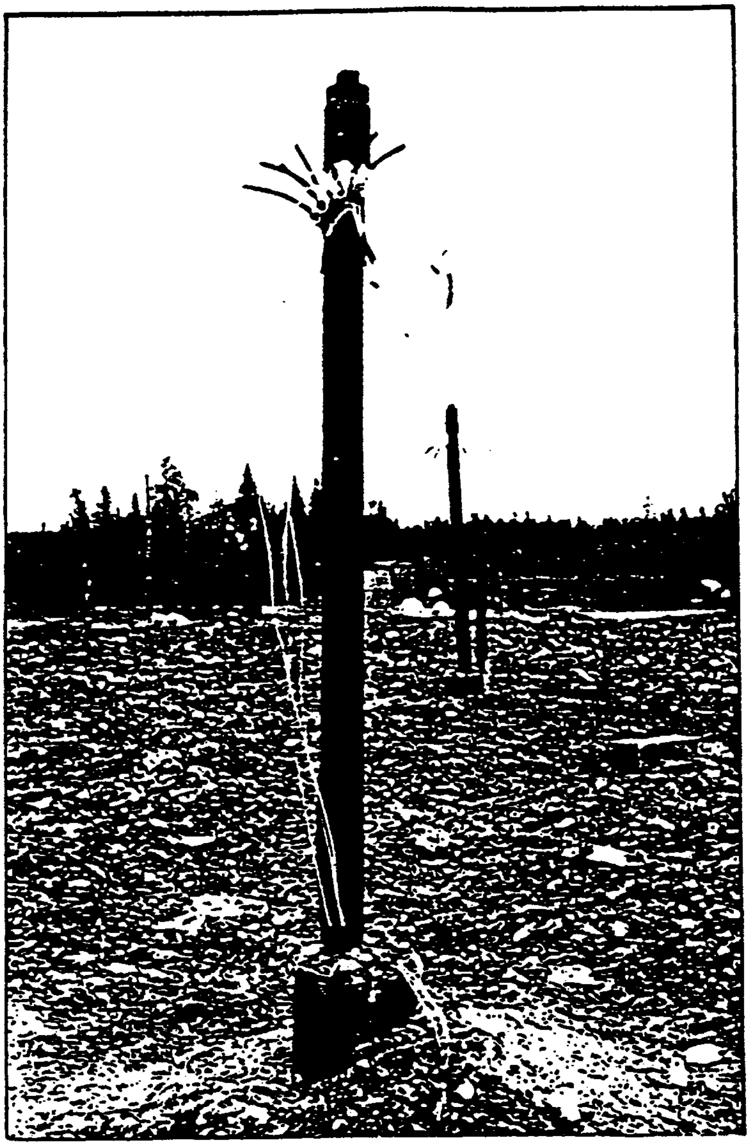

FIGURE 2

PHOTOGRAPH OF TYPICAL SAMPLING STATION
HEATH STEELE MINES

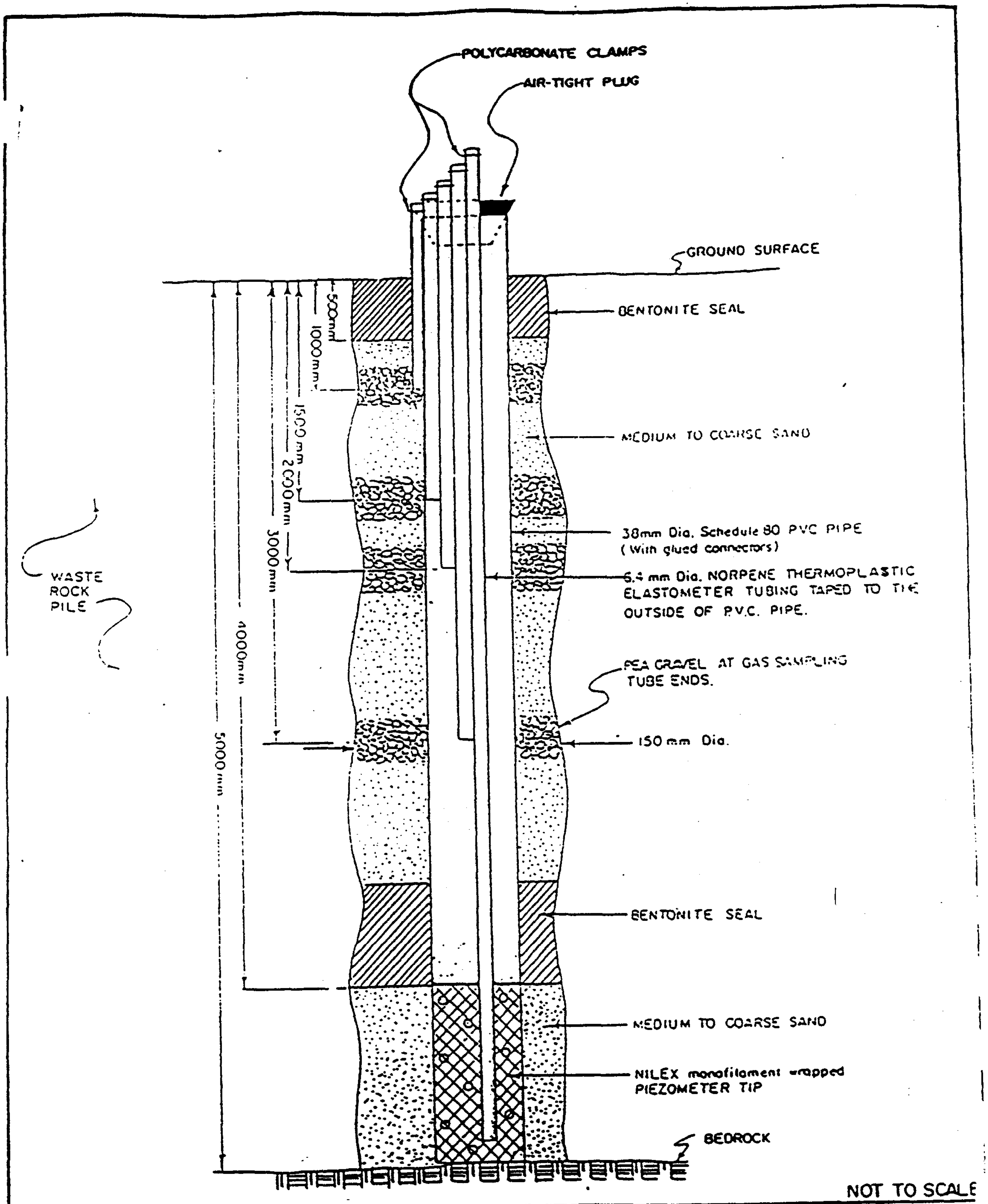

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FIGURE 3

TYPICAL GAS SAMPLING AND PIEZOMETER INSTALLATI
HEATH STEELE MINES

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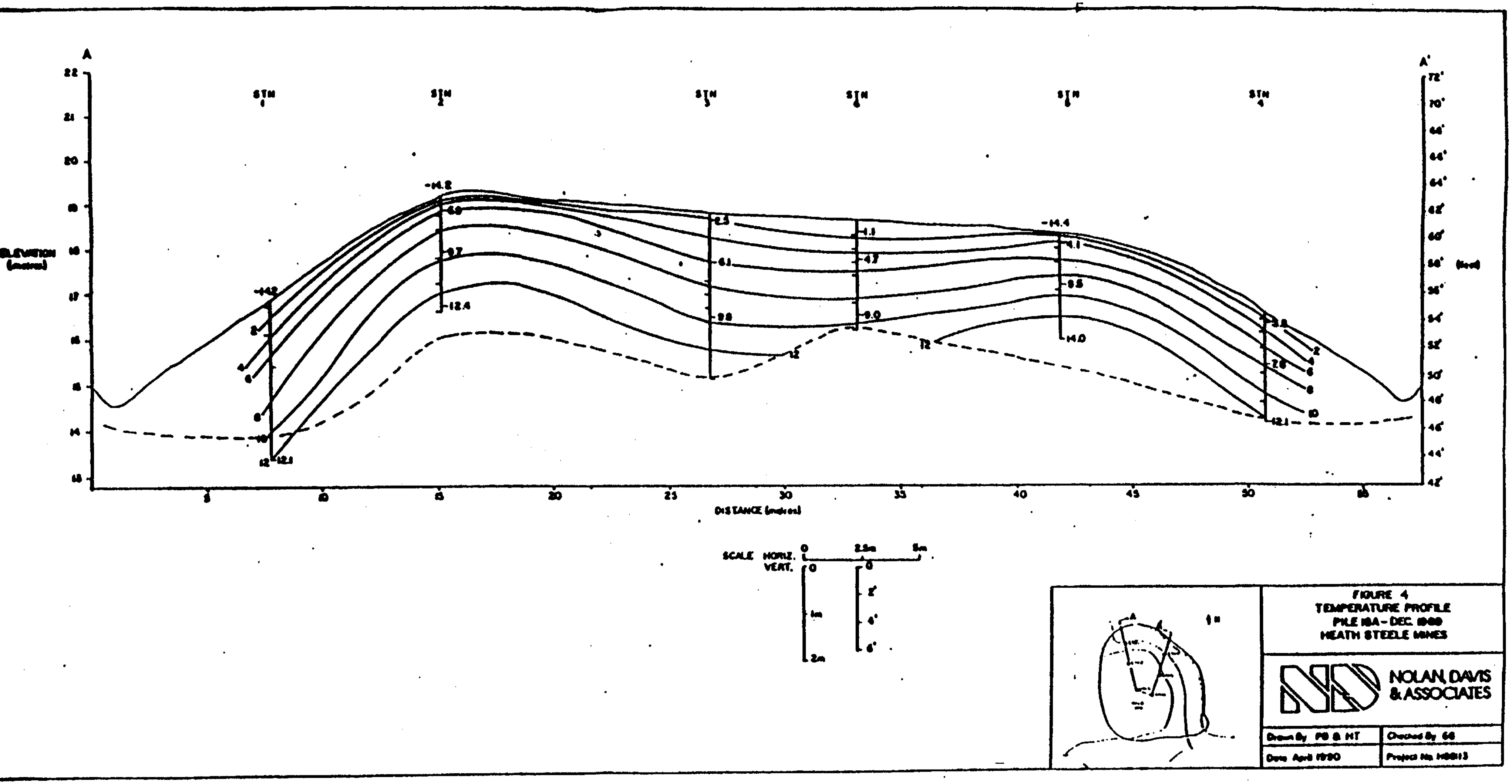

FIGURE 4
TEMPERATURE PROFILE
PILE 18A - DEC. 1989
HEATH STEELE MINES

NOLAN, DAVIS & ASSOCIATES

Drawn By PB & HT	Checked By GG
Date April 1990	Project No. H8813

Heath Steele Mine
Waste Rock Study

							Mineralogy			
Pile	Surface Area (m^2)	Average Depth (m)	Maximum Depth (m)	Estimated Volume (m^3)	Estimated Tonnes (a)	Foundation Condition (b)	AP (kg/tonne)	/ AC (c)	Sulphides Present	Percent
18A	1,210	1.6	3.4	1,900	3,250	Thin OB over rock	79.6	1.5	Pyrite	5 - 7
									Galena	<1
									Sphalerite	<1
18B	3,570	2.3	6.7	8,300	19,500	Thin OB over rock	158.4	0.5	Pyrite	7 - 10
									Fe-S	7 - 10
									Sphalerite	<1
									Galena	<1
									Chalcopyrite	<1
17	25,640	3.9	10.5	100,300	235,700	Thin OB over rock	35.7	0.8	Sphalerite	7 - 10
									Pyrite	<1
									Arsenopyrite	<1
									Chalcopyrite	<1
									Galena	<1
									Silver	<<1
7/12(d)	2,320	2.6	5.0	6,000	14,100	Rock	210.7	0.4	Pyrite	7 - 10
									Fe-S	5 - 7
7/12(e)	2,100	2.9	5.0	6,200	14,700	Impermeable Base			Galena	<1
									Chalcopyrite	<1
									Arsenopyrite	<1
									Sphalerite	<1
									Pyrrhotite	<1

(a) Based on assumed waste rock density of 2.35 tonnes/m^3
(b) Based on geophysical, borehole and field observations
(c) AP/AC represents Theoretical Acid Production / Acid-Consumed
(d) Original conditions
(e) Relocated pile (June 1989)

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TABLE 1

SUMMARY OF STUDY PILE CHARACTERISTICS
HEATH STEELE MINES

Stn	Port	Depth (m)	Minimum	Maximum	Average	Temperature (C) 10-Nov-88	10-Dec-88	14-Jan-89	04-Apr-89	30-Apr-89	15-May-89	04-Jul-89	03-Aug-89	04-Sep-89	22-Sep-89	12-Oct-89	22-Nov-89	29-Dec-89
1	Red	3.8	2.5	20.6	11.8	13.0	12.6	8.8	5.0	2.5	3.9	9.2	11.8	20.5	20.1	18.3	16.7	12.1
	Blue	2.4	0.8	21.9	11.1	10.5	9.5	4.6	1.4	0.8	5.5	14.9	17.3	20.1	21.9	18.9	12.1	8.2
	Black	1.5	-0.1	23.4	9.5	6.5	3.7	1.1	-0.1	0.3	8.0	19.3	23.4	19.8	19.8	10.3	5.0	8.8
	Surface	0.0	-14.2	32.5	9.2	3.2	-7.5	-12.9	7.7	15.0	17.7	29.3	32.5	20.3	21.8	10.7	-4.5	-14.2
2	Red	2.4	3.9	20.4	11.0	12.7	13.6	9.0	4.7	4.0	3.9	8.7	12.0	20.4	13.8	14.1	14.1	12.4
	Blue	1.2	1.6	20.4	11.0	10.6	10.7	5.8	1.6	2.5	5.4	13.7	17.6	20.4	17.2	14.8	12.5	9.7
	Black	0.3	-0.7	21.2	10.1	8.6	7.6	2.4	-0.7	0.3	6.9	17.7	21.2	18.8	18.8	13.1	10.0	8.9
	Surface	0.0	-14.2	32.0	8.6	3.2	-7.3	-12.9	7.7	15.0	17.7	29.0	32.0	17.0	17.1	11.4	-4.0	-14.2
3	Red	2.3	2.2	17.3	9.9	9.8	9.9	5.7	3.1	2.2	5.6	13.0	17.3	14.8	13.5	12.4	11.8	8.8
	Blue	1.1	0.3	22.7	9.5	7.3	7.3	2.3	0.3	0.7	6.7	18.4	22.7	16.1	15.8	11.3	9.1	8.1
	Black	0.2	-3.4	24.2	8.2	4.4	3.7	-3.4	0.1	-0.1	8.3	20.0	24.2	17.8	17.2	7.8	4.4	2.8
	Surface	0.0	-14.2	32.0	8.5	3.2	-7.2	-12.9	7.7	15.0	17.7	29.0	32.0	17.0	16.4	11.7	-5.1	-14.2
4	Red	2.4	4.6	18.1	11.2	12.8	11.5	7.4	4.9	5.8	4.6	10.1	13.6	18.1	15.7	14.8	13.9	12.1
	Blue	1.2	0.9	20.0	10.0	4.6	7.3	1.8	0.9	2.8	6.2	17.2	20.0	18.8	18.6	13.8	10.2	7.8
	Black	0.2	-2.0	23.1	8.4	5.4	2.5	-2.0	-0.9	1.9	7.8	19.0	23.1	18.5	18.3	8.3	4.1	3.3
	Surface	0.0	-12.9	31.8	9.7	3.2	-7.2	-12.9	7.7	15.0	17.7	28.4	31.8	18.3	18.6	8.7	-3.8	-
5	Red	2.4	3.9	18.9	11.0	12.8	10.8	7.4	3.9	4.5	3.9	10.3	13.7	18.9	15.4	14.7	13.2	14.0
	Blue	1.2	0.3	20.1	10.2	9.2	6.1	2.8	0.3	2.3	5.1	16.8	20.1	18.6	18.3	14.0	9.8	9.6
	Black	0.3	-3.4	23.1	8.1	5.0	0.3	-3.4	-0.3	1.4	7.8	20.1	23.1	18.0	17.4	9.0	3.2	4.1
	Surface	0.0	-14.4	32.7	9.1	3.2	-7.2	-12.9	7.7	15.0	17.7	28.6	32.7	20.3	21.9	8.9	-3.8	-14.4
6	Red	2.1	0.7	17.9	8.7	8.6	6.9	3.3	0.7	2.0	2.6	11.6	14.7	17.9	14.4	12.0	9.8	9.0
	Blue	0.9	0.2	19.5	8.3	6.6	2.2	1.8	0.2	1.5	4.9	16.2	19.5	18.0	15.9	9.6	8.4	4.7
	Black	0.3	-6.8	21.8	7.2	4.7	-2.1	-6.8	0.8	2.1	6.8	18.1	21.8	18.7	16.8	7.7	3.3	1.1
	Surface	0.0	-12.9	33.0	10.5	3.2	-7.2	-12.9	7.7	15.0	17.7	29.0	33.0	20.3	25.1	10.3	-4.2	-

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TABLE 2

PILE 18 A
TEMPERATURE DATA

Stn	Port	Depth (m)	Oxygen Concentration (% of pore gas)												
			Minimum	Maximum	Average	10-Dec-88	14-Jan-89	30-Apr-89	15-May-89	04-Jul-89	03-Aug-89	04-Sep-89	22-Sep-89	13-Oct-89	22-Nov-89
1	1	2.4	3.6	19.5	10 4	19 5	15.6	13 0	3 6	10 8	6 0	5 2	9 0	11.7	9.6
	2	1.3	7.5	20.6	15.3	20 6	17.7	16.0	7.5	18.6	13 0	14 8	14.0	15.1	
	3	0.8	9.0	19.2	14.6	19.2	17.2	15.0	18.0	16.5	10.3	12 0	9.0	14.0	14.0
	4	0.2	2.2	18.7	11.5	18.7	15.6	18.7	18.5	8.3	2.2	5.7	5.8	10.0	
2	1	2.6	18.8	20.8	20.1	20 8	20.6		18.8						
	2	2.0	15.5	18.6	17.7	18 6	18.6	15.5	17.6	18.0	18 0	10 2	16 8	18.2	17.5
	3	1.3	12.4	18.6	15.4	18.6	18.6	15.0	12.4	16.0	15.5	14 0	12.8	18.0	
	4	0.7	5.2	17.0	10.7	17.0	17.0		12.5	8.0	6.5	8 5	5.2	10.5	9.0
	5	0.4	2.8	16.4	9.7	16.4	16.4	14.0	13.5	7.3	4.2	5 0	2 8	8.0	8.3
	6	0.1	2.2	17.0	9.6	17.0	16.4	17.0		8.0	4.1	4 8	2.2	7.5	9.5
3	1	3.7	0.5	13.0	4.6	4.2	11.5		13.0	2.9	1.8	0 6	2.5	0.5	1.3
	2	3.0	0.1	17.8	8.1	7.4	14.4	14.6	17.8	15.0	1.3	0 8	0.1	1.5	2.0
	3	2.4	8.0	18.8	14.8	17.5	18.8	17.5	16.0	17.5	14.0	12.7	8.0	11.5	10.8
	4	2.1	12.1	19.4	15.7	18.5	19.4	18.0	12.1	17.5	15.0	15.2	13.5	12.2	
	5	1.8	12.7	18.6	16.0	18.6		18.2	12.7	18.0	14.5	14.7	13.3	17.6	15.8
	6	1.5	13.0	20.8	16.9	18.8	19.0	17.1	20.8	16.8	13.5	15.2	13.0	17.6	17.0
4	1	2.0	7.9	18.5	13.9	18.5	16.8		12.2	7.9					
	2	1.4	0.7	18.2	8.9	15.0	18.2	12.0	12.0	7.7	0.7	7 8	0.8	7.6	8.0
	3	0.8	0.4	15.0	6.8	12.8	15.0	10.5	9.5	4.3	0.5	3.8	0.4	4.2	7.0
	4	0.6	0.5	14.4	6.2	12.4	14.4	12.0	8.5	2.5	0.5	1.7	0.8	2.8	
	5	0.2	0.5	14.6	7.0	11.0	13.6	10.0	9.5	14.6	0.5	0.6	0.9	2.4	3.5
5	1	1.8	12.2	19.0	16.1	17.2	18.4	16.5	19.0	17.7	15.7	13.5	14.5	12.2	16.6
	2	1.3	4.2	19.2	11.6	16.8	18.0	14.6	19.2	10.1	4.6	8 1	4.2	9.0	
	3	0.7	3.3	19.5	11.7	16.6	18.0	14.6	19.5	10.6	4.6	8.1	3.3	10.0	12.6
	4	0.4	3.2	19.3	10.9	16.6		15.0	19.3	10.7	4.5	8.1	3.2	9.5	
	5	0.1	16.5	17.6	17.1	16.5	17.6		17.2						
6	1	2.6	15.5	19.5	16.8	17.1	18.2		19.5	15.8	15.5	16.4	16.0	16.0	17.0
	2	1.9	17.0	20.0	18.4	18.0	19.2		20 0	18.4	17.0	18 4	17.5	18.6	
	3	1.3	17.0	20.8	19.6	19.0	20.0	20.8	20.5	20.0	17.0	19 9	18.5	20.5	20.8
	4	1.0	17.0	20.8	19.1	19.2	20.0	20.8	20.5	19.1	17.5	18 4	17.0	19.5	
	5	0.7	15.5	20 5	18.2	19 0			20.5	19.5	16.0	17 6	15.5	19.2	
	6	0.4	18.0	20.8	19.6	19.5		20.8	20.5	20.2	19 5	18 6	18.0	20.0	20.8

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TABLE 3

PILE 18 A
OXYGEN CONCENTRATIONS

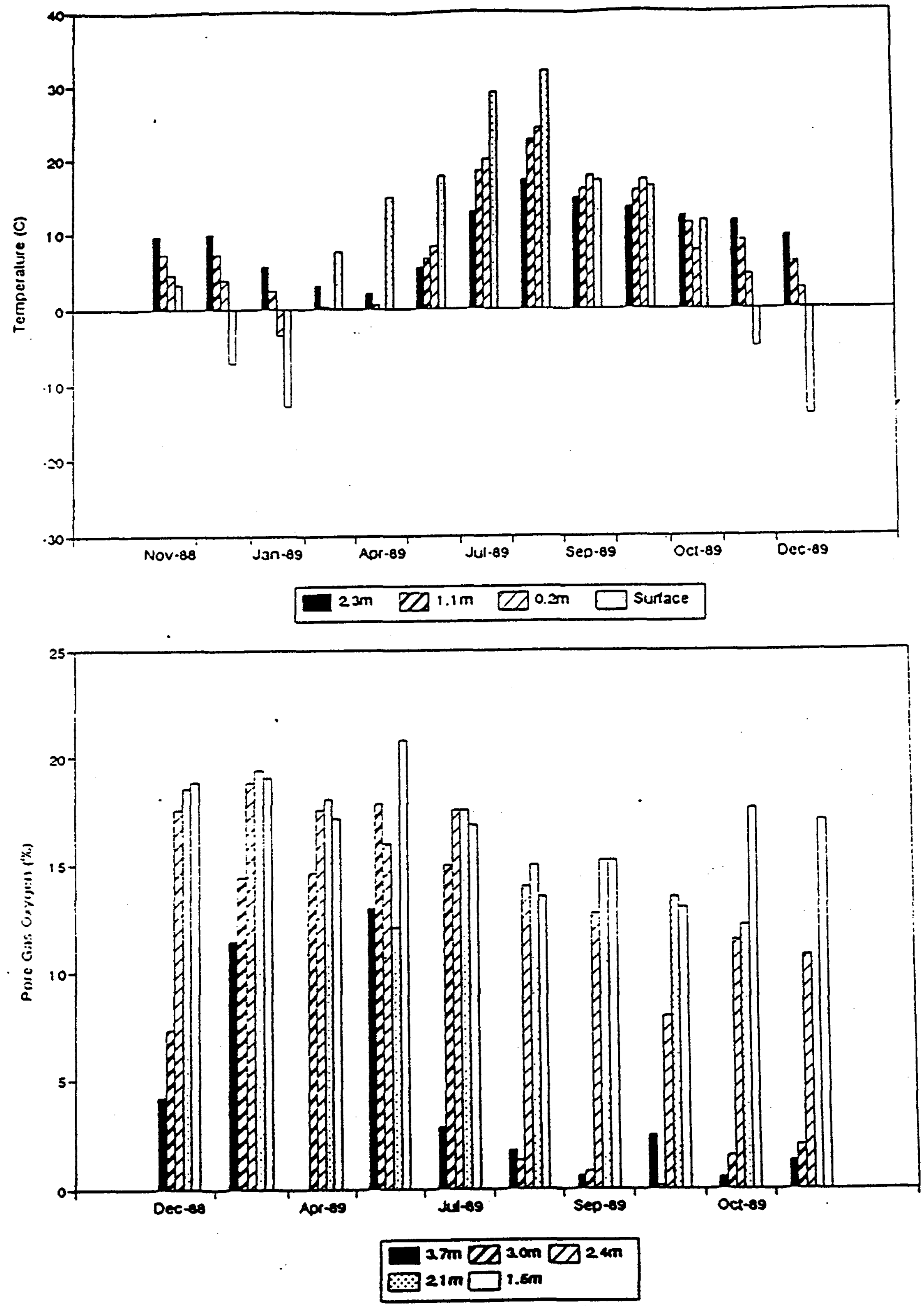

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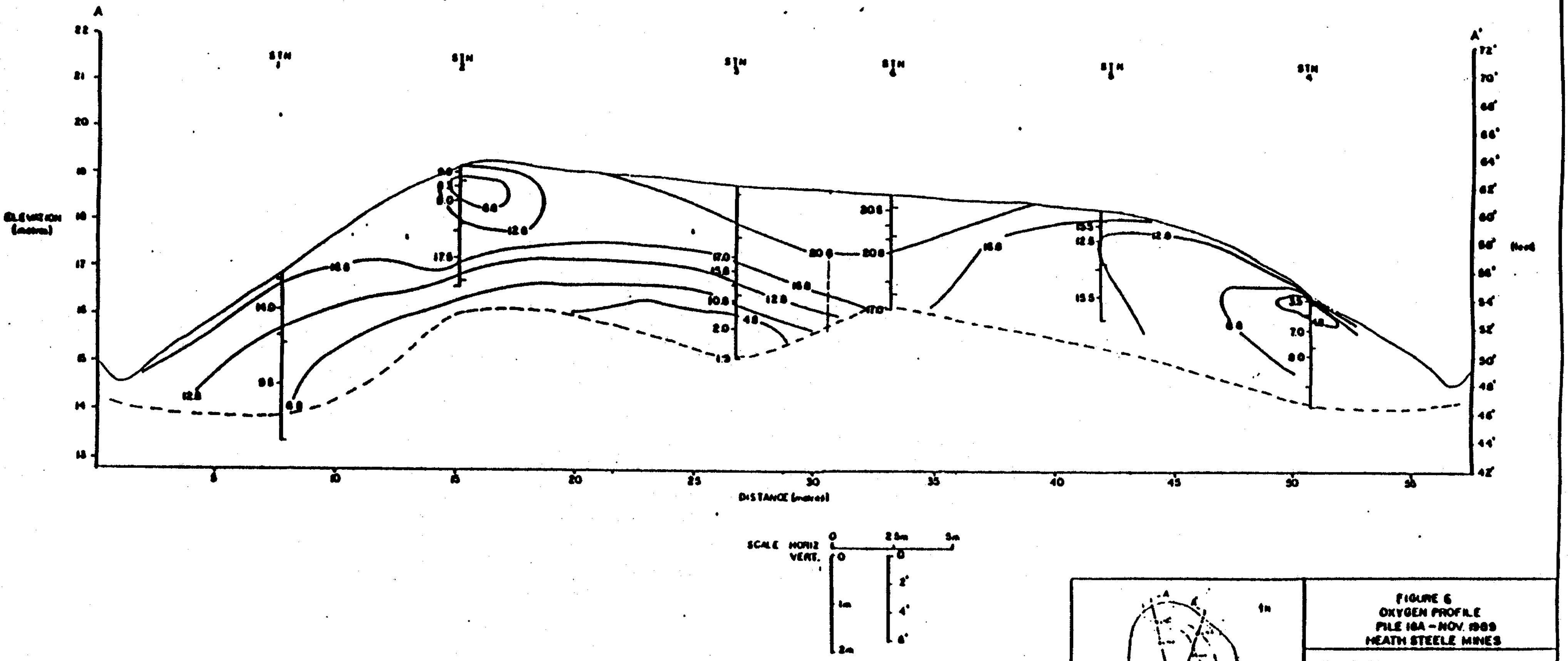
FIGURE 5

SEASONAL VARIATION IN TEMPERATURE AND OXYGEN
PILE 18A
HEATH STEELE MINES



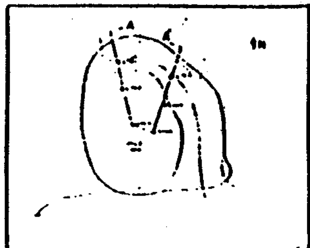


FIGURE 6
OXYGEN PROFILE
PILE 16A – NOV. 1989
HEATH STEELE MINES

NOLAN, DAVIS & ASSOCIATES

Drawn By	DSP & HT	Checked	BG
Date	April 1990	Project No	H0883

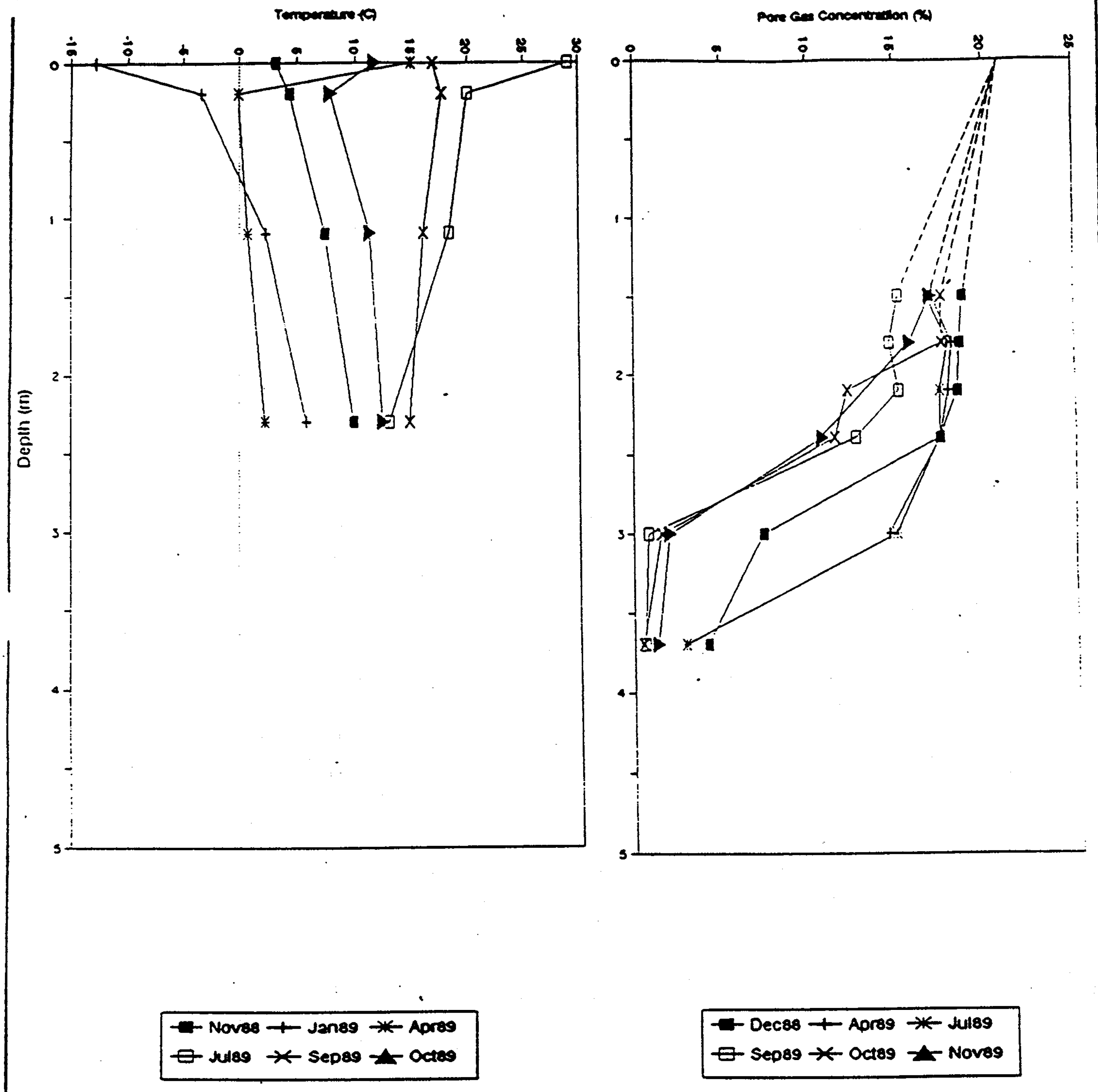


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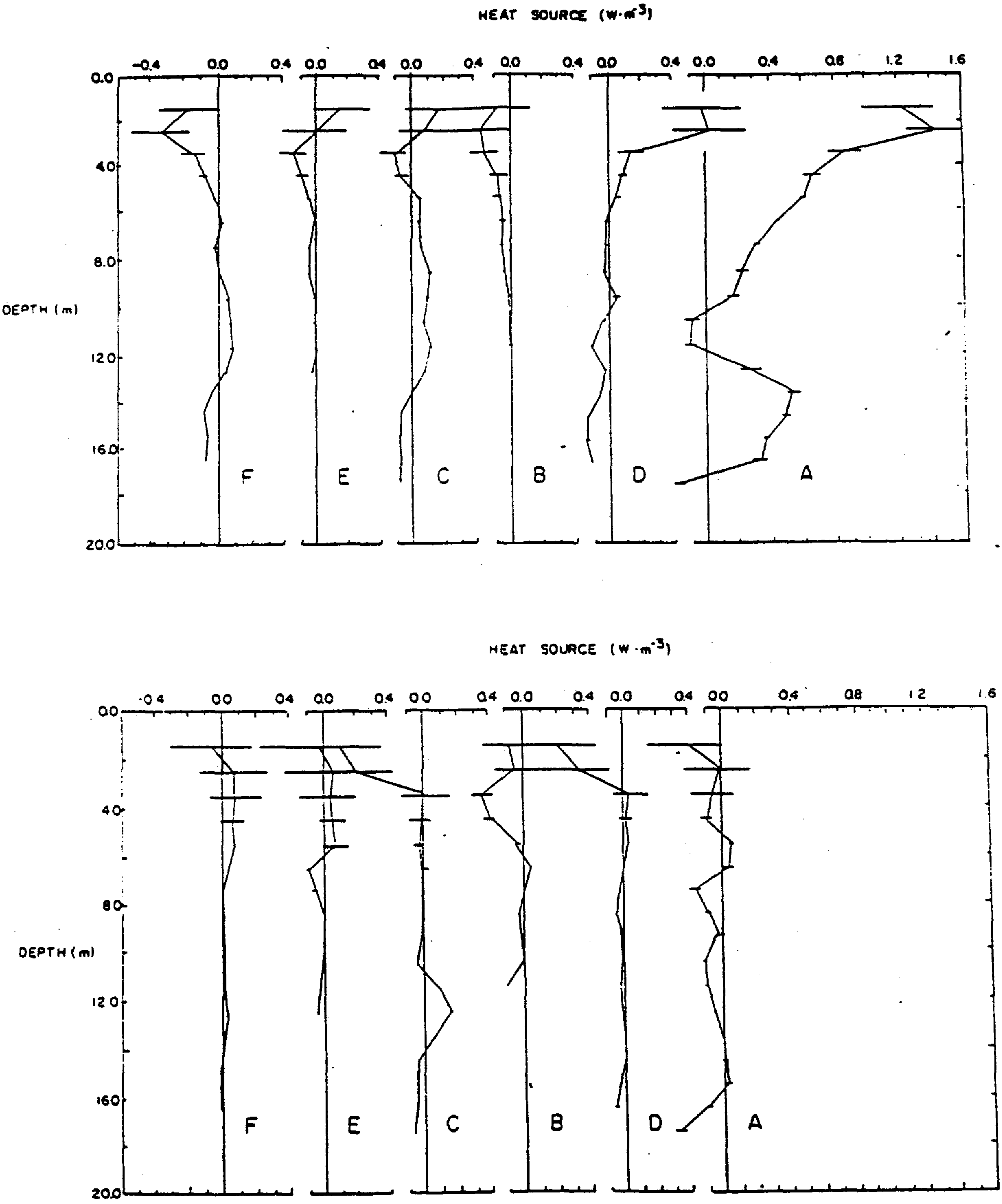
FIGURE 7

MATCHED TEMPERATURE AND OXYGEN DEPTH PROFILES
PILE 18A, STATION 3
HEATH STEELE MINES



FROM : BENNETT ET AL ,1988

NOLAN, DAVIS
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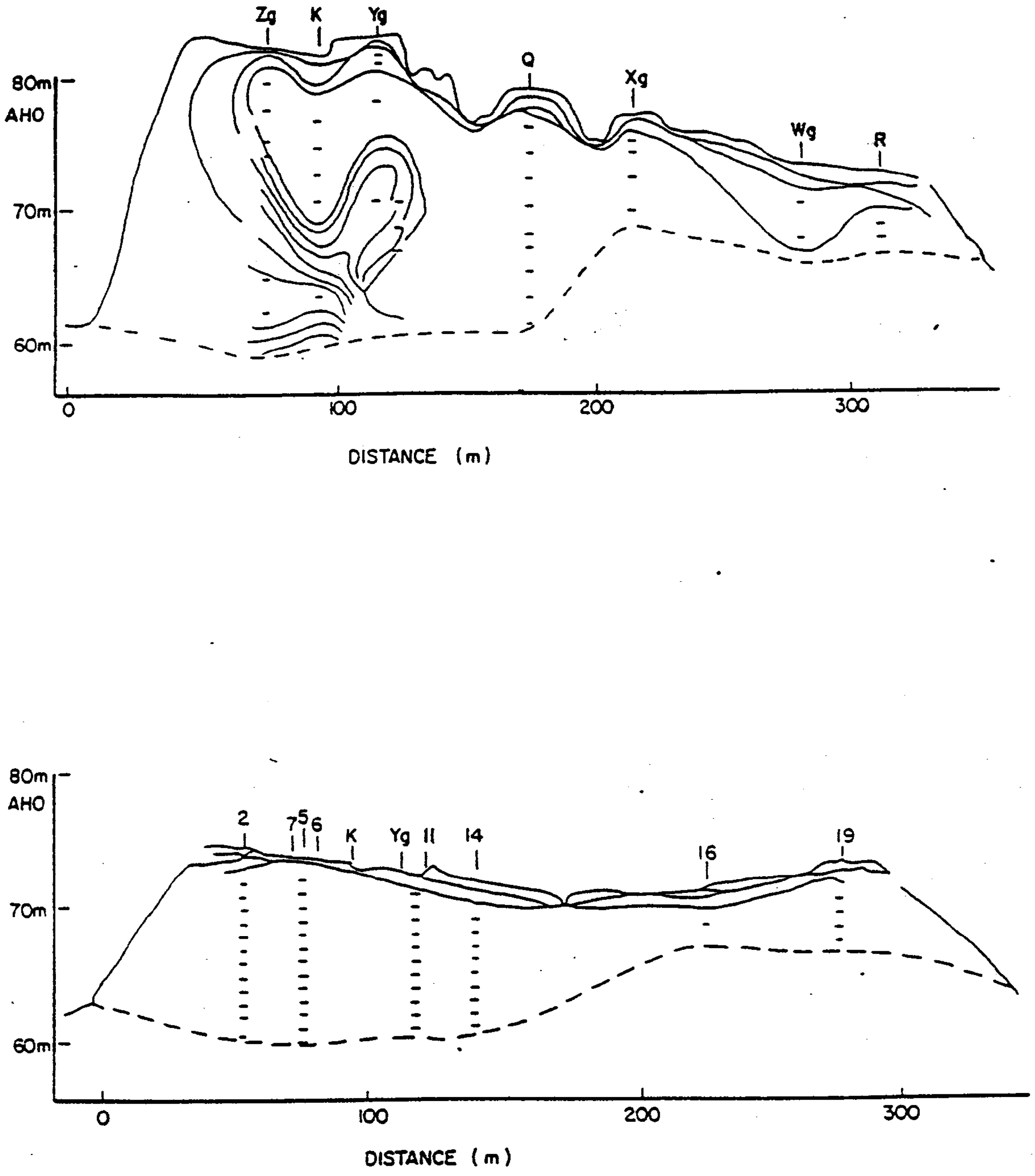
FIGURE 8

HEAT SOURCE PROFILES
WHITE'S DUMP
RUM JUNGLE, AUSTRALIA
HEATH STEELE MINES



From: BENNETT ET AL, 1988

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FIGURE 9

OXYGEN PROFILE
INTERMEDIATE DUMP
RUM JUNGLE, AUSTRALIA
HEATH STEELE MINES

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

STEFFEN ROBERTSON & KIRSTEN (B.C.) INC. - DR. A.M. ROBERTSON

Dr. Robertson's presentation dealt with the modelling of acid generation in tailings. Please refer to the following documents found after these minutes:

- Modelling of Acid Generation in Tailings, Contribution to Workshop on Modelling of Reactive Tailings by Dr. A. M. Robertson, P.Eng.
- US Bureau of Mines Report: In Situ Testing for Geohydrological Investigations of Tailings Dams by Dirk van Zyl, A. MacG. Robertson, Steven E. Follin and George L. Chedsey.

At the start of his presentation, Dr. Robertson made some comments on RATAP.BMT and on what he had heard earlier today. He made an analogy with a Ferrari, it looks great; however it is locked. Unless RATAP is released and tested we will not be able to comment further on it. RATAP is a tool that addresses the reactions very well; but it does not address the flow path. We must encourage CANMET to continue its development and improvement. RATAP must be released and tested by industry, we have to have answers now and we will be able to do better with RATAP than without it.

He made a comparison between the model structure of RATAP.BMT used for modelling tailings (Page 2, section 2.0 and Figure 1 of his Contribution) and the real tailings world. He showed slides of tailing sites: Westmin, Norway site and highlighted the cracks and the fact that oxygen is breathing through the cracks. The remediation must also be modelled and it consists of a nine layer system. This is a lot of modelling. Synthetic layers play an important role because they provide an immediate short term solution.

Dr. Robertson showed a slide of Mines Doyon's lime consumption. The steep increase in lime consumption is believed to be caused by flushing, not by generation. Storage of acid is very important in a waste dump, not so much in a tailings site. So, Mines Doyon needs to know what the acid consumption will be in 1991, we need these predictive tools. Not all waste is producing acid at Mines Doyon and our models must recognize this. Tailings dams have edges, thus the geometry and the materials properties dictate that the models be broken up into sections.

Dr. Robertson continued with the information he obtained at Uravan situated close to Grand Junction, Colorado. He did the study for the US Bureau of Mines in 1985. He described the area, the sections, and the 'fancy' equipment he used, example: piezocones, 'Delft' continuous samplers. As indicated, the report is presented in this section. Drying and cracking occurred due to changing conditions of the saturated state. The layering was intense due to the spigotted tailings system. The presence of slime pancakes leads to huge differences in moisture retention and creates complicated regimes. Up to five water tables have been identified with the piezocone.

Dr. Ritchie asked if the water infiltration was right through and the answer was 'yes'.

Dr. Robertson referred to the oxidization of bulbs of sand as could be seen in South Johannesburg when a freeway and interchange system was cut through the dry tailings piles. It is very important that the modelling exercise take this cracking and layering into account. The acid generation will be very different from the various areas.

Dr. Robertson continued with the example of the test facility at Faro, in the Yukon Territory, which is basically the installation of a composite cover (waste rock, till, slimes) intended to allow water to pass through, to create a permafrost condition and to prevent oxygen to enter. He described the testwork which has been going on for 2 1/2 years. No sampling has been carried out yet. He gave some results of temperature measurements.

The temperature is maximum 16°C at the surface, but under the cover the maximum temperature is 5°C at the top of the tailings and the permafrost is down 2 to 2 1/2 metre. The temperature at the top of the cover is 8°C. This cooling down has very significant implications on the rate of acid generation. The acid generation will be limited to 2 1/2 months a year.

The oxygen profiles were determined in winter only. The value obtained of 19.6% to 21.0% would seem to indicate that the instruments were not working.

A discussion resulted (Dr. Nicholson/Dr. Scharer) related to the ratio of diffusion to oxygen uptake which would determine the oxygen values.

Dr. Robertson concluded his presentation by reflecting on the storage in waste rock dumps, the storage of acid salts in the dry state and in the dissolved state. Predictions in the downstream environment must take into account this storage as it will control our remediation measures. A large waste rock dump has a large storage capacity and it can take up to three years before anything comes out of it. Modelling of acid generation must be attempted using multi-flow channel models which will give a stochastic variation of the acid generation.

QUESTION AND ANSWER PERIOD:

Mr. Davé:	Is there any compaction during the continuous sampling using the 'Delft' sampler?
Dr. Robertson:	He explained that the 'Delft' sampler is designed to eliminate this problem.
Dr. Nicholson:	What is the effectiveness of any control measures with regard to the composite cover consisting of nine layers? Is it a brute force approach?

Dr. Robertson: He replied that the tailings are acid generating, the cover was put up five years ago. The operation seems to be successful; there are no signs of acid generation.

Mr. Ferguson: What are Dr. Robertson's thoughts on monitoring the effectiveness of any control technologies?

Dr. Robertson: Dr. Robertson replied with an example and a discussion resulted on bonding. The costs at 3% rate of return are 22% of today by putting on a cover today and delaying treatment cost for 200 years.

Ms Erickson: Are the different layers of the different covers installed monitored, example, measurement of the permeability, to compare the projected permeability with the actual figure?

Dr. Robertson: Yes, piezometers are installed, the permeability is not monitored, samples were taken and tested. They will go back and take some more samples.

Mr. Ferguson: Mr. Ferguson asked a philosophical question related to input data for RATAP.BMT and if Dr. Robertson has such input data or can get such data?

Dr. Robertson: He replied that there is some new and old tailings data and indicated that he has asked for four to five months now to have access to RATAP but without success. He felt that is will be necessary to talk to the developers of RATAP but until then he cannot answer the question.

A question was asked if any modelling techniques were used for the Gray Eagle pit?

Dr. Robertson: Yes, but it was related to cyanide. The model is a solids transport model, the solution being squeezed out at the bottom. The estimate was to stop the treatment plant after 25 to 30 years, but they stopped it after 2 1/2 years. This should give you any confidence(!) in modelling, we were out by one order of magnitude.

A question was asked related to the natural vegetation on the covers in the next five years?

Dr. Robertson: He replied that there is no walk away solution, only low maintenance.

* * * * * *

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MODELLING OF ACID GENERATION IN TAILINGS

CONTRIBUTION TO

WORKSHOP ON MODELLING
OF REACTIVE TAILINGS

BY

DR. A. MACG. ROBERTSON P. ENG.

STEFFEN, ROBERTSON AND KIRSTEN (B.C.) INC.
800 - 580 Hornby Street.,
Vancouver, B.C., V6C 3B6

MAY 1990

MODELLING OF ACID GENERATION IN TAILINGS

1.0 INTRODUCTION

This report is submitted in support of the verbal presentation to be made by Dr. A. MacG. Robertson at the Workshop on Modelling of Reactive Tailings, organized by Kilborne Engineering on behalf of the MEND Prediction Committee, held at the Wigamog Inn on the 23rd and 24th May, 1990.

This report follows on a review of the report prepared by SENES Consultants Limited and BEAK Consultants Limited entitled 'Adaption of the Reactive Acid Tailings Assessment Program (RATAP) to Base Metal Tailings - Main Report' dated March, 1988. This report provides an overview of the adapted RATAP model (RATAP.BMT) and the results of a calibration using data from the Waite Amulet tailings site.

The overview describes the equations and algorithms that are used in the program and the program structure. The program and program details and solution processes are not provided. It is therefore not possible to review or evaluate the program as a whole. The program has not been available to test in any manner and the reviewer is therefore able to evaluate only the equations presented and the structure as briefly described.

The calibration/test on Waite Amulet tailings does not indicate clearly how calibration values were selected and evaluated and field data often varies widely (eg permeability values vary through three orders of magnitude). It is therefore not possible to determine if the model provides representative results because modelling processes are correct and accurate or whether the latitude in 'calibration' values are so great that a 'fit' can be obtained regardless of the deficiencies of the model.

The above criticism does not reflect on the model, but on the material available for this review. The model is clearly an excellent and valuable development and a credit to those responsible for its creation. Continued development and evolution of the model represents an essential and hugely beneficial activity. The objective of this workshop is commendable in that it brings together a 'thinktank' of specialists to provide ideas and recommendations to for the development of the model. Such model development is an evolutionary process and substantial contributions can come from a wide variety of sources. Unfortunately the restricted access to the model, its application and testing, has limited its development to date, as it limits the value of the review of those attending the workshop.

The author is not as competent to comment on the chemical aspects of the model as many of the other delegates to the workshop and this review therefore concentrates on the physical aspects of the model.

2.0 MODEL STRUCTURE

The concept adopted for modelling tailings is illustrated in Figure 1. Note that a fairly large number of horizontal layers are provided for above the water table but only a small number below the water table. The model does not provide for lateral variation.

The conceptual flow diagram for the model is illustrated in Figure 2. Each module performs its functions separately after importing values from other module results. A fixed number of iterations are used to converge on a solution. How these modules are applied to the various layers defined in Figure 1 is described in general terms in the overview. Based on this general description it is difficult to evaluate how the interaction between layers are handled within and between layers and modules.

A good description is provided of the equations and algorithms used in the various modules.

Table 1 shows the geochemical results used in performing the calibration assessments with Waite Amulet tailings. It is noted that at 1.4 m depth there is a perched water table.

3.0 CHEMICAL SIMULATIONS

The validity of the chemical simulations is left to the better understanding of other delegates to the workshop.

It is noted that for tailings, in contrast to waste rock, the fine particle size and milling process results in a much more homogenous mix with acid generating and acid consuming particles in close proximity. The pore water connecting these particles may have a chemical composition which is similar on a scale of a few centimeters and varies slowly with depth.

The model does allow of the multiplicity of layers, with differing acid generating characteristics that may exist as a result of tailings layering above the water table. It does not provide for many layers, and their varying attenuation capacities below the water table.

4.0 PHYSICAL SIMULATIONS

The validity of the model depends in part on its ability to model the physical conditions in the tailings impoundment. The current model considers only a single vertical column. Clearly this vertical differs across the tailings impoundment as illustrated in Figure 3. There is also lateral variation due to the sequence, pattern and nature of tailings discharge. This variation is not addressed in the model. To demonstrate the variation of tailings conditions a copy of a study and report by a SRK subsidiary Geothechnical Engineering and Mining Services (GEMS) for US

Welcome Screen Search Report List

Bureau of Mines is appended. Data is extracted from this report to illustrate physical conditions in a tailings impoundment.

The tailings dam investigated was the Uravan tailings impoundment in Colorado. The section investigated is shown in Figure 4 and the investigation procedure described in the attached report. The location and spacing of the probeholes and piezometer installations are indicated in Figure 5.

4.1 GRAINSIZE DISTRIBUTION IN A TAILINGS IMPOUNDMENT

Grainsize distributions through a tailings impoundment are of critical importance in that it determines many of the primary physical parameters controlling the rate of oxidation such as permeability, moisture content, oxygen entry and chemical composition. The range of grain size associated with various layers in the Uravan impoundment is illustrated in Figure 6. This ranges from almost pure sand to clayey silts.

4.2 GROUNDWATER TABLE AND MOISTURE CONTENTS

The permeabilities associated with these various layers are tabled in Figure 7, indicating a range of at least 4 orders of magnitude. The site is underdrained by the layer of natural alluvium. Numerous perched water tables were measured in the impoundment as illustrated in Figure 8. Downward flow conditions were very complex with pressure distributions which did not follow hydrostatic distributions as illustrated in Figure 9. The Dynamic Cone point resistance plot on this Figure also serves to illustrate the sand and slime layering at the location of this probe. A summary of the depths to the top of the uppermost water table at each probe location is tabled on Figure 10. This indicates that there are substantial depths on continuous partial saturation above the uppermost water table.

Based on the probe data a model for the physical distribution of sand and slime zones in the tailings impoundment, and the associated hydrological model was developed as illustrated in Figures 11 and 12. The presence of 'pancakes' of slime in the sand layers and 'flashes' of sand into the slime zones considerably complicates the hydrologic regime in the tailings impoundment.

To provide a better appreciation of the tailings layering and variability expanded probe logs for three probe locations are included as Figure 13.

4.3 VARIATIONS IN TAILINGS REACTIVITY

The reactivity of tailings has been shown to vary as the total tailings properties change and also with grain size for any specific tailings stream. The distribution of the reactivity between the outer sand zones and flashes are expected to be very different from the inner slime zones and pancakes.

4.4 VARIATIONS IN OXYGEN AVAILABILITY

The oxygen entry into the tailings impoundment is determined partly by diffusion, partly by convection as a result of atmospheric pressure changes.

Diffusion is substantially controlled by moisture content and is therefore as complicated as the hydrological regime (with its seasonal variations as determined by precipitation and infiltration followed by downward percolation).

Convection entry or 'breathing' of the dump is determined by the air filled void ratio, total depth to the water table the most air permeable routes. The moist slime pancakes act as barriers if they are continuous. Experience has shown that they are seldom continuous. Because of their low initial density and high clay content they crack as the moisture content in them is reduced. The cracks form permeable air passages for preferential air flow. This results in deep penetration of air into the tailings impoundment and complex oxidation conditions. The current model does not include for this type of oxygen entry.

4.5 VARIATIONS IN SOLUTE TRANSPORT

The discussion of the hydrologic regime (section 4.2) and Figure 3 illustrate the need to include for considerably more complex conditions in modelling before it will be possible to predict AMD from a tailings impoundment.

5.0 LINKED MODEL TO ALLOW FOR VARIATIONS IN TAILINGS IMPOUNDMENTS

To allow for a more complex modelling system it is suggested that an approach such as that proposed for waste rock modelling be integrated with the RATAP.BMT model. This concept is illustrated in Figure 14 and described in Appendix A.

Welcome Screen | Search | Report List

APPENDIX A

CONCEPT FOR ROCK WASTE MODELLING

Acid Generator Reactor Oxidation of sulphide minerals is initiated in local sulphide reactor zones throughout the waste rock dump producing acidity, sulphate and dissolved metals. These processes are reasonably well understood within tailings with relatively uniform sulphide/alkalinity distribution, however appear to be much more complex within the more variable waste rock dump. The larger particle size of waste rock can result in separation of the acid generating and acid consuming minerals that would not be predicted using standard laboratory acid generation potential testing (i.e typical humidity cell test).

To develop a mathematical model for the rate of acid generation, the effects of the each of following must be determined for the scale of the waste rock dump:

- type of reactive sulphide minerals
- distribution and exposure of sulphide minerals
- type, distribution and exposure of base minerals
- chemical and biological oxidation characteristics
- effects of temperature
- oxygen and water controls and flux
- chemical concentrations controls

In the absence of a mathematical model a laboratory simulation of this reactor may be developed using a modified humidity cell containing 'large' rock waste with a grading which duplicates that in the dump.

Flow Path Reactor Solution flowing through the dump transports the oxidation products from the acid generation site into the underlying waste rock. Drainage flow paths will be controlled by the physical configuration of the waste rock dump. The migration of contaminant fronts through the waste rock column is controlled both by the physical nature of the flow system and the chemical reactions along this flow path.

Acidic solution flowing through zones of net acid consumption will be neutralized until the base material within the zone is depleted. Acidic solution flowing through a marginally acid producing area rapidly consumes the available base and accelerates the onset of acid generation. The rate of acid consumption and depletion can only be predicted by kinetic testing; static tests indicate total quantities of acid producing and consuming material.

The migration of contaminant fronts is controlled largely by the geochemical nature of the waste rock surfaces along the flow path; as the available neutralization potential is consumed the fronts migrate along the solution flow path. The effects of diffusion and dispersion in the lateral spreading of acidity and low pH zones within the waste rock column are not well defined. Some of the factors which must be considered in determining the conditions within the flow path reactors and the resultant drainage solution chemistry include:

- neutralization potential available to surface flows
- diffusion or exchange of acid/base with interior of rock particles
- flow paths over particles
- effects of diffusion and dispersion on the lateral spreading of acidity and contaminants
- hydrogeological regime of the dump and solution flow path
- factors controlling acid generation as in the acid generation reactor

Again once these relationships are developed it should be possible to develop a mathematical model of the progression of the acid fronts along the solution flow path and predict the solution chemistry of the drainage emanating from the flow path reactor.

In the absence of a mathematical model a laboratory simulation can be developed using large scale columns (such as the 22 ft columns at B.C. Research) with partially saturated controlled flow path establishment and monitoring.

Surface Mixing and Flow Reactor At the base of the dump, a mixed stream will form combining drainage from reactors throughout the waste dump. These seeps will have different solution chemistry depending on various stages of development of the oxidation and drainage processes. The water quality of this mixed stream will depend on solution chemistry and solubility controls. Because of the mass flux of surface water flow the effects of solid surfaces along the flow channel is quickly consumed and solution chemistry is primarily dependant on the chemistry of the component streams. Prediction of the resulting solution chemistry can be done by both mathematical simulation and laboratory mixing.

Subsurface Contaminant Migration Reactor Subsurface flow and contaminant migration is also controlled by a number of physical and chemical parameters which determine drainage quality over time. The potential buffering capacity of solids in the seepage path of the groundwater flow system is much greater than in the surface flow reactors and must be determined. The rate of acidity and contaminant plume migration, and changes in solution chemistry are dependent on the rate and volume of groundwater flux, the neutralising and buffering capacity of the soil, and the contaminant load of the seepage.

Models have been developed for more general contaminant migration studies to predict subsurface chemistry and soil/water interactions and these should be suitable for AMD migration in subsoils. Available groundwater contaminant migration programs will be reviewed to determine models most suitable for modelling the subsurface flow reactor.

Biological or Environmental Reactor Several of the factors determining seepage chemistry in the surface flow reactors are also operative in the biological reactor. The emphasis in this reactor development is the role of wetlands in mitigating acidic drainage. There is considerable interest and research into the treatment of contaminated drainage with enhanced biological environments, primarily wetlands. Studies are currently in progress (Noranda Bell Mine) to evaluate the efficacy of such processes and the resultant drainage quality. Results of these studies would be used to develop the environmental reactor model linked to the overall dump model.

Global Model The ultimate impact on the receiving environment of drainage from waste rock dumps containing reactive sulphide minerals will be determined by the interaction of the preceding processes, and the dilution and solution chemistry of the receiving environment. The model to predict this impact will be developed by linking all the component reactor models in a global model representative of each dump. Individual "string" models representing each flow path may start with a simulation as shown in Figure 2. Many "strings" may be needed to simulate the entire dump as represented in Figure 1.

The nature of each "string" of reactors can be established as follows:

i) The surface mixing flow reactor, subsurface contaminant reactor and environmental reactors can be defined by deterministic means from a knowledge of the surface and subsurface flow paths and the flow path in the environment. i.e. it is possible to go out and determine what the conditions along these portions of the flow paths will be.

ii) The acid generator reactor (AGR) and flow path reactor (FPR) in the dump material will vary in nature depending on the variability of the waste rock source; the mining and dumping procedures; and the surface conditions on the waste dump surface (hence the concentrations of infiltration). These conditions can be simulated by stochastic or probabilistic and geostatistical modelling of the waste material variations in the waste dump.

FIGURE 1

CONCEPT ADOPTED FOR MODELLING OF TAILINGS

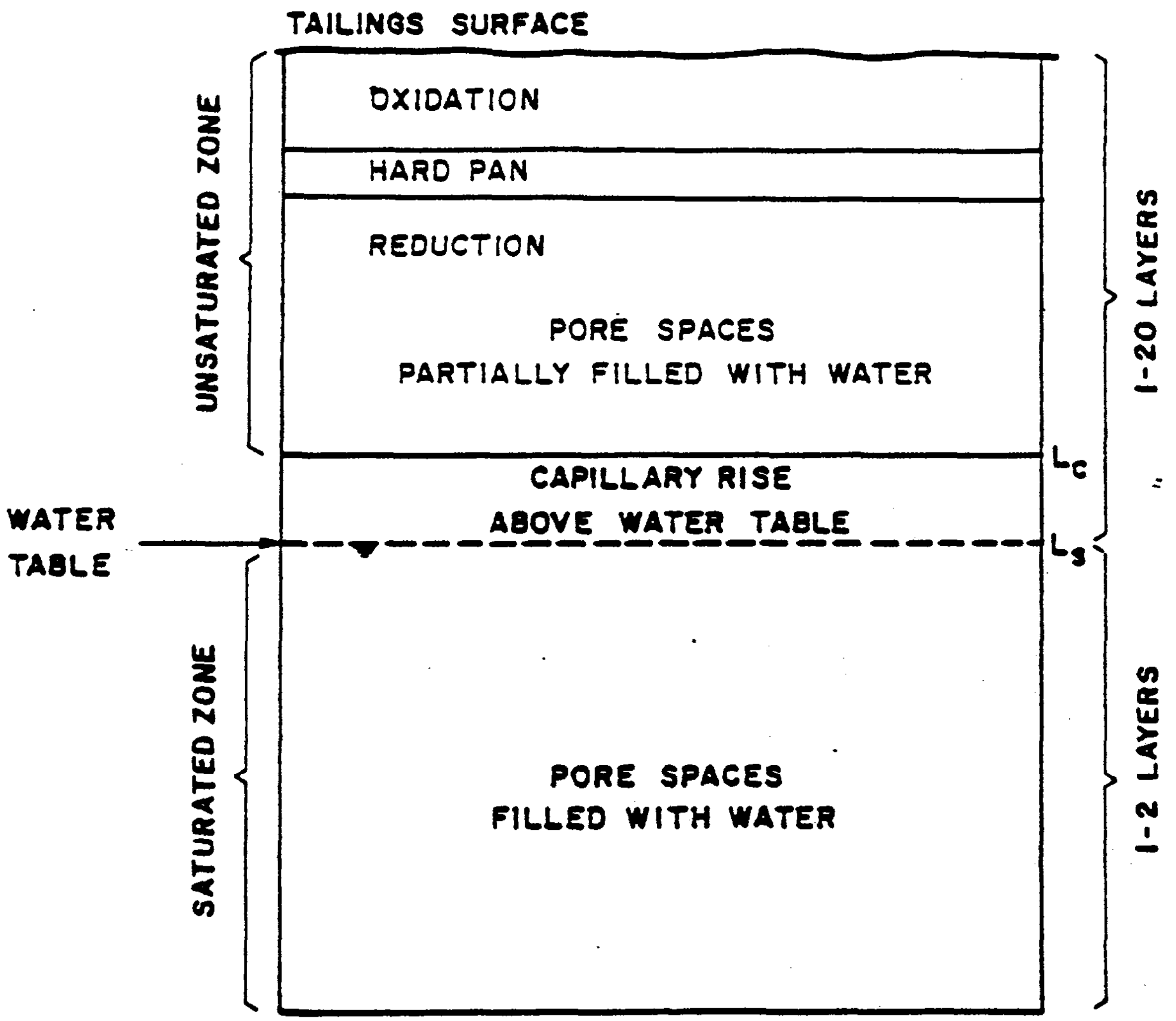
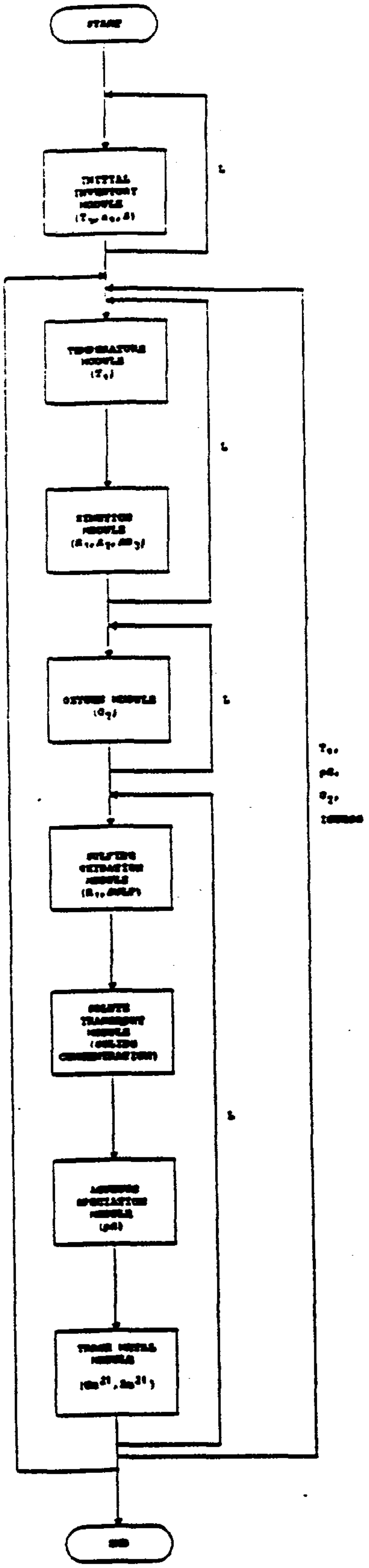


FIGURE 2

CONCEPTUAL FLOW DIAGRAM



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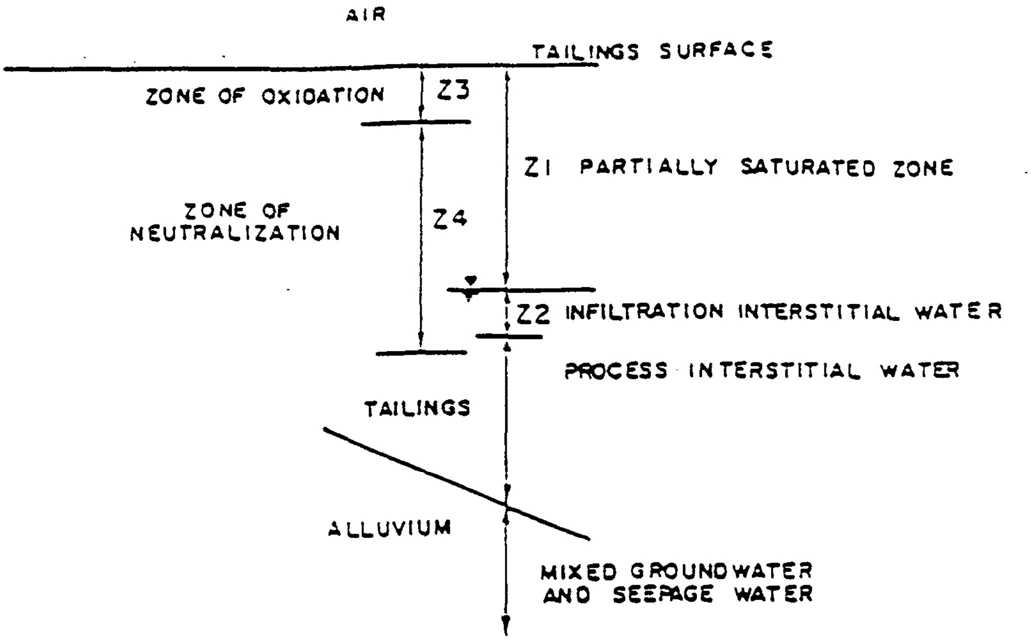
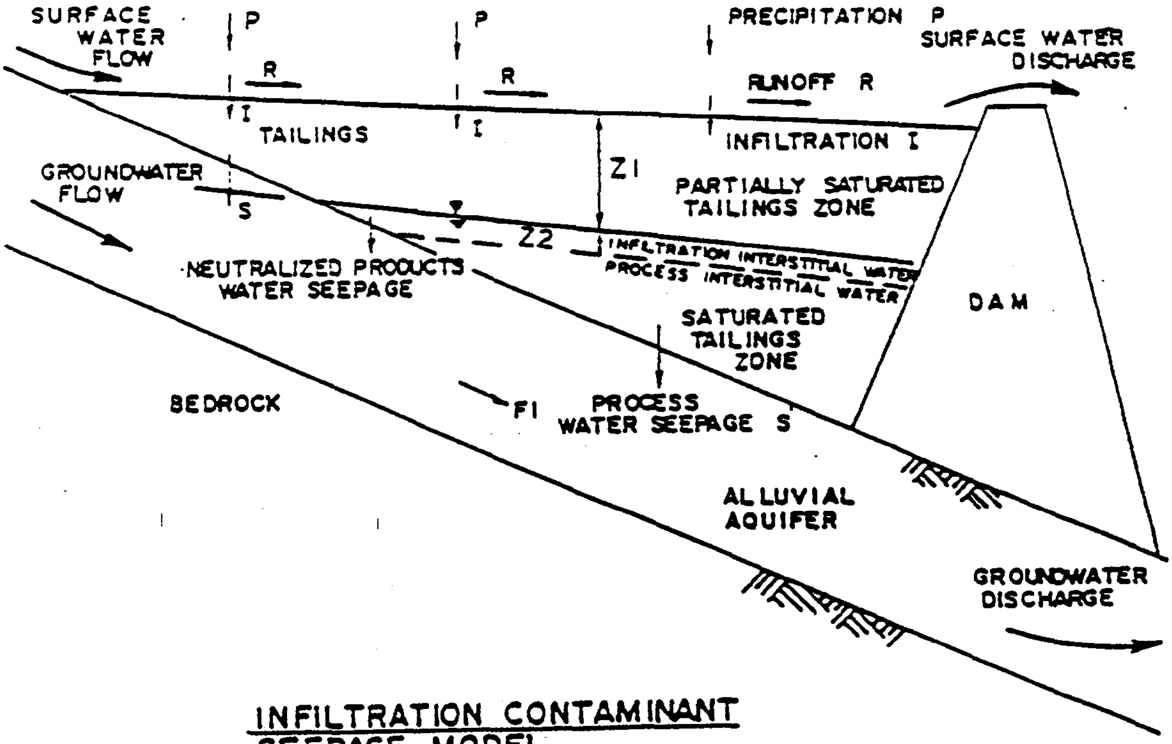


WATER QUALITY MODEL FOR TAILINGS COLUMN



INFILTRATION CONTAMINANT SEEPAGE MODEL

(After Robertson, 1987)

PROVINCE OF B.C. — AMD TASK FORCE

WATER QUALITY MODEL FOR TAILINGS COLUMN AND INFILTRATION CONTAMINANT SEEPAGE MODEL

STEFFEN ROBERTSON & KIRSTEN, Consulting Engineers

DATE APRIL '88
PROJ. NO. 66001
APPROVED
NO. 3

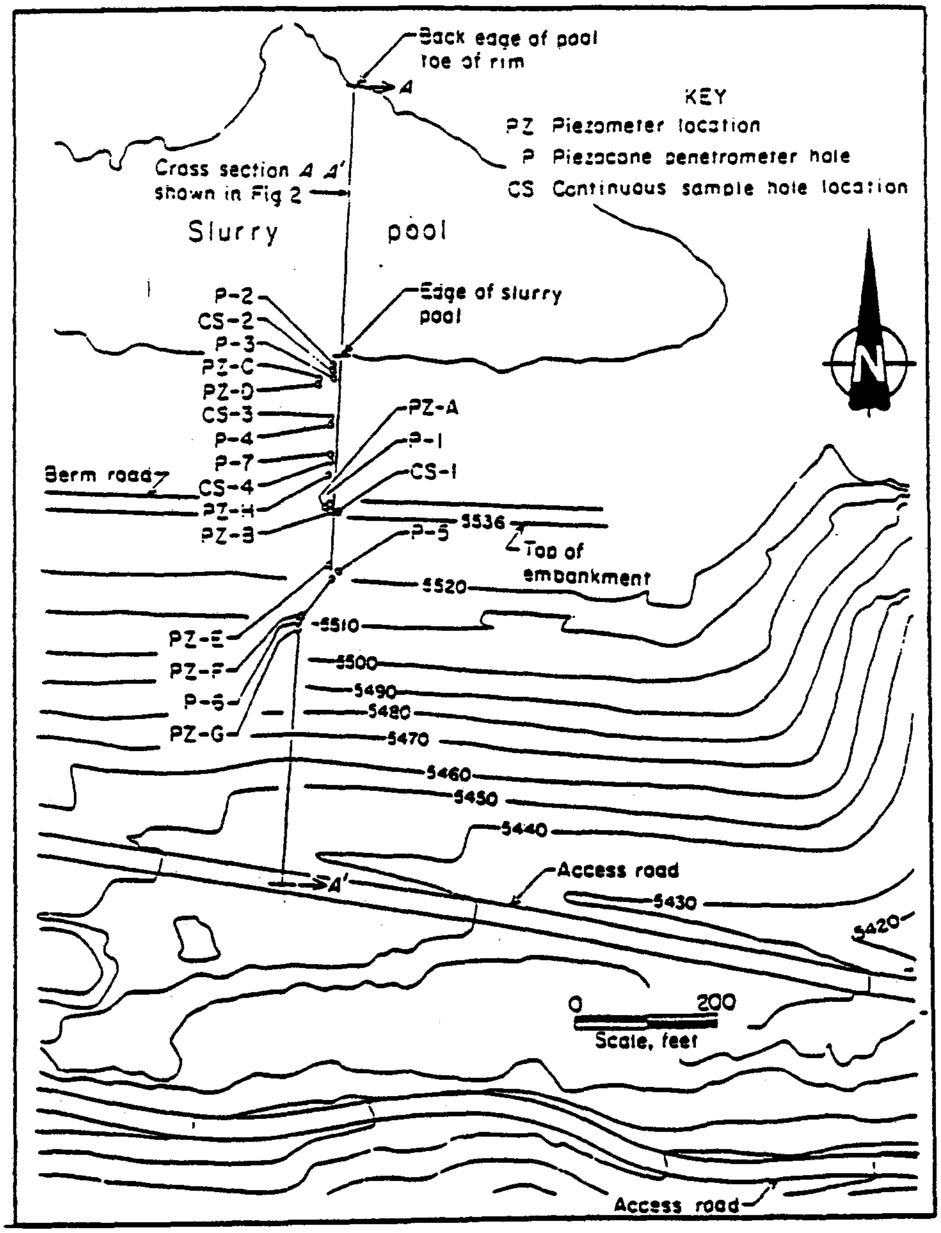


FIGURE 4 - Location of test holes and piezometers.

Welcome Screen Search Report List

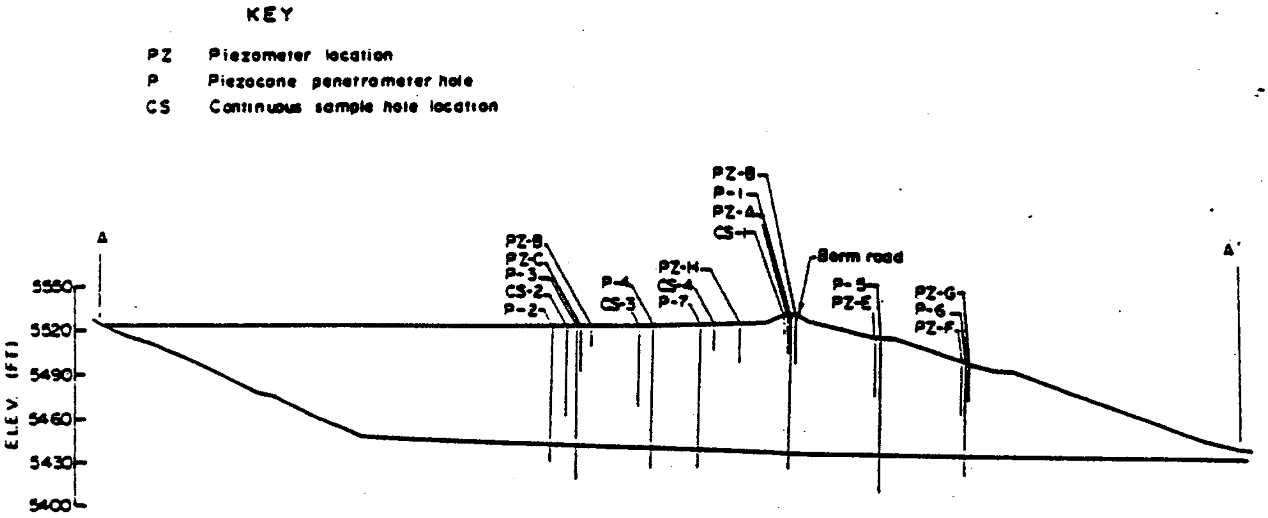


FIGURE 5. - Location and depth of test holes and piezometers on section AA, Figure 4.

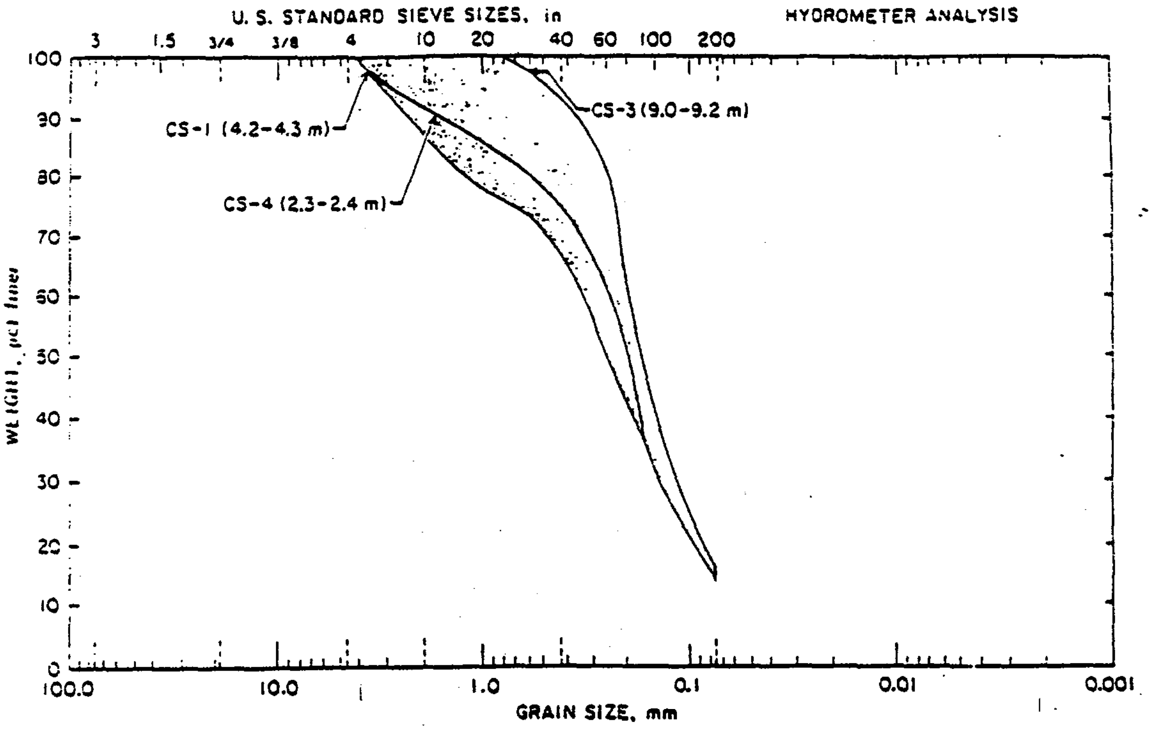


FIGURE 6a. - Grain size distribution. Soil type 1.

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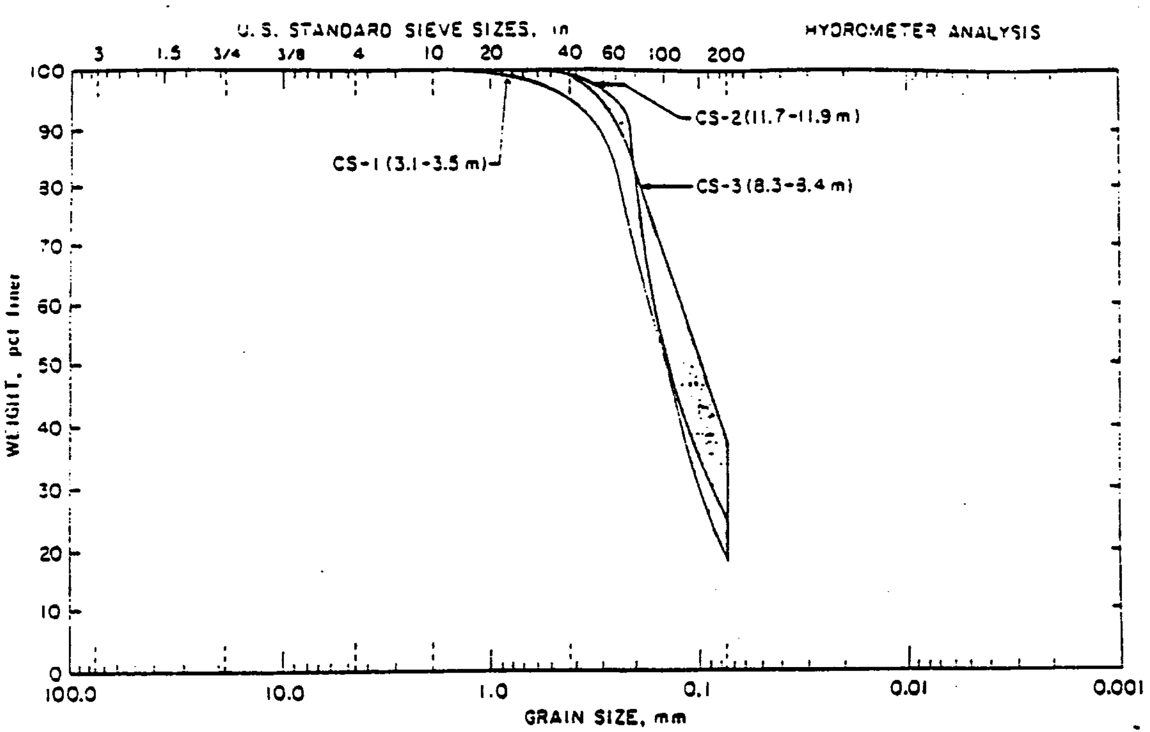
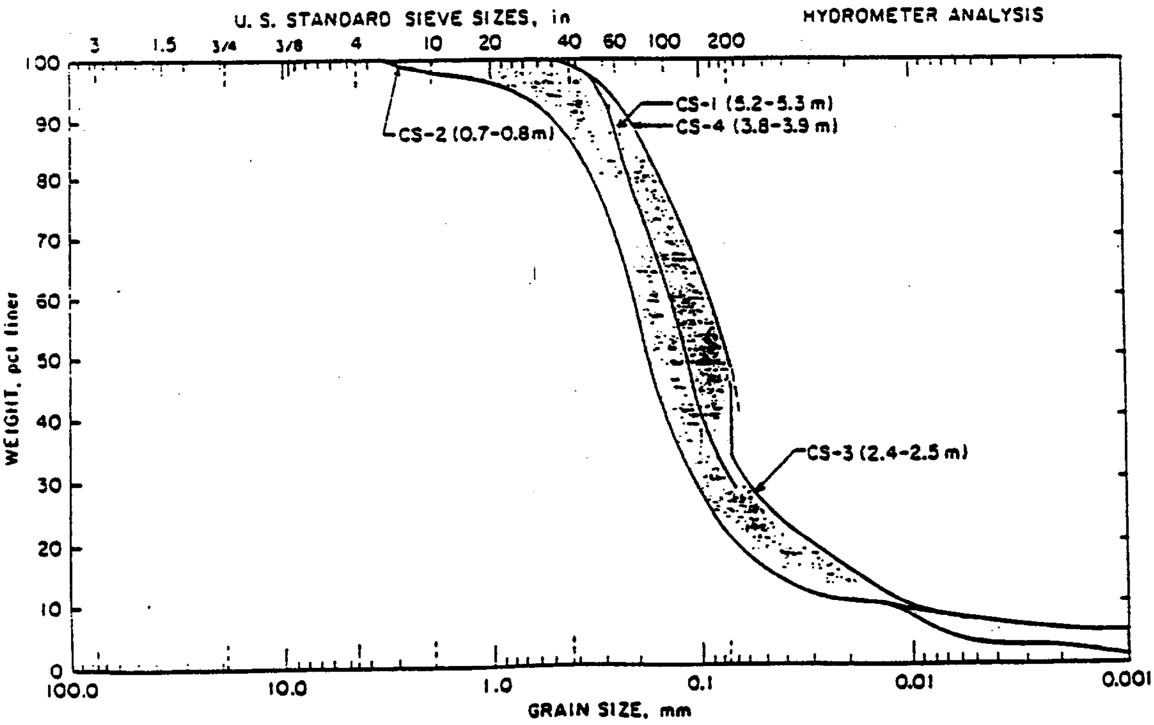
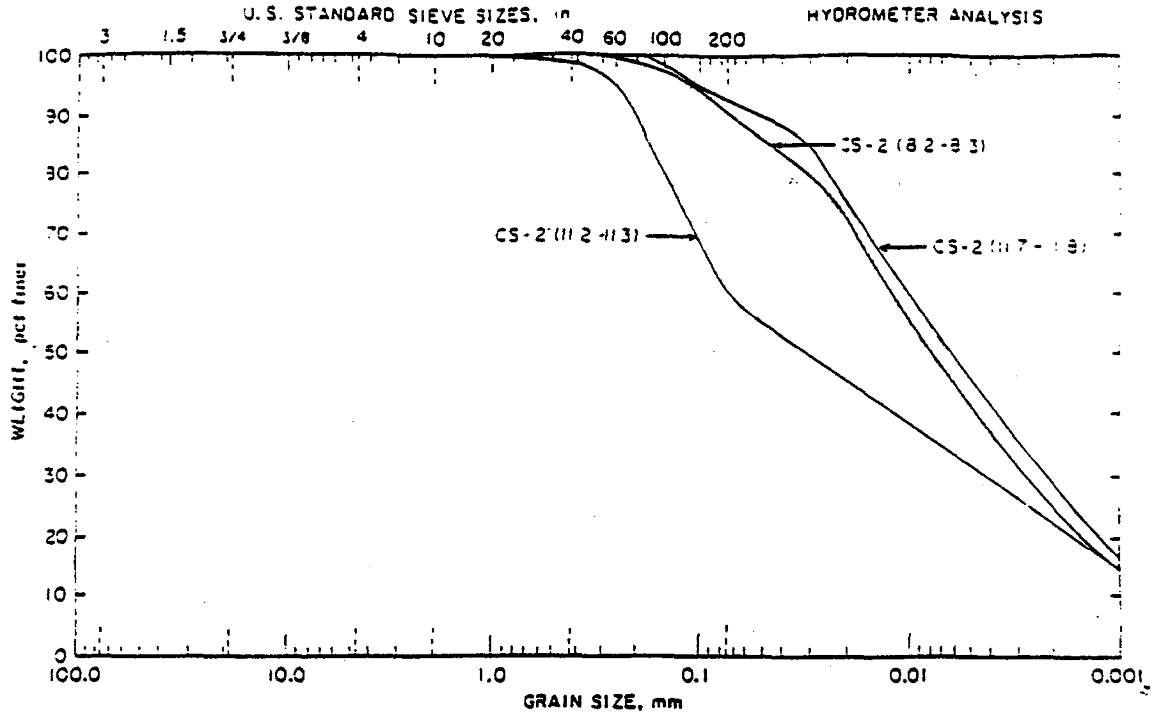


Grain size distribution. Soil type 2.

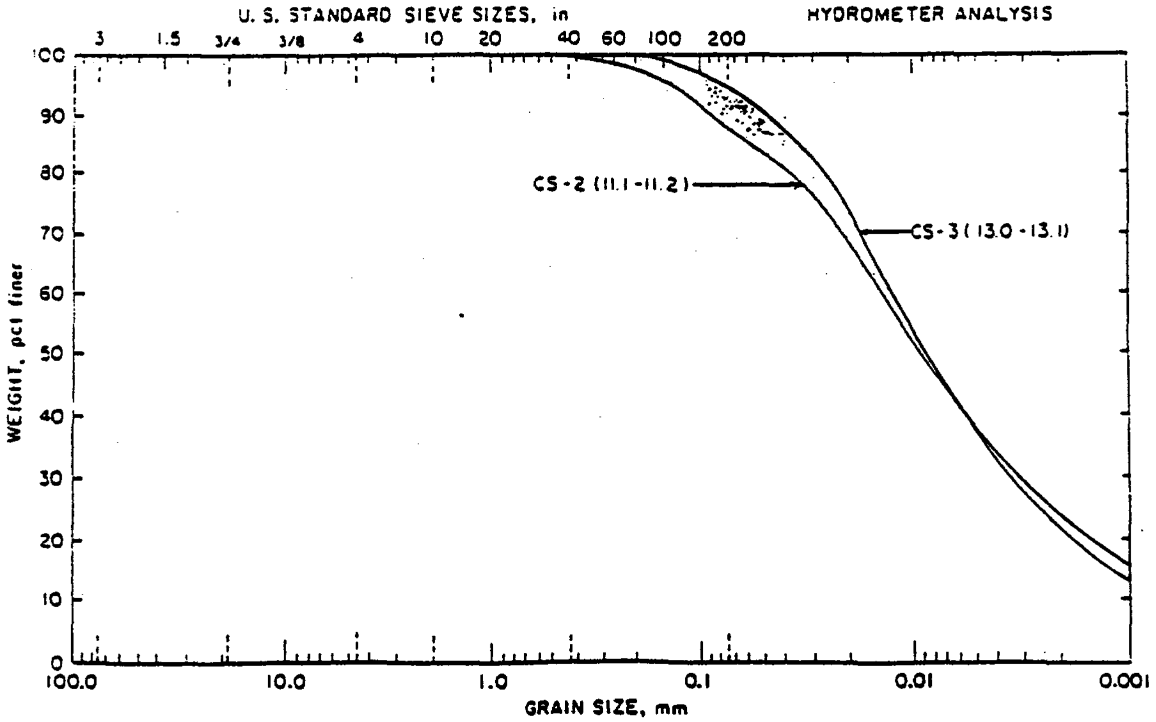


Grain size distribution. Soil type 3.

FIGURE 6b



Grain size distribution. Soil type 4.



Grain size distribution. Soil type 5.

FIGURE 6c

Welcome Screen Search Report List

FIGURE 7 - Summary of hydraulic conductivity values based on laboratory data

Material type	Hydraulic conductivity estimate	
	Hazen's formula (cm/s)	Laboratory testing (cm/s)
1	4×10^{-3}	NA
2	1×10^{-3} to 2×10^{-4}	NA
3	2×10^{-4} to 1×10^{-4}	6.8×10^{-4} to 2.4×10^{-7}*
4	5×10^{-7}	1.5×10^{-6} to 1.1×10^{-7}
5	5×10^{-7}	1×10^{-7} to 6.8×10^{-8}

*This very low value may have been caused by a test on a partially saturated sample

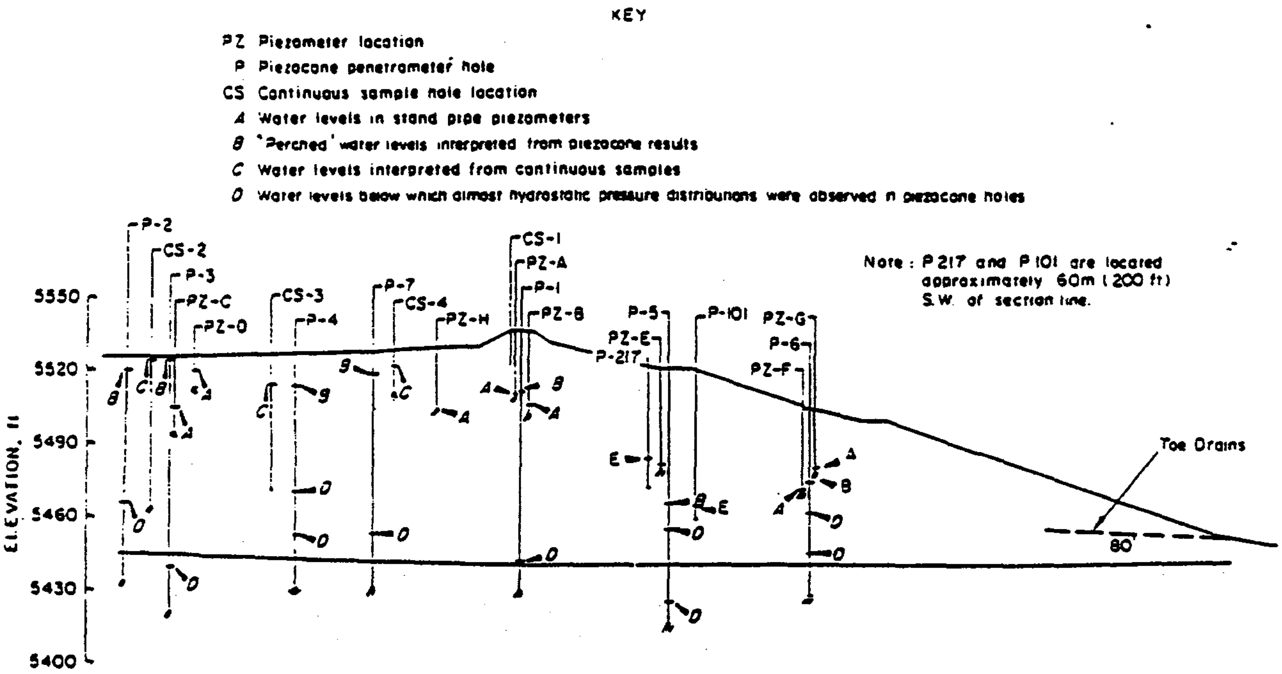


FIGURE 8. - Cross-section through impoundment showing piezometer level interpretations.

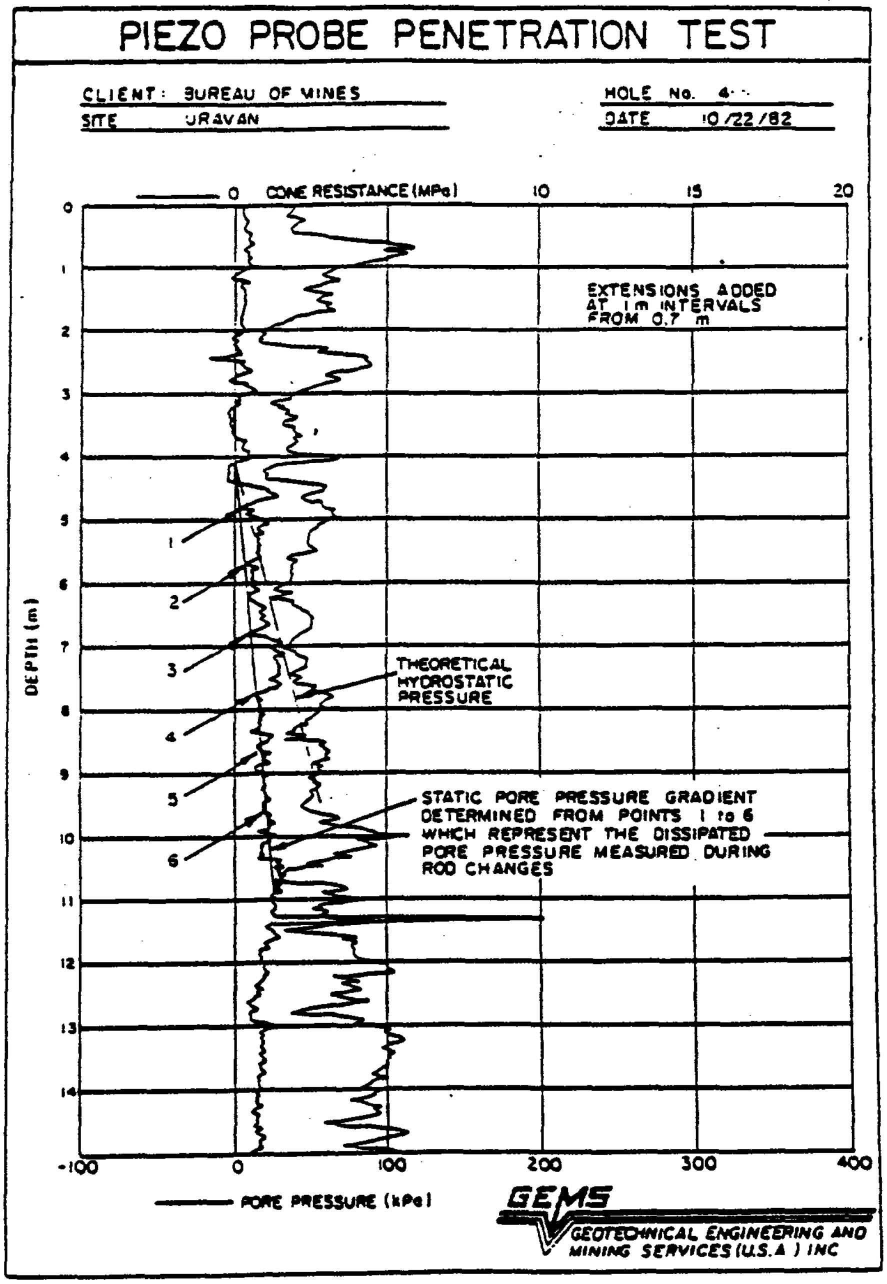


FIGURE 9. - Location of phreatic surface for hole P-4 from piezo probe results.

FIGURE 10. - Estimation of top free surface location from piezo probe test results

Hole No.	Estimated depth (m)*
P-1	7.7
P-2	1.7
P-3	0.5
P-4	4.0
P-5	17.0
P-6	9.0
P-7	2.5

*From tailings surface

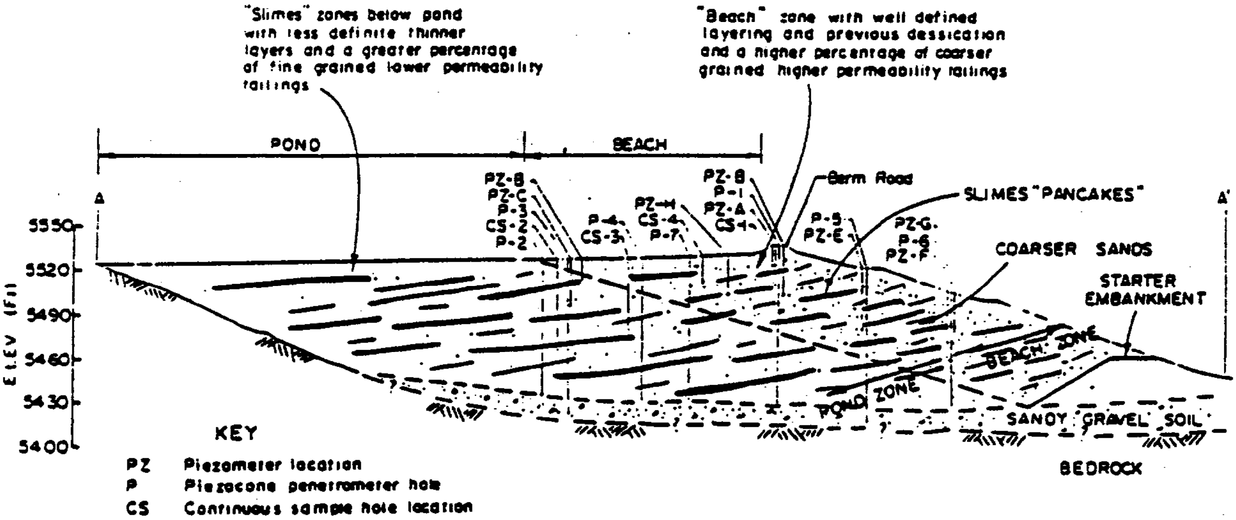


FIGURE 11. - Section through impoundment illustrating discontinuous layering.

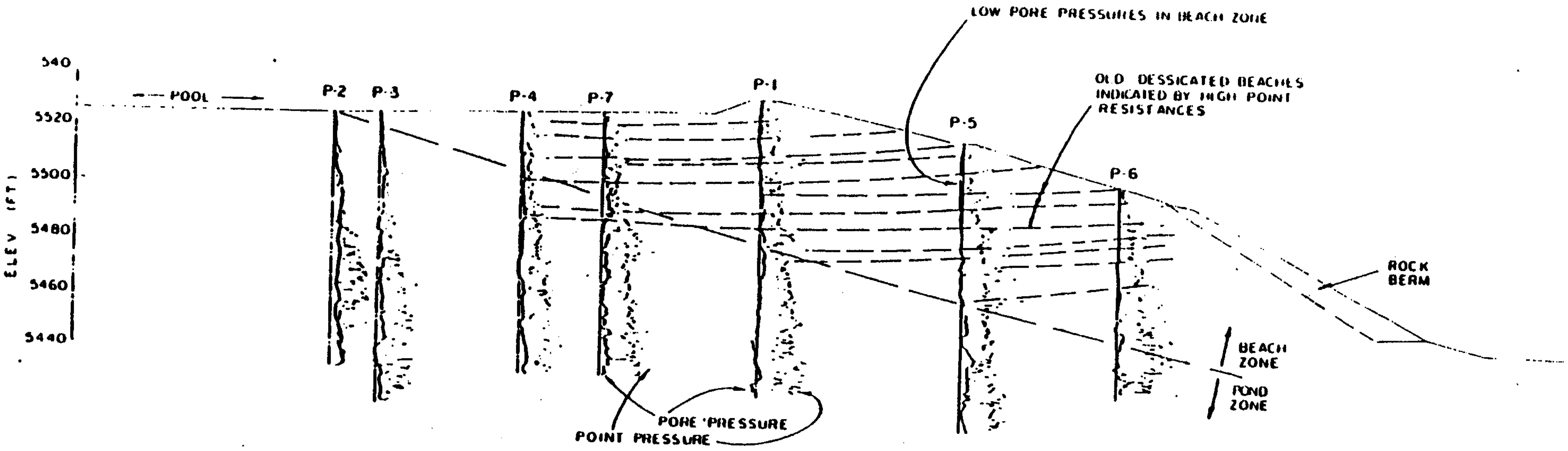


FIGURE 12 - Layering indicated by piezocone results.

PIEZO PROBE PENETRATION TEST

PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 1
DATE 10/19/82

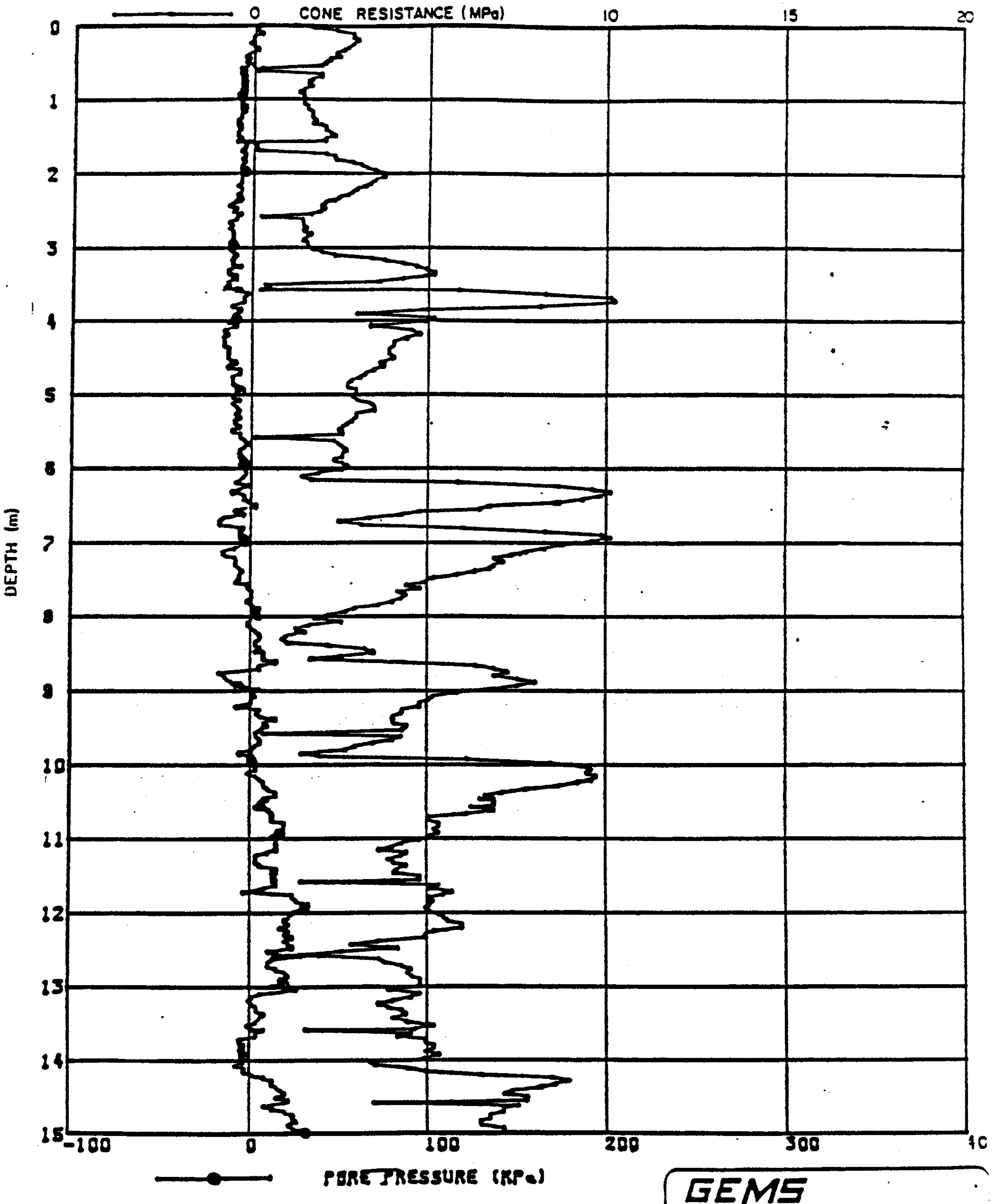


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FIG. 13a (1,

PIEZO PROBE PENETRATION TEST

PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 2
DATE 10/20/82

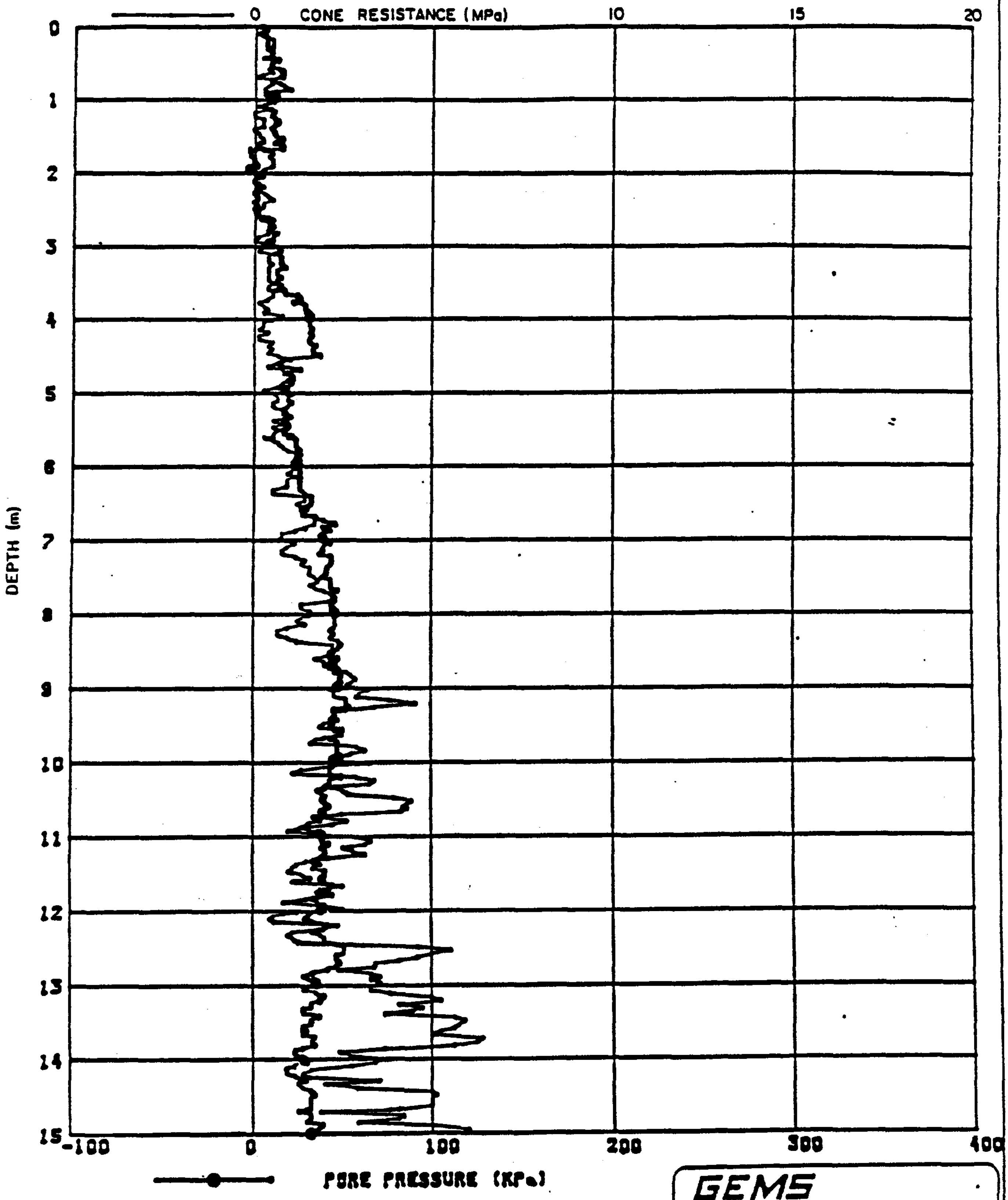

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FIG. 13 b (1)

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PIEZO PROBE PENETRATION TEST

PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 2
DATE 10/20/82

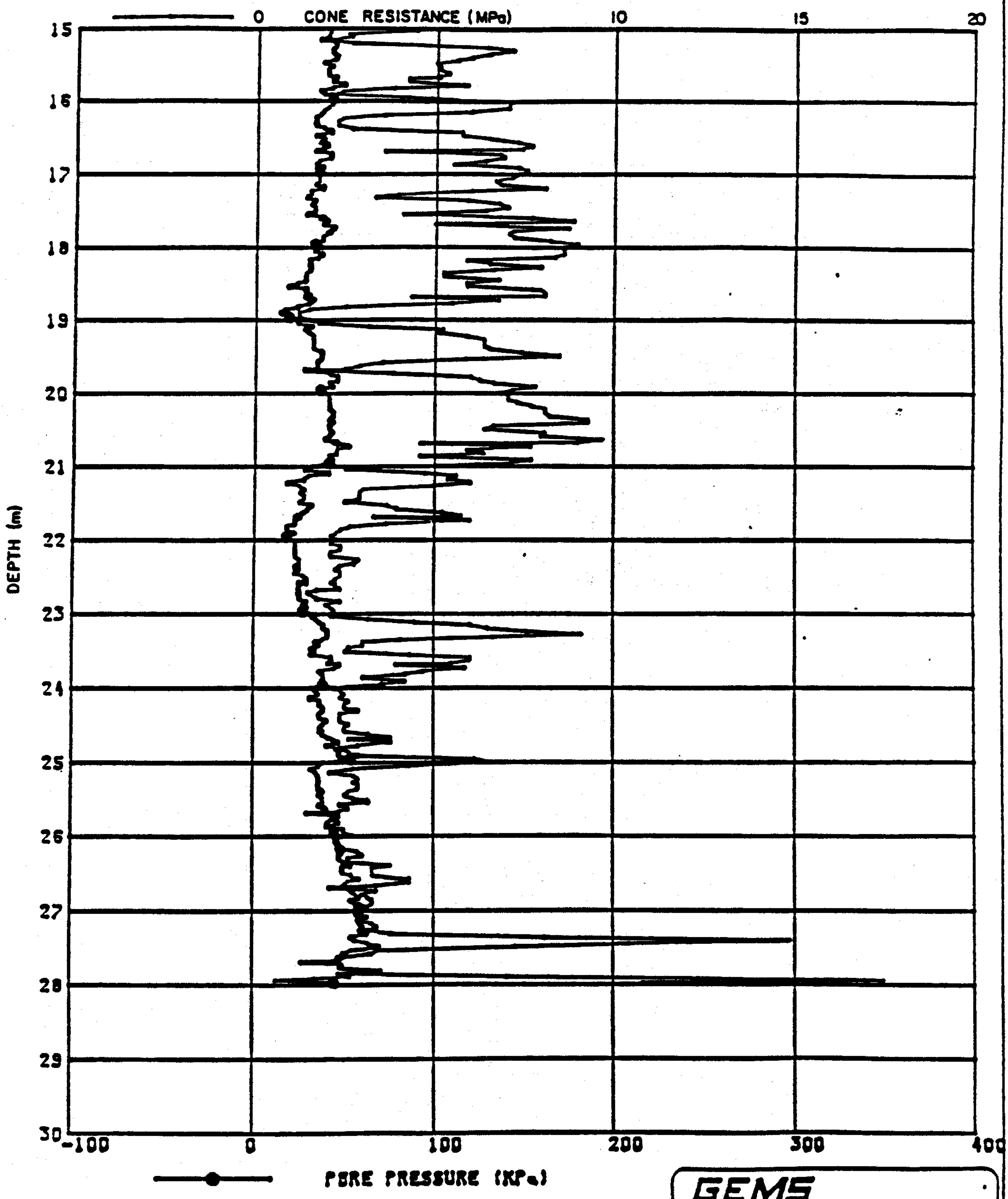

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FIG. 13b (2)

PIEZO PROBE PENETRATION TEST

PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 6
DATE 10/23/82

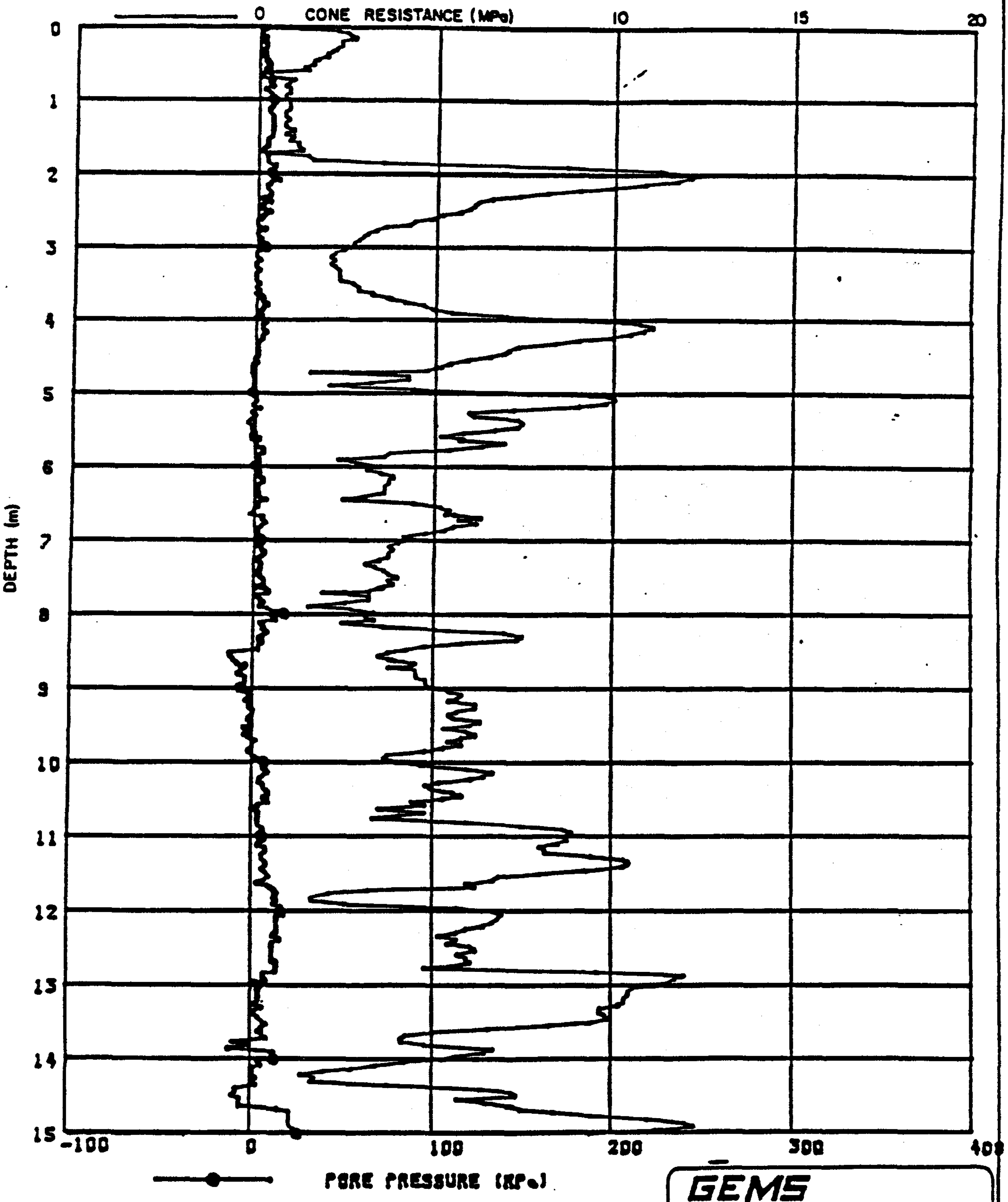

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FIG. 13 c (1)

PIEZO PROBE PENETRATION TEST

PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 6
DATE 10/23/82

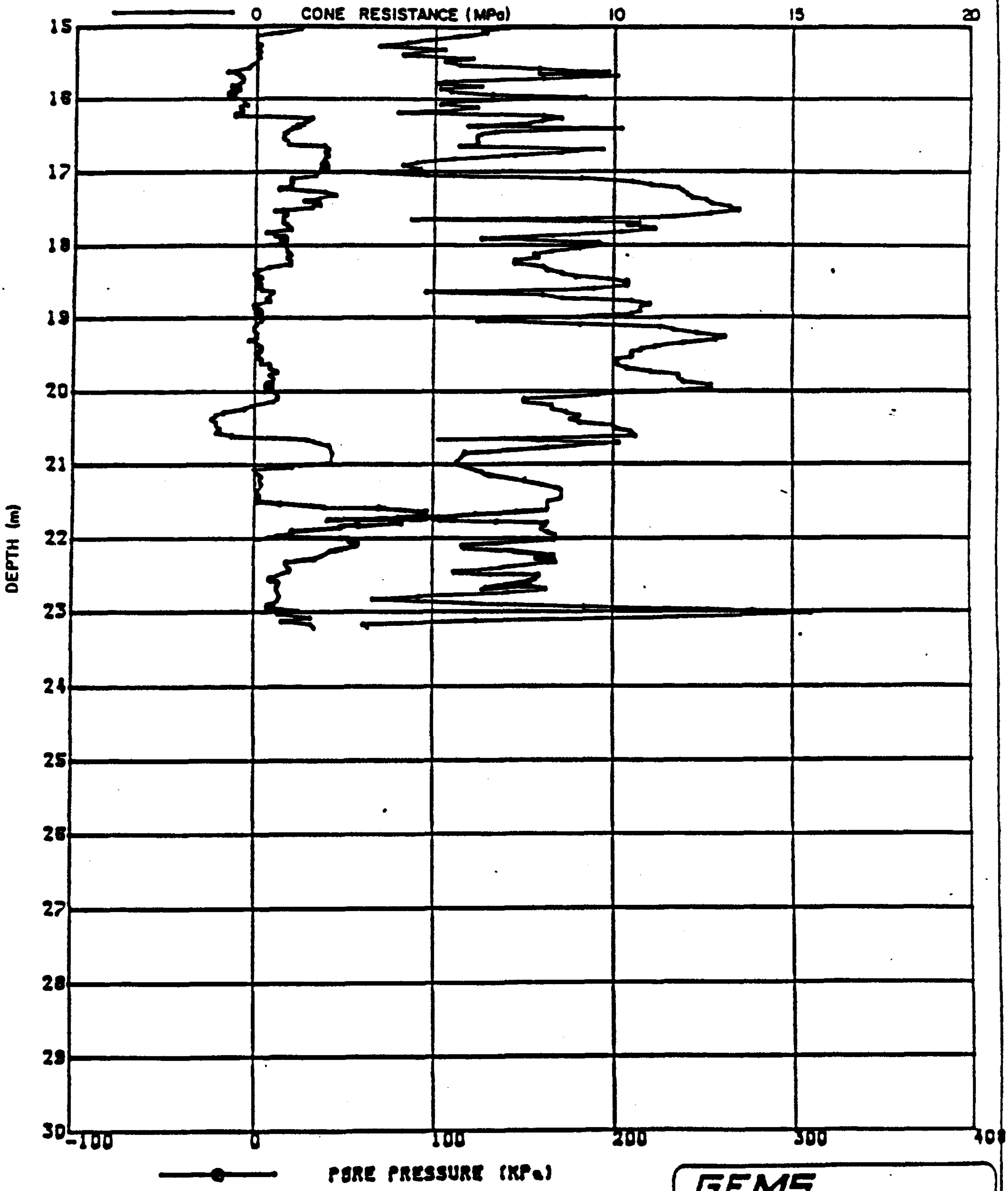

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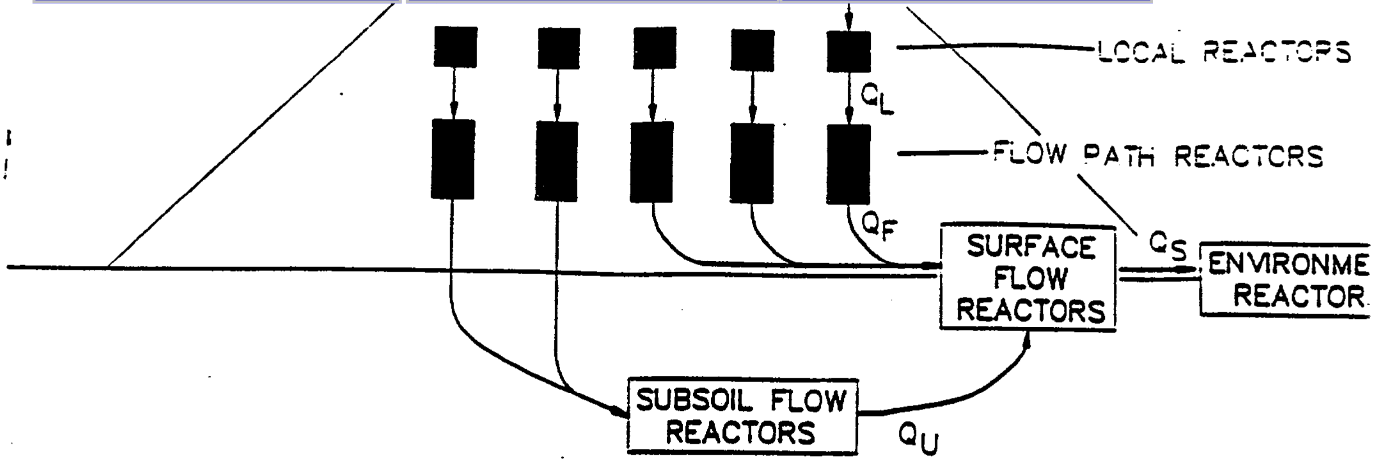
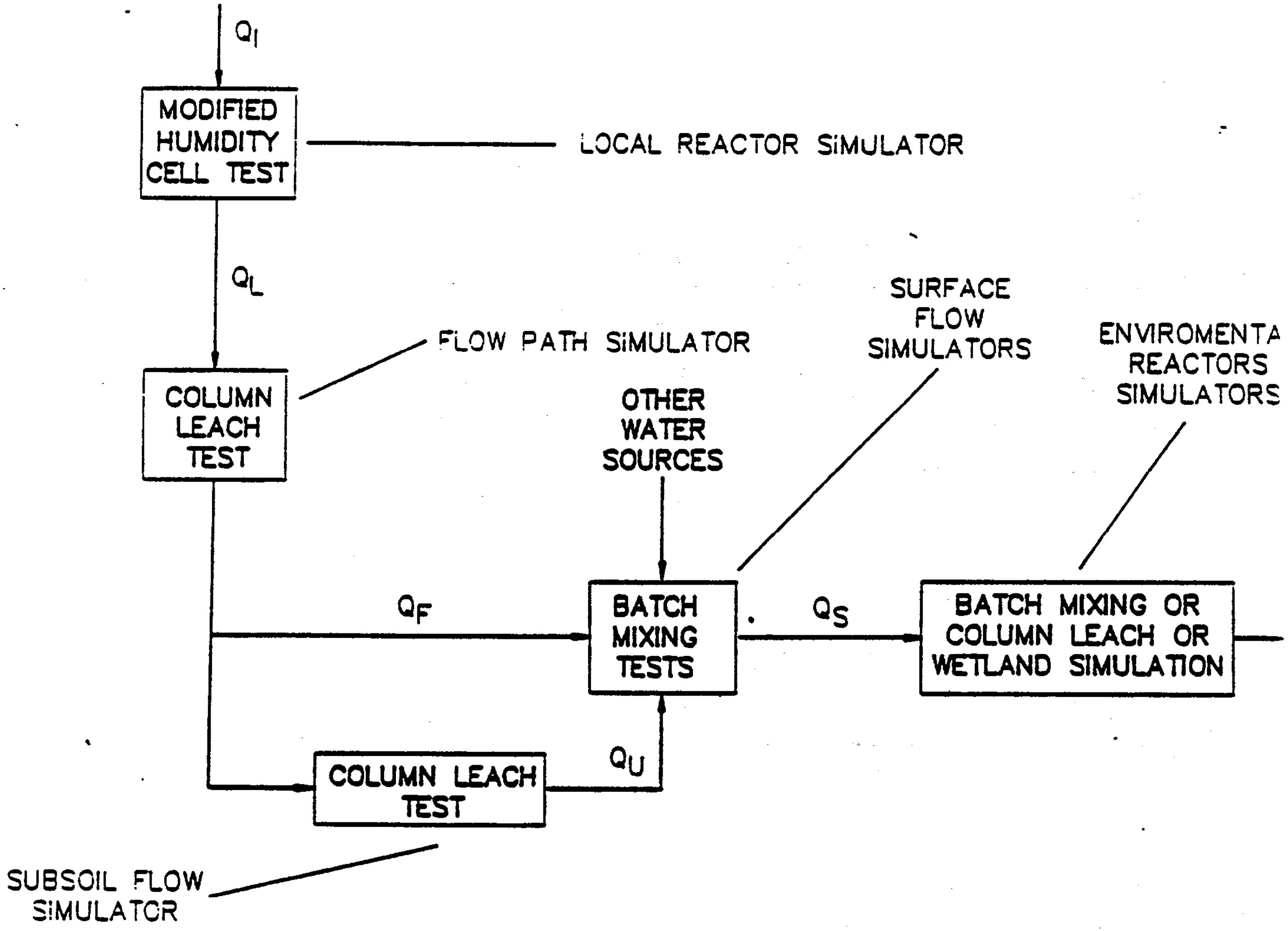
FIG. 13 c (2)



VISUALIZATION OF ACID GENERATION AND MIGRATION AS A SERIES OF REACTORS

FIG. 14 a



SIMULATIONS USED FOR MODELLING WASTE DUMP DRAINAGE QUALITY

FIG. 14 b

Welcome Screen | Search | Report List

TABLE I

GEOCHEMICAL RESULTS

(Location WA-20)

Water Content	Depth (m)	pH	Eh (mv)	S.Cond. (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)	SO_4 (mg/L)
Unsaturated	.1	2.3	686	12.8	58.5	19.7	<0.02	-
Unsaturated	.2	-	-	-	-	13.1	0.05	-
Unsaturated	.3	4.6	650	16.6	6650	7.6	0.07	-
Unsaturated	.4	-	-	-	-	4.3	<.02	-
Unsaturated	.5	4.35	649	16.6	3560	4.0	0.3	-
Unsaturated	.7	4.35	501	18.5	4430	-	-	-
Unsaturated	.9	4.30	582	17.9	4250	-	-	-
Saturated	1.4	-	-	-	-	-	-	-
Unsaturated	2.2	-	-	-	-	-	-	-
Saturated	4.06	6.3	294	2.5	-	-	-	2200
Saturated	6.14	7.5	404	6.7	-	-	-	640

Welcome Screen Search Report List

A mining research contract report
MARCH 1985

IN SITU TESTING FOR GEOHYDROLOGICAL INVESTIGATIONS OF TAILINGS DAMS

Contract 50221076
Geotechnical Engineering and Mining Services (USA) Inc.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

FOREWORD

This report was prepared by Geotechnical Engineering and Mining Services (U.S.A.) Inc., Lakewood, Colorado under USBM Contract number S0221076. The contract was initiated under the Conservation and Development Program. It was administered under the technical direction of Twin Cities Research Center, Minneapolis, Minnesota with Steven E. Follin acting as Technical Project Officer. Kent Charles was the contract administrator for the Bureau of Mines. This report was submitted by the Authors on May 1, 1984.

CONTENTS

Page

Page

LIST OF FIGURES

Figure No.

Appendix B

Appendix B (cont'd.)

Appendix D

Appendix E

LIST OF TABLES

Appendix D

Appendix E

LIST OF PHOTOGRAPHS

Appendix A

Appendix C

Page

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

atm	atmosphere	l/min	liters per minute
cm	centimeter	m	meter
cm/s	centimeters per second	mm	millimeter
ft	feet	MPa	megapascal
ft/y	feet per year	Pa	pascal
gpm	US gallons per minute	pcf	pounds per cubic foot
in	inches	pct	percent
kg/m2	kilograms per square meter	s	second
kg/m3	kilograms per cubic meter	y	year
kPa	kilopascal		

IN SITU TESTING FOR GEOHYDROLOGICAL INVESTIGATIONS OF TAILINGS DAMS

By Dirk van Zyl,[1] A. MacG. Robertson,[2] Steven E. Follin,[3]
and George L. Chedsey[4]

ABSTRACT

This report presents the results of a Bureau of Mines project to determine the usefulness and cost effectiveness of unconventional, in situ, geotechnical testing techniques for the geohydrological characterization of tailings impoundments. The effectiveness of vacuum assisted horizontal drainage was evaluated as part of the study.

The in situ techniques investigated involved the use of:

- o Jones piezocone probe
- o Delft continuous sampler
- o Cambridge drive-in piezometers
- o GEMS tailings drill

The studies were performed on uranium tailings impoundments belonging to Union Carbide Corporation. Their locations were Uravan, Colorado and Gas Hills, Wyoming.

This research indicates that the in situ methods tested offer considerable advantages over conventional techniques for geohydrological investigations. The in situ methods provided more accurate and complete information about the impoundment (Uravan) investigated. As a result, the geohydrologic characterization obtained was substantially different from previous ones based on conventional methods. Vacuum-assisted drainage, tested at the Gas Hills site, was able to increase drainage rates by a factor of about 2 over the short term. Long term effects were not investigated.

---

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[2] President, Steffen Robertson & Kirsten, Denver, Colorado

[3] Mathematician, Twin Cities Research Center, Bureau of Mines, Minneapolis, Minn.

[4] Manager, Geotechnical Engineering and Mining Services, Denver, Colorado

INTRODUCTION

This report describes the geohydrological characterization of a uranium tailings impoundment using in situ and laboratory testing techniques. Portions of this work were performed by Geotechnical Engineering and Mining Services (USA), Inc. (GEMS) for the United States Department of the Interior, Bureau of Mines under Contract No. S0221076.

The geohydrological characteristics of a tailings impoundment are a major factor determining the seepage that occurs from that impoundment as well as its stability. An accurate knowledge of impoundment geohydrology is therefore important in the design, construction and reclamation of a tailings impoundment. As the deposits of tailings in the USA accumulate it is becoming increasingly important to develop cost-effective methods of impoundment construction, rehabilitation, reclamation and pollution control. The geohydrology of a tailings impoundment is often complex and difficult to determine using conventional drilling, sampling and in situ testing techniques. This study was undertaken by the Bureau to assess the usefulness and cost-effectiveness of techniques not conventionally used for tailings investigation.

The results of this project may be used to assess the applicability of these methods at other tailings sites. It provides a detailed description of the equipment and methods used, evaluates the results obtained and provide estimates of the costs associated with the techniques.

Horizontal drains have been installed into the embankment areas of tailings dams in order to improve drainage, lower the pore pressures and improve embankment stability. Recently, a patented system of horizontal drains which includes the application of vacuum suction has been developed and applied to mine dewatering problems. The system can, potentially, increase the drainage rates and, therefore, enhance drainage ability. A test of the horizontal vacuum system was included in this study with the intent of obtaining both an evaluation of the effectiveness of the system and also to provide a change in geohydrological conditions at the test site where the alternative geohydrological investigation techniques were evaluated.

Testing of the geohydrological investigation techniques was undertaken at the No. 3 tailings impoundment of Union Carbide Corporation, Metals Division's Uravan Mill in Uravan, Colorado. This site did not prove to be suitable for the installation of the vacuum drainage. A separate horizontal vacuum drainage test was undertaken at the tailings impoundment at Union Carbide's Gas Hills Mill in Wyoming. Because of the different locations, the two studies were essentially separate studies and are described separately in this document.

Part I describes the testing and evaluation of the alternative geohydrological investigation techniques used to determine the geohydrology of the Uravan site.

Part II describes the testing and results of the horizontal vacuum drainage testing at the Gas Hills site.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from Union Carbide, Uravan, Colorado and Gas Hills, Wyoming during the performance of the field work and subsequent piezometer monitoring. In addition they would like to thank Eben Rust of Steffen, Robertson and Kirsten, Pretoria, South Africa and Arnold Buys of Delft Soil Mechanics Laboratories, Delft, Holland for their contributions.

PART I - GEOHYDROLOGICAL CHARACTERIZATION OF URAVAN TAILINGS IMPOUNDMENT NO. 3

INTRODUCTION

General

Tailings impoundments constructed by upstream methods using spigoted techniques rely on the drainage of the outer walls for stability. Usually, spigoting techniques and impoundment management methods are used that result in the more free draining sands being deposited near the walls while the slimes are concentrated in the pool area remote from the walls. In a properly constructed impoundment, the elevation of the phreatic surface is highest in the low permeability 'slimes' zone under the pool area and drops in the more sandy, permeable zones under the wall. If the foundation material is relatively impermeable and if no under-drainage is provided, then the phreatic surface intersects the face of the impoundment wall. Seepage then emerges from the lower portion of the walls. Variations occur in the placement conditions resulting in horizontal layers of sand, silts and silty clays. The permeability of these layers may vary by as much as four to five orders of magnitude. Their location, geohydrological properties and variation must be known before any meaningful determination of impoundment geohydrological conditions can be done.

The use of conventional methods of site investigation in the geohydrological investigation of tailings impoundments is often more difficult and less effective because of the following conditions:

(i) Access on the beach, pool area and wall slope is restricted by poor access and steep slopes.

(ii) Conventional sampling of the tailings, using thin wall shelby or piston samplers, is often difficult to achieve without considerable sample loss or disturbance.

(iii) The act of drilling punctures holes through layers of different permeability and pressure head. Retraction of drill casing, following placement of piezometers, may leave a vertical path of greater hydraulic conductivity leading down to the piezometer. Thus the piezometer may measure heads that are not representative of the layer in which it is installed.

(iv) Drilling and casing retraction causes a relatively large zone of disturbance around the borehole. This disturbance is particularly extensive in very soft zones, where material movement toward or away from the advancing drill may occur during drilling. Subsequent sampling and testing done in such disturbed zones yields results which are not representative of the undisturbed tailings.

(v) Conventional sampling and testing yields estimates of the geohydrological properties only at discrete points where a sample is taken for testing purposes. A continuous measurement of properties along any line is not practical to obtain.

Purpose and Scope of Study

The purpose of the study was to use an electric cone piezometer system and conventional geotechnical methods to obtain the hydrologic data necessary to determine the flow pattern at a selected site. In addition, other tools and techniques not commonly used in the United States for the geohydrologic investigation of tailings impoundments were used in this study. These included:

a. the Delft continuous sampler,
b. Cambridge drive-in piezometers, and
c. the GEMS tailings drill.

The work was performed at Union Carbide Corporation's Uravan uranium tailings impoundment no. 3 in Uravan, Colorado.

Summary of Work

A combination of field and laboratory geotechnical testing was performed in order to define the geohydrological characteristics of a uranium tailings impoundment. The field work involved piezocone testing, sample collection (using the Delft continuous sampler) and the installation of drive-in standpipe piezometers. Water levels were measured in the standpipe piezometers. Falling head tests were made in the piezometers to estimate in situ hydraulic conductivity. Piezocone data were used to define the position and characteristics of layers in the impoundment and to obtain information on the distribution of pore pressure in the tailings. Piezocone dissipation tests were used to estimate the in situ hydraulic conductivity.

Samples from the continuous sampler were opened, profiled, and photographed. Five material types, ranging from medium sand to clayey silts were identified in the samples. Laboratory testing (grain size analyses, dry density, falling head permeability, flow pump permeability and consolidation tests) was performed on all these material types. The laboratory test results were compared to the results obtained from in situ testing.

Summary of Results

Summary

The piezocone test results (cone resistance, sleeve resistance, and dynamic pore pressure) provide a graphic record of the nature and variability of the material encountered. From the piezocone results, sampling and test locations for other methods may be selected.

Samples from the continuous sampler were of exceptional quality; but the sampler could be pushed to great depths only in the softer, saturated zones of the impoundment.

Welcome Screen Search Report List

The two most important geohydrological parameters measured in this study were the piezometric pressure and the hydraulic conductivity of the tailings material. Each is described briefly below.

Piezometric Pressure

The results from the drive-in piezometers show that non-zero water (pore) pressures exist even at the relatively high elevations where the piezometers were installed in the tailings impoundment. Assuming that the pore pressure changes hydrostatically below these would lead to the conclusion that high pore pressures exist in the impoundment. The piezocone results indicate that such a simple pressure distribution -- a single phreatic surface with hydrostatic pressure beneath it -- is incorrect. A series of perched water tables and downward flow is indicated by the piezocone data. This pressure distribution results from the highly stratified nature of the impoundment. The piezocone probing provides a clearer definition of the piezometric pressure in the impoundment than would normally be obtained using conventional drilling and a limited number of piezometers.

Hydraulic Conductivity

The hydraulic conductivities obtained from laboratory testing (for the five material types) provide a basis for comparison with the values obtained from falling head tests using the drive-in piezometers and from dissipation tests using the piezocone. The latter values are obtained from semi-empirical interpretations. Estimates of permeability obtained from the dissipation tests were generally two orders of magnitude lower than those obtained by the other methods. This difference is attributed to partial saturation of both the piezocone filter tip and the materials being penetrated. Air bubbles in the tailings result in a "soft system" that reduces the rate of pore pressure dissipation and causes the permeability of the tailings to be underestimated. This limits the use of this method of permeability measurement to situations where the tailings are saturated and cone filter tip saturation can be maintained.

The hydraulic conductivities estimated from the falling head tests in the drive-in piezometers were reasonable, average values when compared with the laboratory data.

SITE DESCRIPTION

Location

The site studied was Tailings Impoundment Number 3 at Union Carbide's Uravan Mill in Uravan, Colorado (see figure 1). The town of Uravan is approximately 80 km (50 miles) south of Grand Junction, Colorado on the San Miguel River and at an elevation of approximately 1,525 m (5,000 ft) above sea level. The tailings ponds are on a rock terrace above and adjacent to the town of Uravan and the San Miguel River. The crest elevation of Tailings Impoundment Number 3 was, at the time of the investigation, approximately 1,688 m (5,536 ft). The depth of the tailings at the test site was about 30 m (100 ft).

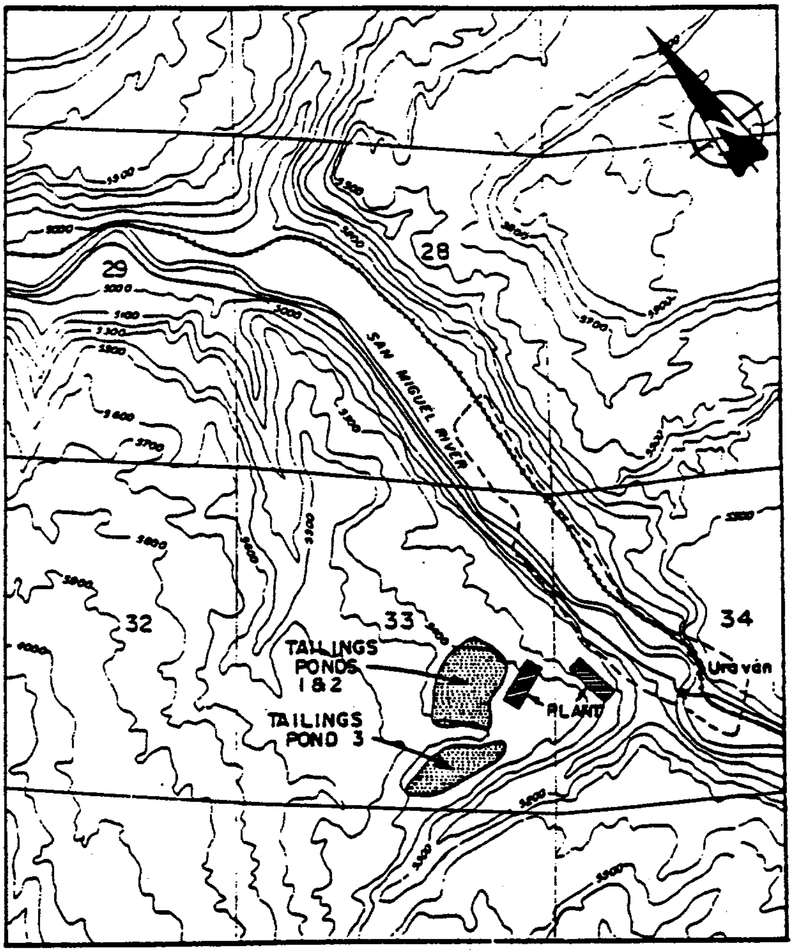


FIGURE 1. - Vicinity map.

History of Impoundment

The uranium/vanadium mill at Uravan has operated since 1915. In the early years of milling, tailings were deposited in three large pits beneath the area of the present Impoundment Number 3. Figure 2 shows the contours of the area of Impoundment Number 3 prior to tailings deposition in the present impoundment. The date of this map is unknown. The surface which underlies the selected test section was largely undisturbed at that time.

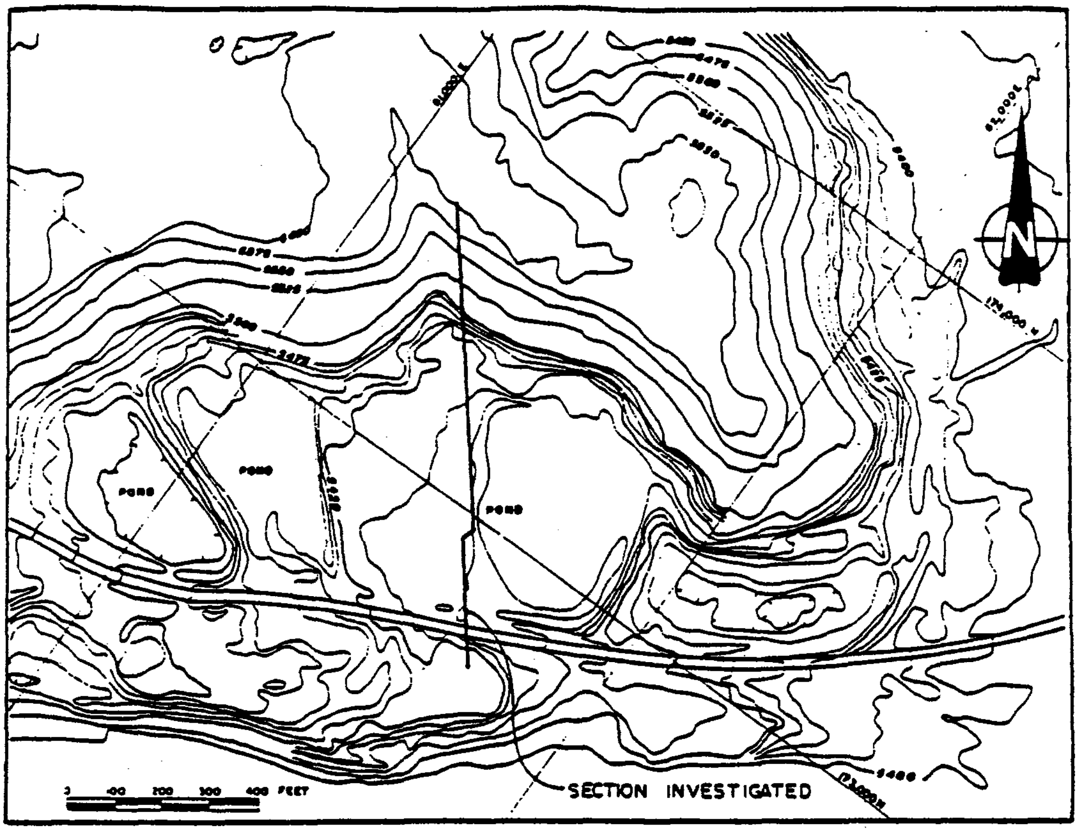


FIGURE 2. - Contours prior to tailings impoundment construction.

The present tailings impoundment was constructed by upstream methods. It was started in the early 1960s. It is understood from Union Carbide that there is no underdrainage system and there was no foundation preparation other than the excavation and clearing that had been done to construct the slimes pits. The fine portion of the tailings were deposited in the slimes pits, while the coarser portions (sands) were used to build an initial embankment. Berms for consecutive lifts were constructed with tailings from the beach. Approximately 3 m (10 ft) lifts were used and the spigoting was done adjacent to the berm. There were spigot point discharges at various locations along the berm. Generally, coarse tailings were deposited near the berms and the finer tailings were deposited near the pool. Differences in elevation of the beach resulted in variable deposits or layers of coarser and finer tailings.

Two previous geotechnical evaluations of tailings impoundment No. 3, done for Union Carbide, used traditional geotechnical drilling and sampling methods, and the results may be compared with those obtained in this study. A geotechnical investigation was performed in 1978 by Dames and Moore as a part of the mine's licensing requirements [1]. Union Carbide retained Acres American Incorporated in 1980 to perform an extensive geotechnical investigation to determine the drainage conditions and stability of the tailings impoundments [2]. The second study included drilling 65 geotechnical boreholes and placing 30 piezometers. An extensive system of horizontal drainage pipes were installed, and a filter layer and rock stabilization berm were installed upon completion of the second study.

Over the last several years, the mill has operated intermittently. The mill had been shut down from January 1982 until the time the field work for this study was performed in October 1982.

Test Sections

Because of economic constraints, only one cross section through the embankment of Impoundment Number 3 was selected for detailed evaluation. The location of this section is shown in figure 3 and the section on figure 4. This impoundment and section were chosen for the following reasons (see overleaf):

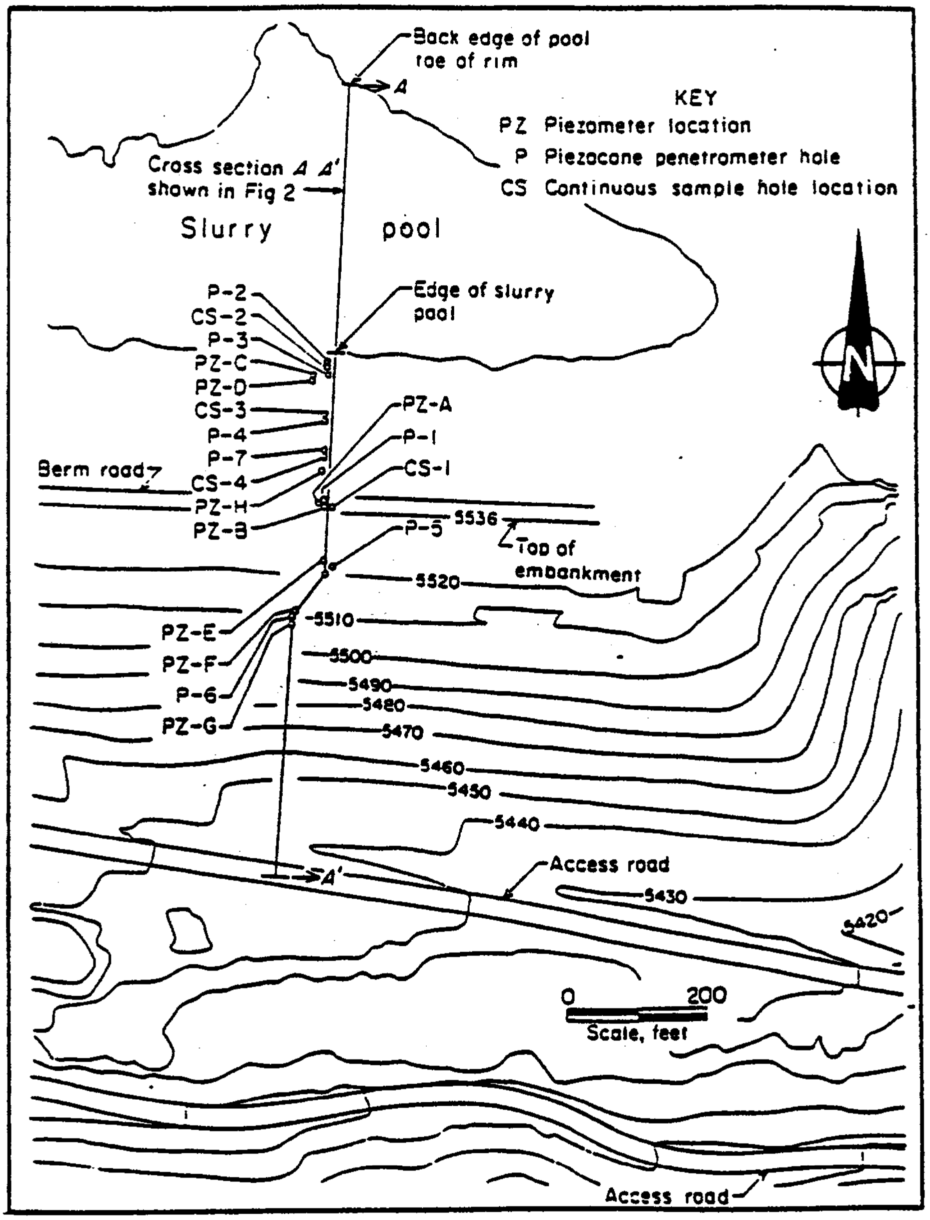


FIGURE 3. - Location of test holes and piezometers.

- seepage at the toe of the embankment indicated a relatively high phreatic surface;
- the geometry and construction history of the impoundment at this section are simple;
- information from previous investigations at the section is available; and
- seepage and stability control measures had been implemented previously at the section.

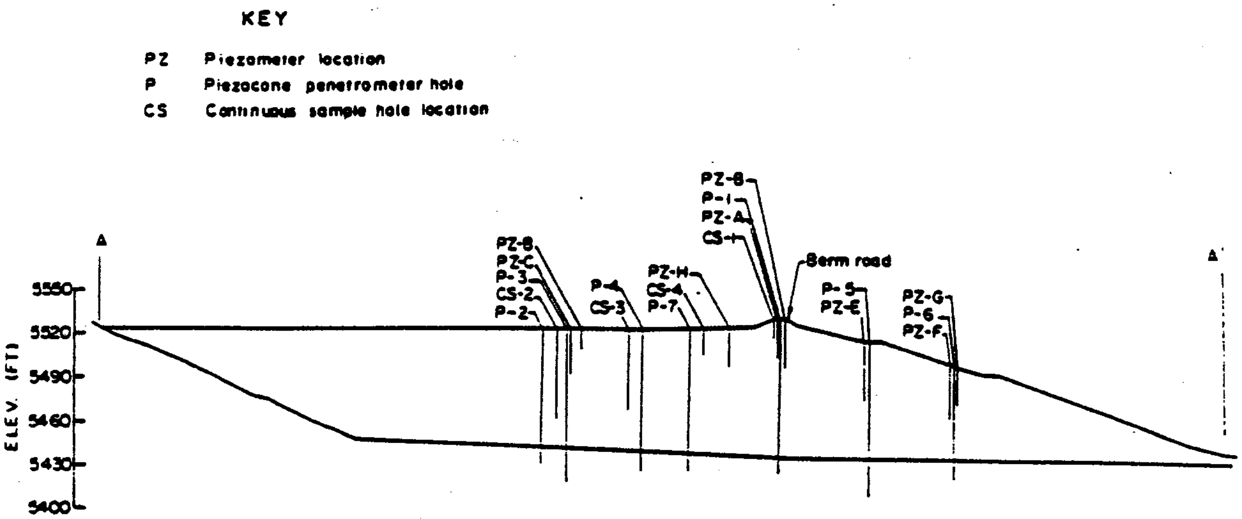


FIGURE 4. - Location and depth of test holes and piezometers on section AA, Figure 3.

The locations of the piezometer cone holes, continuous sampler positions and piezometer installations, shown in figures 3 and 4, were selected after considering the available data, site conditions and the capability of the equipment. The piezometer cone holes and continuous sampler locations are relatively closely spaced to facilitate data correlation. The depths for installation of the filter elements of the drive-in piezometers were chosen after considering the piezometer cone results.

DESCRIPTION OF EQUIPMENT AND FIELD TESTING

Equipment Selection

The hydraulic placement of tailings at Uravan produced variable layers of sands, silts and silty clays. The location and thickness of these layers, their geohydrologic properties and variation must be determined in order to obtain meaningful analyses and designs. Accurate definition of the complex layering by means of conventional methods of site investigation is extremely difficult because:

- Access on the beach, pool area and embankment slope is difficult due to poor trafficability or steep slopes. The cost of providing access for conventional drilling equipment is large.

- Very soft or very loose saturated tailings are difficult to sample or test in an undisturbed condition. Drilling often disturbs the tailings prior to sampling or in situ testing. Wet, loose and soft samples are difficult to retain in the sampler. Loose samples are almost invariably disturbed during sampling. Laboratory tests on the disturbed samples yield erroneous estimates of field conditions.

- Drilling makes holes through layers of different permeability and can disturb perched water conditions. Retraction of the drill casing often leaves vertical connections between layers of varying piezometric head and permeability. Measurements of pressure heads or in situ permeability may then yield erroneous results.

The main objectives of this project were to evaluate the usefulness of new equipment and techniques to obtain geotechnical and geohydrological information about tailings impoundments.

The piezocone (or piezometer cone) was selected because of its ability to measure material properties in situ, particularly the layered nature of the materials, and its ability to measure the ambient pore pressure at numerous places in a vertical profile.

The Delft continuous sampler was selected because of its ability to recover continuous undisturbed samples in very soft, loose and wet deposits.

The Cambridge drive-in piezometers were selected because of the low disturbance that can be achieved during installation; this makes them more effective for in situ permeability testing.

The GEMS tailings drill was selected because it is portable and can be used to assist in the installation of the Cambridge drive-in piezometers.

Piezocone System Equipment

Components

The piezocone system consists of eight parts (see figure 5):

- Jones Piezocone
- Goudsche Pushing Unit
- Depth Encoder
- Control Box and A.C. Generator
- TOA Strip Chart Recorder
- Sharp Microcomputer
- Sharp Floppy Disc Drive

- o Watanabe X-Y Plotter.

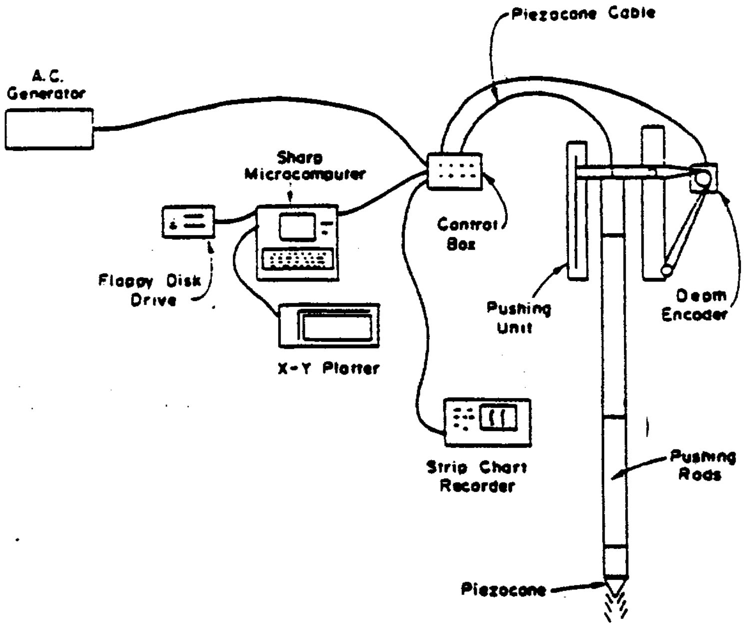


FIGURE 5. - Schematic of components of piezocone system.

The details of each of these eight components are described in Appendix A. A schematic cross section of the piezocone is shown in figure 6(a).

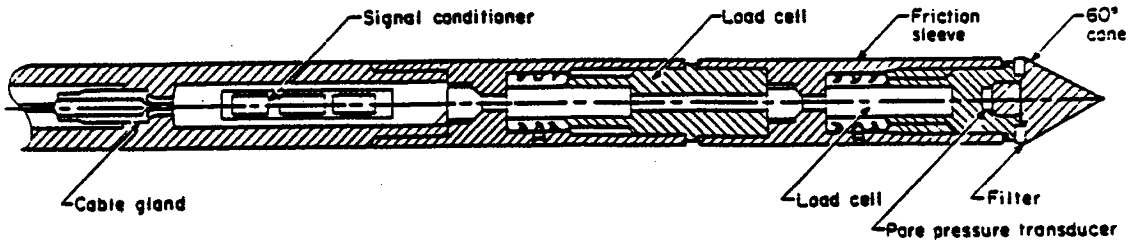


FIGURE 6(a). - Schematic of piezocone.

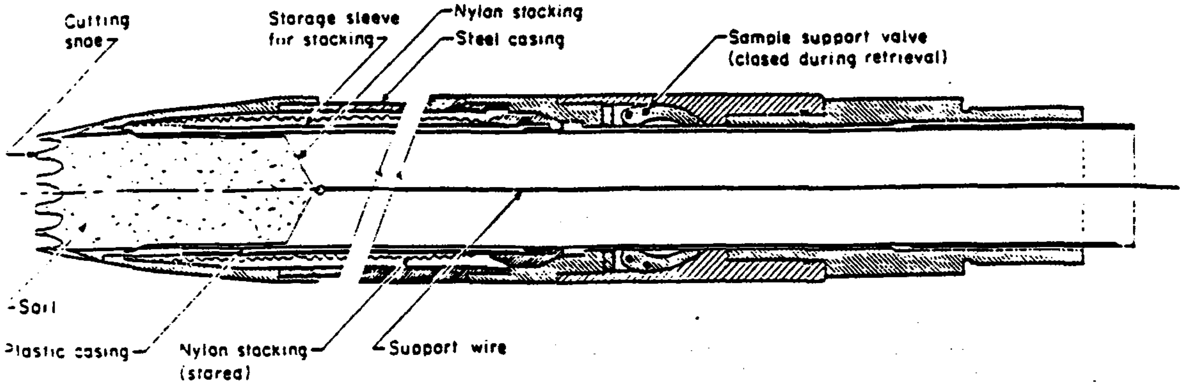
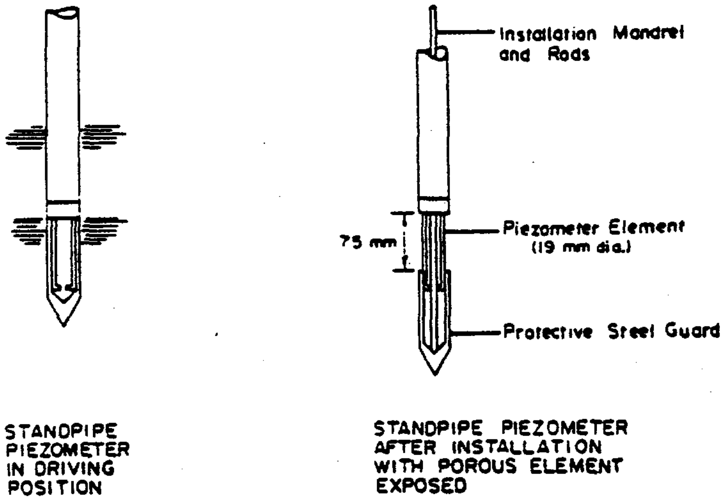


FIGURE 6(b). - Schematic of delft continuous sampler.



STANDPIPE PIEZOMETER IN DRIVING POSITION

STANDPIPE PIEZOMETER AFTER INSTALLATION WITH POROUS ELEMENT EXPOSED

FIGURE 6 (c). - Schematic of Cambridge drive-in piezometers.

Field Testing Procedures

Seven piezocone soundings (206 meters of sounding) were performed during this investigation. The piezocone sounding depths varied from 23 to 32 m (71 to 98 ft). Soundings were stopped when hard material was encountered. The hard material is presumed to be the dense colluvial gravels overlying bedrock.

The general procedure for performing piezocone soundings is described in Appendix A.

The following parameters are measured directly with the piezocone:

- tip resistance, q_c

- tip resistance plus sleeve friction, $q_c + f_s$ (this allows the calculation of sleeve friction)

- pore pressure (measured directly behind the conical tip), u_e

Dissipation tests are performed at selected depths. Penetration is stopped and the pore water pressure allowed to return to the ambient pressure. These dissipation tests are used to evaluate the coefficient of consolidation and the hydraulic conductivity of the tailings. During the dissipation tests, the strip chart recorder remains on and is set to operate at a chart paper speed of 5 mm/s rather than being controlled by the depth encoder. The trace of pore pressure, u_e, on the strip chart records the dissipation of pore water pressure.

The time taken to change rods can be used for abbreviated dissipation tests. The 45 seconds needed to add a rod is sufficient, in sands, for the excess pressures generated during probing to dissipate. In more silty, fine-grained material, complete dissipation does not occur in such a short time. Trends in dissipation behavior, however, are an indication of material type, permeability and ambient pore pressure. Where complete pore pressure dissipation is required the period allowed for dissipation is appropriately increased.

Delft 66 mm Continuous Sampler

Samples were taken at four locations with the Delft 66 mm continuous sampler (see figures 3 and 4). Two samples were taken on the beach near the pond, one on the berm road and one just below the berm on the beach. A total of 46 m (152 ft) of sample were taken.

The basic attributes of the continuous sampler are:

- The sampler can be adapted for use with the 20 ton Goudsche pushing unit.

- One long continuous sample is taken rather than several shorter samples.

- There is practically no friction between the sample and the downward-moving sampling tube surrounding it.

- The sample, after entering the device, is provided with a horizontal supporting pressure which duplicates, as closely as possible, the original in situ stress. The sample does not undergo appreciable deformation.

The mechanics and operating principles and procedures are explained in Appendix A. A schematic cross section of the Delft continuous sampler is shown in figure 6(b).

Welcome Screen Search Report List

GEMS Tailings Drill

The GEMS Tailings Drill was used to obtain disturbed tailings samples during the initial investigation and to pre-drill holes for the installation of the Cambridge Drive-in piezometers. The Tailings Drill provides a relatively inexpensive way to gather samples and was used in this investigation to obtain initial information on the layering and variation of tailings.

The Tailings Drill was originally developed for mineral exploration of deep beach sand deposits in Australia. The main advantage of the Tailings Drill is its portability. It can be carried by two men and used on tailings beaches and embankments.

The Tailings Drill was used to drill approximately thirty meters (100 ft) of sample and starter holes in the beach, berm road and embankment. Its configuration and operating method is described in Appendix A.

Cambridge Drive-in Piezometers

Cambridge drive-in piezometers were used:

- o to monitor the water level (phreatic surface) in the tailings, and
- o for falling head permeability tests.

They were selected because traditional methods of drilling and installing sealed standpipe piezometers cause extreme disturbance of the tailings during the retraction of the drill casing. This leaves a preferential vertical seepage path through layers with differing permeabilities and pore pressure heads. Consequently, erroneous values of pore pressure head may be measured at the piezometers. In addition, drilling disturbs material adjacent to the piezometric tip and affects the value of permeability measured by falling head tests using the piezometers. The Cambridge drive-in piezometers are driven to the selected depths from either the surface or from access (starter) holes. By driving the piezometer, tight contact is obtained between the piezometer pipe and the tailings. In addition, less disturbance is introduced in the materials adjacent to the piezometer tip. Once the tip has been driven to its installation depth a mandrel is used to advance the tip cover 100 mm, exposing the filter stone.

Eight Cambridge drive-in piezometers were installed as shown on figures 3 and 4. Installation depths ranged from 5 m to 11 m (15 to 35 ft).

A schematic of a section through a Cambridge drive-in piezometer is shown in figure 6(c) and its nature and method of installation is described in Appendix A.

FIELD TEST RESULTS

Piezo probe test results for the seven test locations are included in Appendix B. The odd numbered figures presents cone resistance (q_c in MPa) and pore pressure (u_e in kPa) versus depth for the test, while the even numbered figures presents cone resistance (q_c in MPa) and friction ratio (R_f as percent) versus depth for the test. Friction ratio is defined as the ratio of sleeve friction to cone resistance ($R_f=f_s/q_c$).

A total of 14 dynamic pore pressure dissipation tests were performed; results are listed in Table 1. Two typical examples of pore pressure dissipation versus time are given in figures 7 and 8. The time for a particular percentage dissipation can be obtained from such dissipation curves. t_{50} is the time taken for 50% of the dynamic pore pressure to dissipate. The definition of t_{50} is shown in figures 7 and 8. The values estimated for t_{40}, t_{50} and t_{60} and q_c for the various tests are listed in Table 1.

TABLE 1. - Summary of piezocone dynamic pore pressure dissipation test results

Test location	Depth (m)*	t_{40}^{+}	t_{50}^{+}	t_{60}^{+}	q_c (MPa)
3............	5.7	1.3	1.8	2.6	.52
	7.7	1.4	2.2	2.8	1.9
	15.7	15.2	19.8	24.7	5.8
	20.7	6.7	10.9	13.2	5.2
	31.75	.5	.7	.9	8.3
4............	19.7	14.4	20.0	26.6	6.2
	29.6	1.6	1.9	2.4	9.6
5............	27.7	3.6	4.4	5.8	10.5
	31.6	3.8	5.0	6.2	11.1
6............	16.7	4.9	6.8	9.8	3.8
	23.2	6.6	11.2	18.0	6.5
7............	15.7	0.3	0.4	0.5	2.5
	23.7	1.6	1.8	2.4	3.8
	30.2	0.8	1.0	1.4	3.4

*With respect to tailings surface

+Normalized excess pore pressure values taken at time t, in minutes

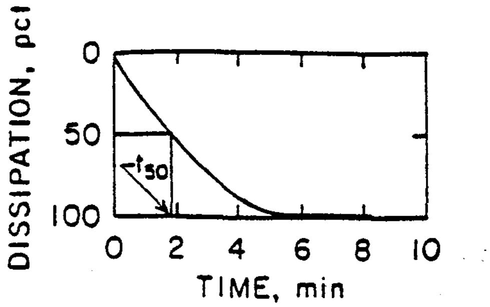


FIGURE 7. - Pore pressure dissipation curve for hole 4 at 29.6 m.

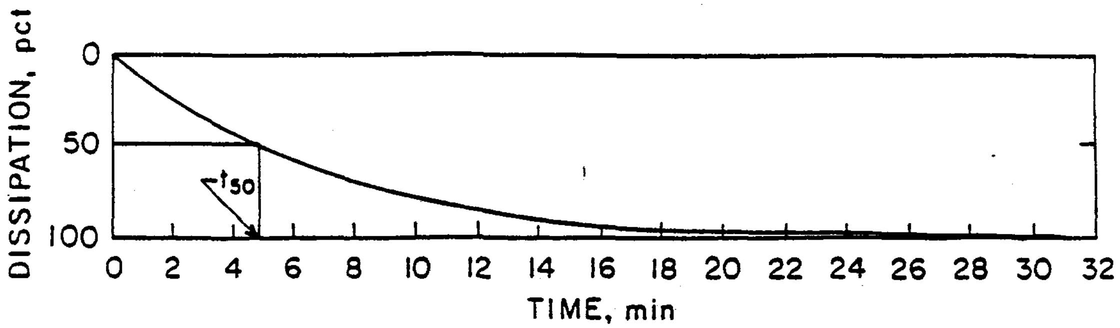


FIGURE 8. - Pore pressure dissipation curve for hole 5 at 31.6 m.

Observed Piezometric Levels in Drive-in Piezometers

Piezometric levels were measured when the piezometers were installed and at five times thereafter. The water level elevations measured in these are presented in Table 2.

The piezometer readings stabilized during the monitoring period. The readings taken on December 22, 1982 and thereafter, represent equilibrium. The pond level did not change significantly during this period.

Two piezometers (P217 and P101) had been installed previously in the same area, as shown in figure 16. The elevations measured on February 25, 1983 were:

P217	5,484 feet
P101	5,467 feet

Falling Head In Situ Permeability Test Results

In situ falling head permeability tests were performed one to two days after installing the drive-in piezometers. This test involved adding a quantity of water to the standpipe and recording the change in water level as a function of time.

The hydraulic conductivity is calculated using the method proposed by Hvorslev (9). The change of $(H-h)/(H-H_0)$ with time is plotted on semi-log graph paper. (H is the initial head, h the observed head, and H_0 is the head at t_0, the time at the start of the falling head test.) Figure 9 illustrates the geometry and analysis for this test. The coefficient of permeability is calculated from the following relationship:

$$k = \frac{0.508\ r\ \ln\ (L/R)}{2Lt_0}\quad \text{cm/s} \qquad (1)$$

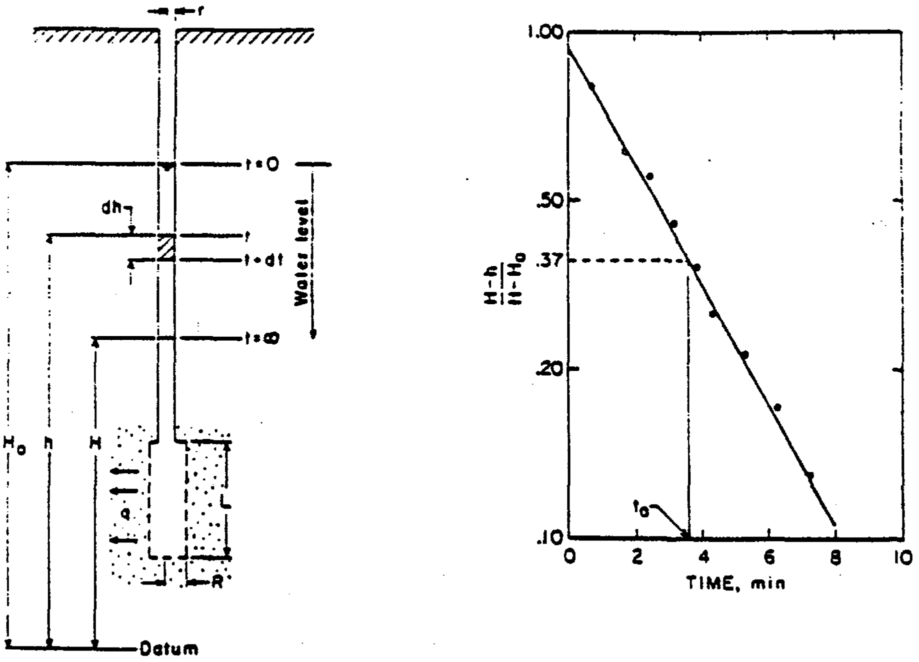
where L = length of piezometer tip (ft)

r = radius of piezometer tip (ft)

R = radius of borehole (ft)

and t_0 = time at which $(H-h)/H-H_0) = 0.37$

A summary of the coefficients of permeability obtained from the falling head tests are presented in Table 3.



(a) (b)

FIGURE 9. - Hvorslev piezometer tests. (a) Geometry; (b) Method of analysis (9).

Piezometer	Depth to Bottom (m)	After installation		October 28, 1982		November 24, 1982		December 22, 1982	
		Depth (m)	Elevation (ft)	Depth (m)	Elevation (ft)	Depth (m)	Elevation (ft)	Depth (m)	Elevation (ft)
A.........	8.18	8.04	5,510.26	7.83	5,510.95	8.02	5,510.32	8.03	5,510.28
B.........	10.14	9.50	5,505.46	9.11	5,506.76	9.53	5,505.38	9.50	5,505.47
		9.27*	5,495.83*						
C.........	9.26	6.65**	5,504.42**	6.44	5,505.13	6.66	5,504.42	6.62	5,504.53
D.........	4.53	2.00*	5,516.91*	2.02	5,519.83	2.19	5,519.28	2.07	5,519.65
		0.72**	5,524.08**						
E.........	12.78	11.89	5,481.65	11.93	5,481.53	12.11	5,480.93	12.02	5,481.22
F.........	10.84	8.86*	5,474.46*	9.42	5,472.64	9.92	5,471.00	9.92	5,471.00
		9.82**	5,471.33**						
G.........	7.87	7.51	5,479.41	7.43	5,479.66	7.57	5,479.00	7.59	5,479.13
H.........	8.52	8.13	5,502.34	7.67	5,503.84	7.92	5,503.05	7.79	5,503.47
Pond level					5,525.10		5,525.35		5,525.53

*After installation

**One day after falling head test

Piezometer	Depth to Bottom (m)	January 27, 1983		February 24, 1983	
		Depth (m)	Elevation (ft)	Depth (m)	Elevation (ft)
A.........	8.18	7.84	5,510.93	8.08	5,510.13
B.........	10.14	9.28	5,506.20	9.52	5,505.40
C.........	9.26	6.66	5,504.42	6.66	5,504.42
D.........	4.53	2.15	5,519.39	2.18	5,519.29
E.........	12.78	11.80	5,481.94	11.80	5,481.95
F.........	10.84	9.94	5,470.94	9.64	5,471.93
G.........	7.87	7.59	5,479.13	7.59	5,479.13
H.........	8.52	7.90	5,503.10	7.87	5,503.20
Pond level			5,525.75		5,525.80

TABLE 2. - Piezometric levels measured in Cambridge drive-in piezometers

Welcome Screen Search Report List

TABLE 3. - Coefficients of permeability calculated from falling head tests

Piezometer	k(cm/s)
A.........	2.7×10^{-5}
B.........	4.6×10^{-5} (average of 5.6×10^{-6} 8.7×10^{-5})
C.........	2.6×10^{-5}
D.........	1.7×10^{-6}
E.........	3.6×10^{-5}
F.........	2.2×10^{-5}
G.........	1.9×10^{-4}
H.........	2.3×10^{-4}

LABORATORY TEST RESULTS

Sample Handling, Profiling and Specimen Selection

The 1 m long tubes containing material retrieved by the Delft continuous sampler were transported and stored upright. Tubes were opened January 3-5, 1983. Each P.V.C. tube was cut along its length with a circular saw. The blade of the saw was set so that the cutting did not damage the samples. The upper half of the nylon stocking was removed after completing the cuts.

The samples were profiled and photographed. Profiling consisted of assigning a numerical value based on a visual description of the soil. The coarsest material was designated No. 1, while the finest material was designated No. 5. Table 4 presents the descriptions for the different materials from the laboratory testing results. The numerical values assigned were indicated on strip charts that were placed alongside the samples and included in the photographs. Photographs of a typical set-up is shown in figure 10; Appendix C contains a complete set of photographs. Layers were more easily identified when the core was cut in half lengthwise. Samples for grain size analyses were obtained by removing the top half of the core. The undisturbed samples for permeability testing were removed prior to splitting the core. Permeability test samples were wrapped in plastic foil and waxed with paraffin to retain moisture.

TABLE 4. - Soil descriptions used in profiling

Soil type no.	Description based on laboratory test results
1	Medium to coarse sand (85% sand, 15% silt)
2	Silty fine sand (65-80% sand, 20-35% silt)
3	Silty fine sand to sandy silt (50-80% sand, 15-45% silt, 5% clay)
4	Clayey silt (8-40% sand, 40-62% silt, 20-30% clay)
5	Clayey silt to silty clay (5-15% sand, 60-70% silt, 25% clay)

Most of the samples examined did not fill the complete length of sampling tubes. This indicated that some density increase occurred during transport and storage of the samples. The photographs in Appendix C indicate that the volume decrease was typically 3 percent but was as high as 5 percent. Free water was present at the top of a number of sampling tubes; this was due to consolidation and water movement from the samples. Despite the very careful handling of the samples, it is possible that limited liquefaction or vibratory mobility of the material, during transport, caused this. This illustrates the difficulty of obtaining and testing representative samples of low density tailings. The only way to overcome this problem is to reduce handling and transport and to open the samples on site.

Laboratory Testing

Table 5 presents a summary of the specimens selected for laboratory testing as well as the tests performed and the results for each. The complete results are given in Appendix D. All the laboratory tests except the flow pump permeability ones, were performed in the laboratory of Steffen Robertson and Kirsten (Colorado) Incorporated. The flow pump tests were performed by the University of Colorado, Boulder.

Grain Size Analysis

Grain sizes were measured with both sieve and hydrometer analyses, in accordance with ASTM D422. Sieve analyses was performed on the coarser materials (soil types 1 to 3); sieve and hydrometer analyses were performed on soil types 4 and 5. The results are presented in figures 11 to 15.

The laboratory results confirm the visual inspection classification; the percentage of fines increases from 1 to 5. On average, the percentages passing the No. 200 sieve for the materials are (see overleaf):

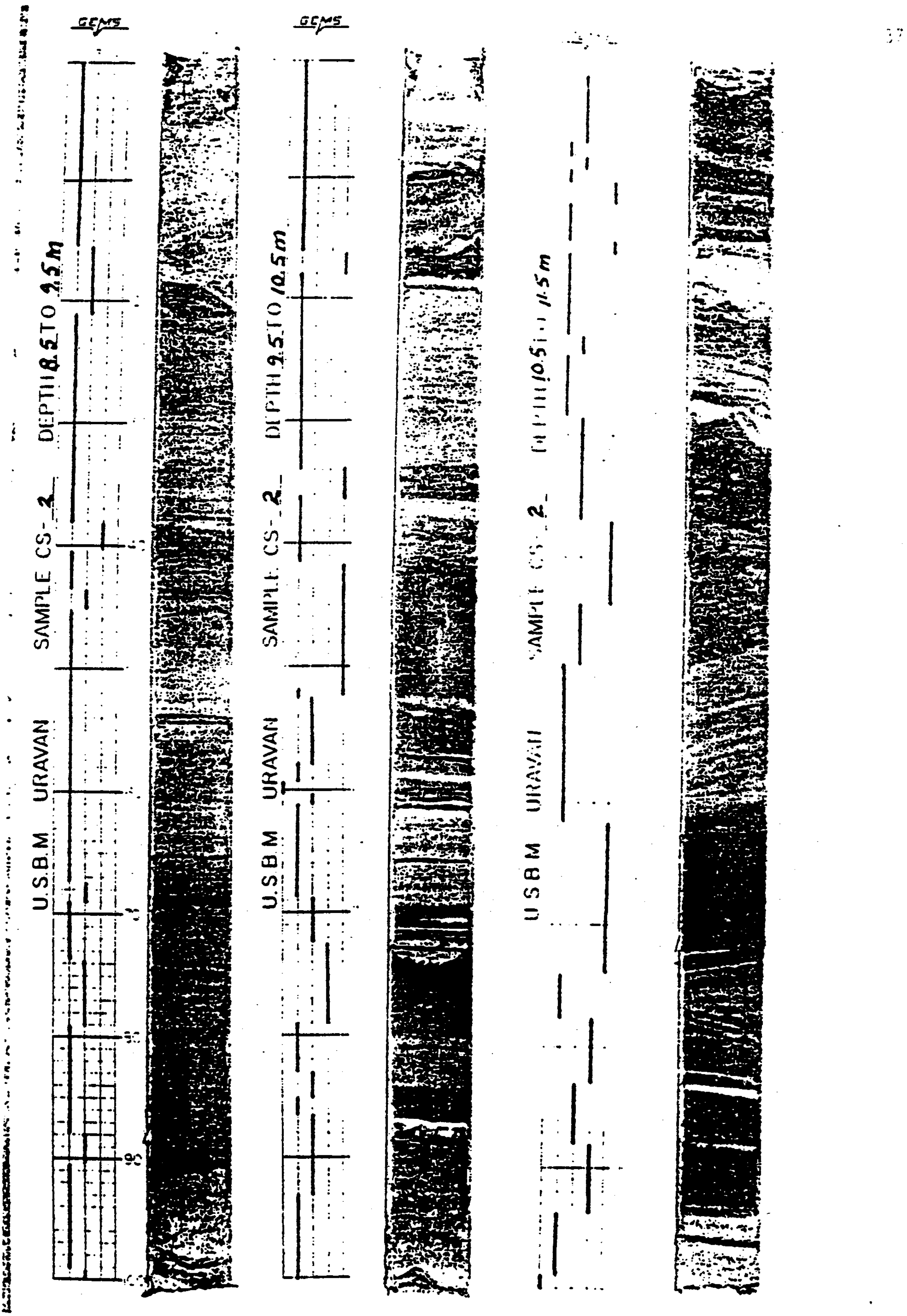


FIGURE 10. - Photograph of a typical profile.

TABLE 5. - Specimens selected for laboratory testing and summary of results

Hole No.	Depth (m)	Soil type No.	Grain size Sieve %-#200	Grain size Hydrometer % 0.002	Moisture Content %	Dry Density kg/m^3(pcf)	Falling head k (cm/s)	Flow Pump k (cm/s)	Remarks
CS-1	3.1-3.5	1	21	NA					
	4.225-4.305	1	14	NA					
	5.24-5.33	3	26	NA					
CS-2	0.77-0.845	3	16	5	15.4	1443(90.2)	6.8×10^{-4}		
	8.2-8.3	4	90	25	45	1112(69.5)	2.5×10^{-6}		$G_s = 3.09$
	11.135-11.220	5	87	22				2.5×10^{-7} to 1.6×10^{-7}	
	11.29-11.325	4	58	NA					
	11.39-11.425	4	NA	NA					$G_s = 2.90$
	11.715-11.745	4	92	17				1.5×10^{-6} to 1.1×10^{-7}	
	11.745-11.9	2	16	NA					
CS-3	1.64-1.71	3			17.7	1445(90.3)	2.4×10^{-7}		$G_s = 2.73$
	2.39-2.57	3	40*	23	21.5	1477(92.3)	5.6×10^{-3}**		
	2.4-2.5	3	39	3					
	3.13-3.18	2	NA	NA					
	5.73-5.83	5	96						
	8.33-8.43	2	36	NA					
	9.03-9.23	1	12	NA					
	13.095-13.160	5	93	24				1.0×10^{-7} to 6.7×10^{-8}	
CS-4	2.34-2.365	1	14	NA					
	3.82-3.885	3	45	NA					

k - indicates hydraulic conductivity by various methods

*Fine layer selected for sieve analysis

**Not reliable test, thin layer of fine material detected after completion of test

+From visual classification

Material	Percent
1	15
2	28
3	36
4	76
5	90

Moisture Content

The moisture content is the ratio of the mass of water to the mass of solids. Only a few values of in situ moisture content were determined. The time lag between sampling and laboratory testing, as well as the sample disturbance described in the section on Laboratory Test Results, influenced these results. The values listed in Table 5 are therefore not necessarily representative of in situ moisture contents.

Dry Density

The dry densities of a few samples were determined. The concerns expressed about moisture content are also applicable to density measurement. Densities listed in Table 5 may be higher than those of the in situ material.

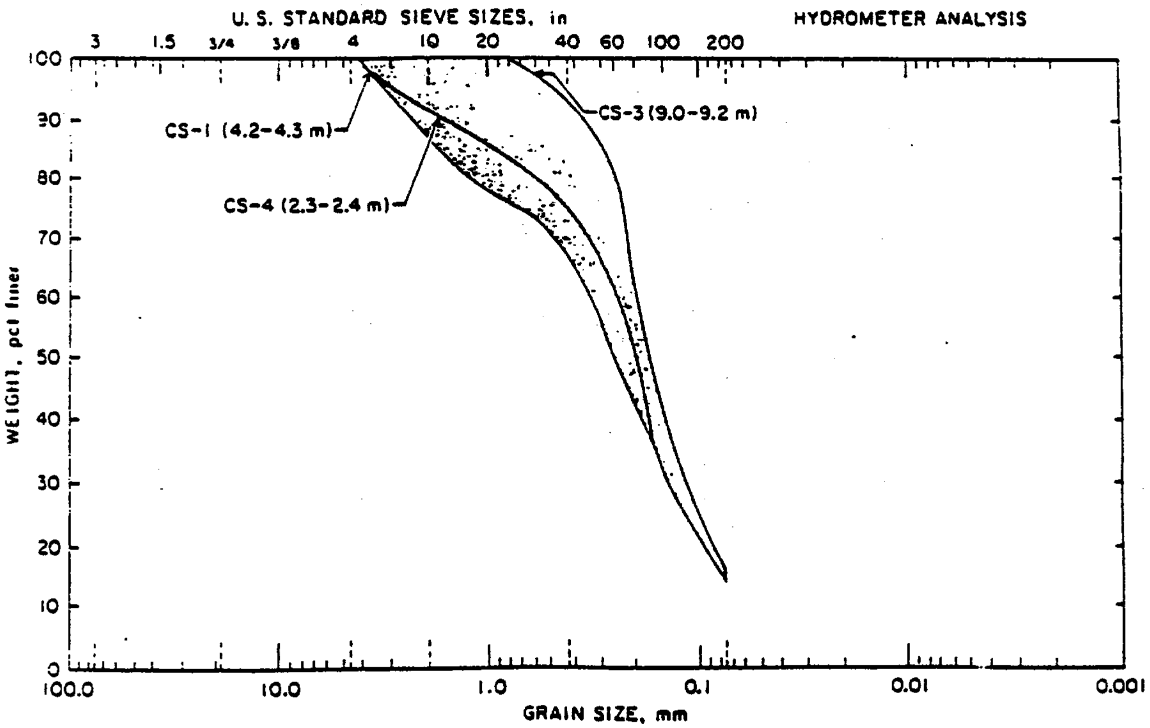


FIGURE 11. - Grain size distribution. Soil type 1.

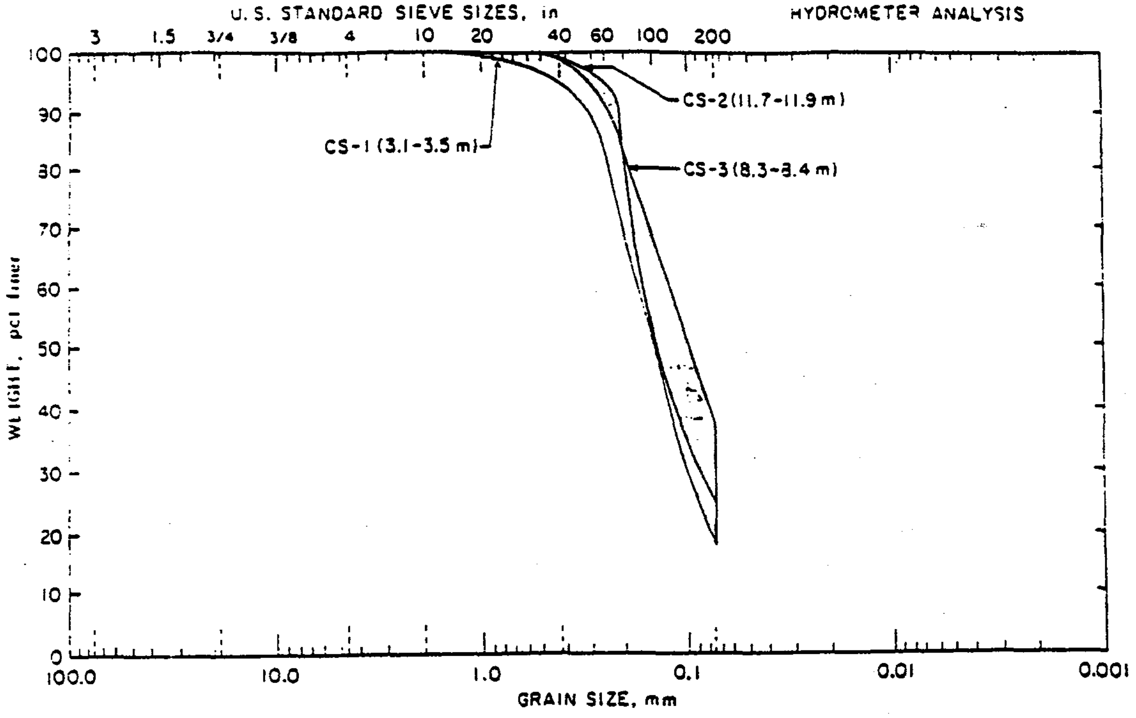


FIGURE 12. - Grain size distribution. Soil type 2.

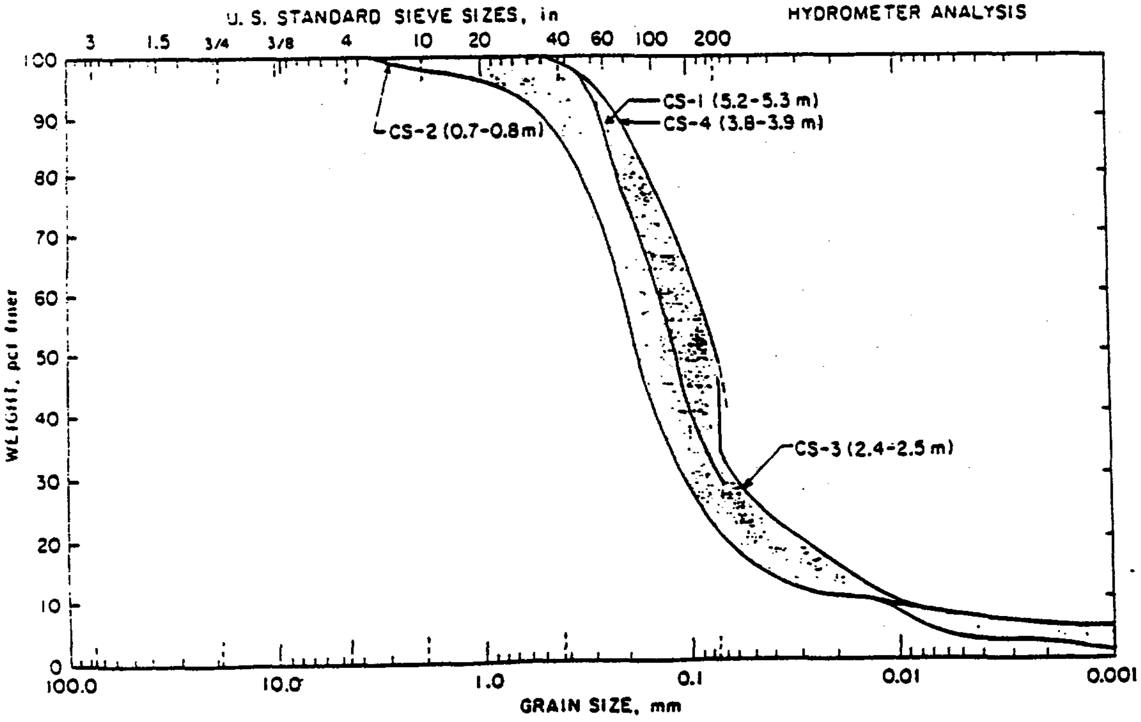


FIGURE 13. - Grain size distribution. Soil type 3.

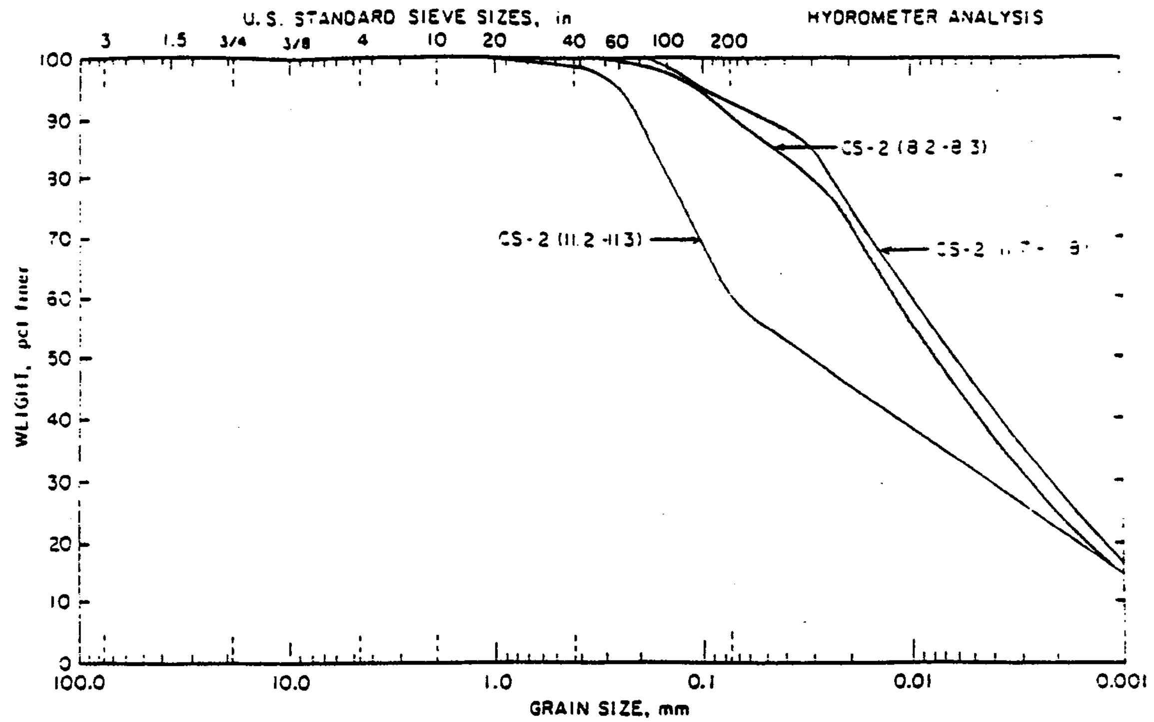


FIGURE 14. - Grain size distribution. Soil type 4.

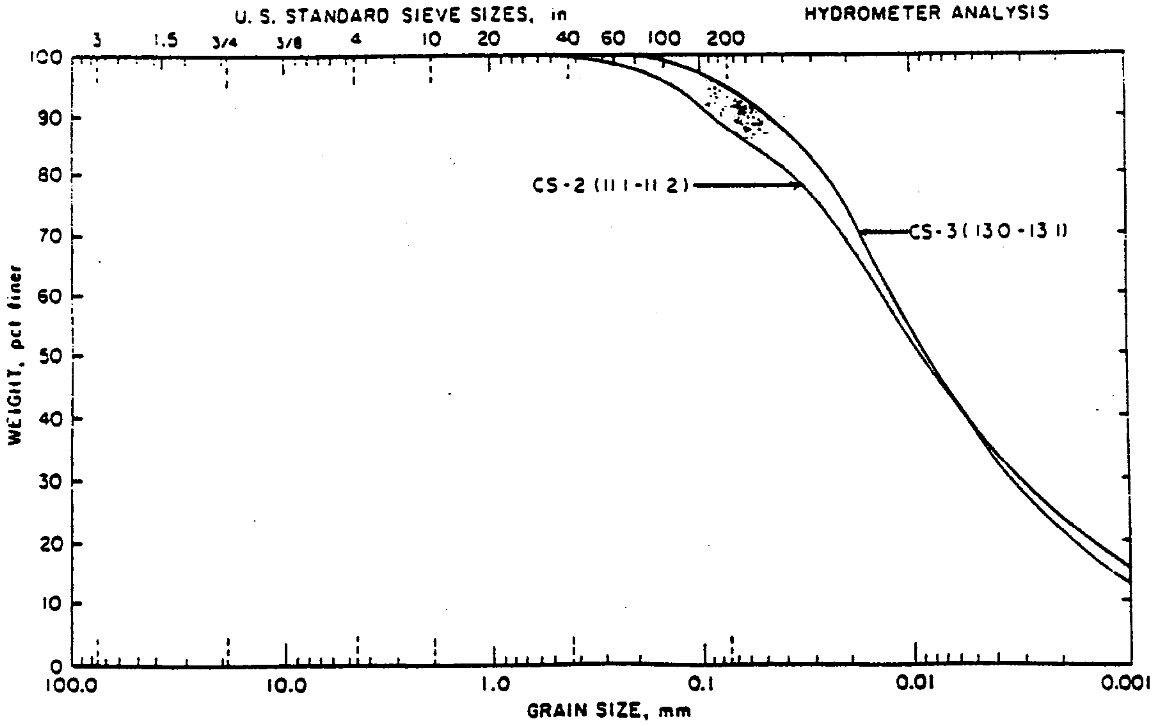


FIGURE 15. - Grain size distribution. Soil type 5.

Specific Gravity

The values listed in Table 5 vary significantly (2.73 to 3.09). This variation was due to changes in the mineralogy of the ores from which the tailings were derived. A complete investigation of this was beyond the scope of this study.

Constant Head Permeability

Constant head permeability tests, using a Marriott bottle apparatus (10), was used for permeability testing of material types 3 and 4. The constant head permeability tests were run over periods exceeding one week. It can be assumed that complete or nearly complete saturation was obtained in all samples.

Estimates of hydraulic conductivity were made for the coarse tailings (material 1 and 2) by using Hazen's formula. It has been shown that this approach can be used for tailings (22).

$$k = 100\, D^2_{10} \qquad (2)$$

where D_{10} is that particle diameter which 10% of the particles (by weight) in the sample are less than. If D_{10} is measured in cm then k is the hydraulic conductivity in cm/s.

Grain size analyses were performed on all the permeability test samples.

Flow Pump Permeability

The hydraulic conductivity of material 5 is too low to use the constant head technique with any degree of confidence (11), so flow pump testing was selected. The falling head and constant head permeability tests both involve passing water through a sample under a known gradient and measuring the flow rate. In the flow pump permeability test, water is passed through a sample at a known flow rate and the gradient across the sample is measured. The advantages of this method include (12):

- It is easier to measure pressures than flow rates and the results are therefore more reliable.
- The system is completely closed, no air-water or water-oil interfaces are present to cause evaporation losses or other effects.
- Testing can be performed much faster than constant or falling head tests.

The flow pump permeability tests were performed in the laboratories of the University of Colorado, Boulder. The test apparatus permits measurement of permeability and deformation at various confining stresses so that a relationship between permeability and stress, and permeability and void-ratio can be obtained.

Specimens of materials 4 and 5 were selected for flow pump permeability testing. The complete test results are given in Appendix D while a summary is included in Table 5.

Discussion of Laboratory Results

Hydraulic Conductivity and Consolidation Characteristics

Table 6 summarizes the hydraulic conductivity for the five material types, as determined from Hazen's formula and the laboratory permeability testing; there is reasonable correspondence between the values.

TABLE 6. - Summary of hydraulic conductivity values based on laboratory data

Material type	Hydraulic conductivity estimate	
	Hazen's formula (cm/s)	Laboratory testing (cm/s)
1	4×10^{-3}	NA
2	1×10^{-3} to 2×10^{-4}	NA
3	2×10^{-4} to 1×10^{-4}	6.8×10^{-4} to 2.4×10^{-7}*
4	5×10^{-7}	1.5×10^{-6} to 1.1×10^{-7}
5	5×10^{-7}	1×10^{-7} to 6.8×10^{-8}

*This very low value may have been caused by a test on a partially saturated sample

The flow pump permeability tests were conducted over the stress range that currently exists in the tailings impoundment. The reduction in hydraulic conductivity that occurs with increased overburden pressures, can be estimated from figures D1 and D2 (Appendix D). The reduction in hydraulic conductivity, with decreasing void ratio, (refer figure D2) is higher for material type 5 than for material type 4. This result is expected. It can further be assumed that the rate of decrease will be progressively less for material types 3, 2, and 1.

The density and in situ stress conditions of a layered tailings deposit depend on the previous stress history. This in turn depends on the depth of cover and also the induced effective stresses caused by high negative pore pressures, which occur during evaporation and dessication of the tailings on the beach of the impoundment. Induced negative stresses may be very high for material types 4 and 5, higher than subsequent impoundment loading.

The estimates of the reduction in hydraulic conductivity based on figures D1 and D2 are, therefore, only an indication of trend, and in situ field conditions cannot be predicted in absolute terms.

The compressibilities of material types 4 and 5 are shown in figure D1 (Appendix D). The results indicate that the compressibility of material type 4 is higher than that of material type 5. The compression indices for these materials are as follows:

Material Type	Compression Index, c
4	0.39
5	0.19

It would be expected that material type 5 would have a higher compressibility than material 4. The laboratory results show the opposite. This discrepancy may be due to sample disturbance or to overconsolidation of the sample of type 5 material by dessication. As the primary interest is the hydraulic conductivity of the tailings, no further testing was done to investigate the compressibility of the tailings.

Definition of Tailings Layering from Continuous Samples

The photographs of the samples in Appendix C show layering of the tailings. Figure 10 is an enlargement of one of the photographs. These samples were taken from Hole CS-2 which is located closest to the pool (see figure 3).

The samples show very little disturbance. Sample disturbance would be indicated by layers which are bent at the interface with the sampler. Some bending can be seen at 10.5 m + 0.55 m. This may be due to two factors which have nothing to do with the sampling technique: deformation during transport of the sample and smear during cutting of the sample prior to photographing. The influence of the latter has been observed when, instead of cutting the sample in half, only a thin layer is removed. From these observations, it can be concluded that sample disturbance is insignificant when the Delft 66 mm continuous sampler is used.

The test hole (CS-2) where these samples were obtained is about 61 m (200 ft) from the edge of the embankment. It was expected that a considerable percentage of fines would have been deposited in this area. An inspection of the profiles shows that the material was predominantly types 2 and 3, with some layers of material type 5 (see Table 4 for material description). These layers were about 10 cm (4 inches) thick. There was even a thin layer of material type 1 in the 9.5 to 10.5 m section (at 10.1 m). Thicker layers of material type 1 were present between 14.5 and 15.5 m (see Appendix C). This result indicates that that tailings material near the pool was not uniformly finer. Significant layering existed even at this distance from the discharge point.

This conclusion cannot be extended to all tailings impoundments as the distribution of materials depends on the discharge method used, the slurry density, the specific gravity of solids, the spacing of the spigots, the discharge rate and the length of beach between the spigots and the pool.

Impoundment layering is not always horizontal. For example, figure 10 shows inclined layers at depths 10.5 + 0.5 m and 10.5 + 0.75 m. Inclination of the layering (cross bedding) can be due to a number of factors. These include: build up of fans having sloping faces causing subsequent layers to be inclined, partial failure or slumping of the beach material after deposition (note that for CS-2 at depth 13.5 + 0.9 m a definite slip plane or "fault" can be observed) and steepening of the beach at the edge of a large pool (the beach slope increases significantly at the edge of the pool). The samples retrieved were not oriented and it is not possible to determine the true direction of dip of the sloping layers.

Very thin layers of different colored materials were evident in some of the samples examined. Such changes in color are not always associated with changes in material type, and may be due to changes in ore.

Abrupt changes in material types can be observed throughout samples from hole CS-2. There is no specific pattern to these changes; material type 2 may be followed by a layer of material type 3, 4, or 5. This observation is very important when interpreting the overall hydraulic conductivity.

GEOHYDROLOGICAL CHARACTERIZATION BASED ON FIELD INFORMATION

Introduction

The purpose of this section is to describe the geohydrological characteristics of the Uravan tailings impoundment based only on the field testing information. The field information includes piezocone data and water levels in drive-in piezometers.

Piezometric levels were obtained using the drive-in piezometers and the ambient pore pressure as measured by the piezocone. Only one water level can be obtained from each drive-in piezometer. The piezocone gives a continuous record of dynamic pore pressure and measures the ambient pore pressure at locations where the dynamic pore pressure is allowed to dissipate.

Material type and the stratification of materials are interpreted empirically from the piezocone tip resistance and dynamic pore pressure measurements. The coefficients of consolidation and hydraulic conductivity for the tailings are estimated from the pore pressure dissipation measured during dissipation tests.

Interpretations in this section are based largely on the strip chart recordings. Detailed digital data could have been used (as is shown below) for a more detailed interpretation. However, it was concluded that the present state of empiricism in the interpretation of piezocone testing in tailings did not warrant such a detailed analysis.

Interpretation of Piezometric Pressure

Water levels measured in the standpipe piezometers are summarized in Table 2. The water level in the pool on the impoundment did not change significantly during the period of observation. It can, therefore, be assumed that the last piezometer readings represent stable conditions. These readings were plotted as 'A' on the cross-section in figure 16. The water levels in the previously installed piezometers are plotted as 'E'.

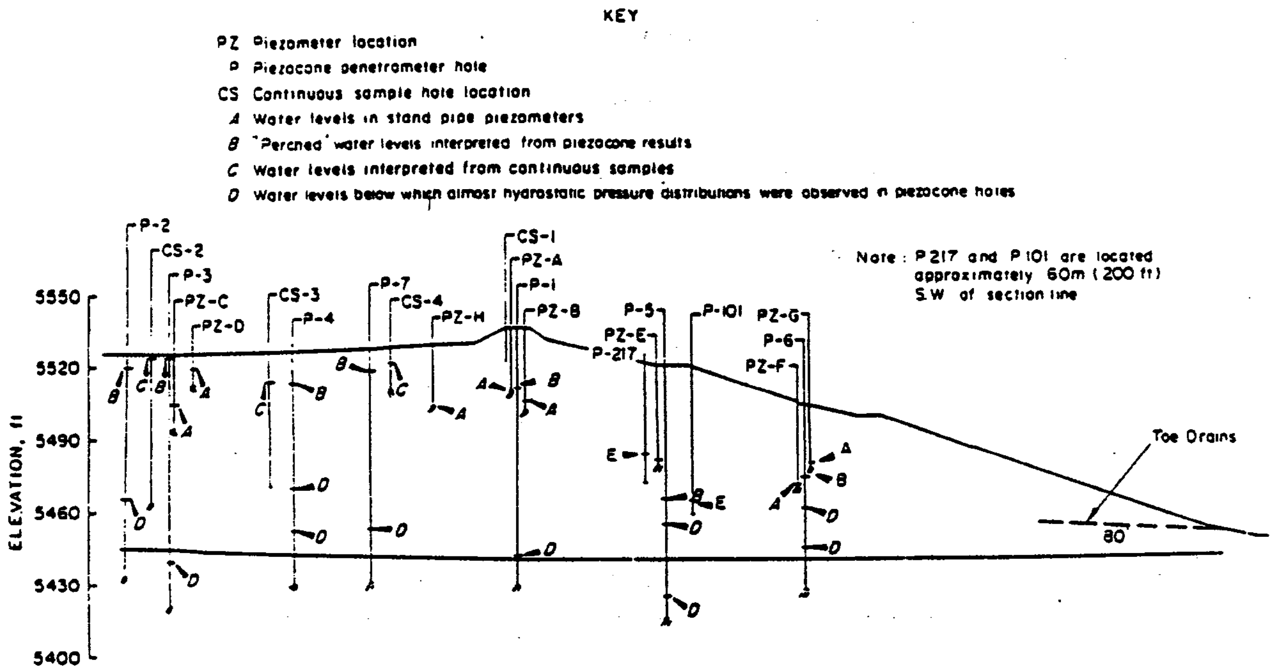


FIGURE 16. - Cross-section through impoundment showing piezometer level interpretations.

The pore pressures measured during cone penetration (u) consist of two components: the static (ambient) pore pressure and the dynamic pore pressure generated by penetration. The upper part of each piezocone hole is usually dry and pore pressure readings are, therefore, close to zero or negative. Once a zone of higher moisture content is penetrated, dynamic pressures are registered. Below the phreatic surface both static and dynamic components are measured. Dynamic pore pressure dissipates during the addition of rod extensions. The static (ambient) pore pressure is measured once the dynamic pore pressure has dissipated completely. In the partially saturated zone above the phreatic surface, the ambient pore pressure is negative or about zero. The levels where the first few positive ambient pore pressures are observed, can be used to estimate the position of perched water tables. This is done by drawing a best average line through the points of ambient pressure. This procedure is demonstrated in figure 17 where the highest perched water surface is estimated for hole No. P-4. It can be observed that the slope of the ambient pore water pressure is less than hydrostatic. This indicates a downward flow component. Thus, this perched water table is not perched on a single very low permeability layer but represents a zone where downward flow is retarded by a series of lower permeability lenses. This same procedure was used to estimate the position of the highest "perched" water surfaces for the other piezocone locations. The results are summarized in Table 7. These values are plotted in figure 16 and are identified as "B".

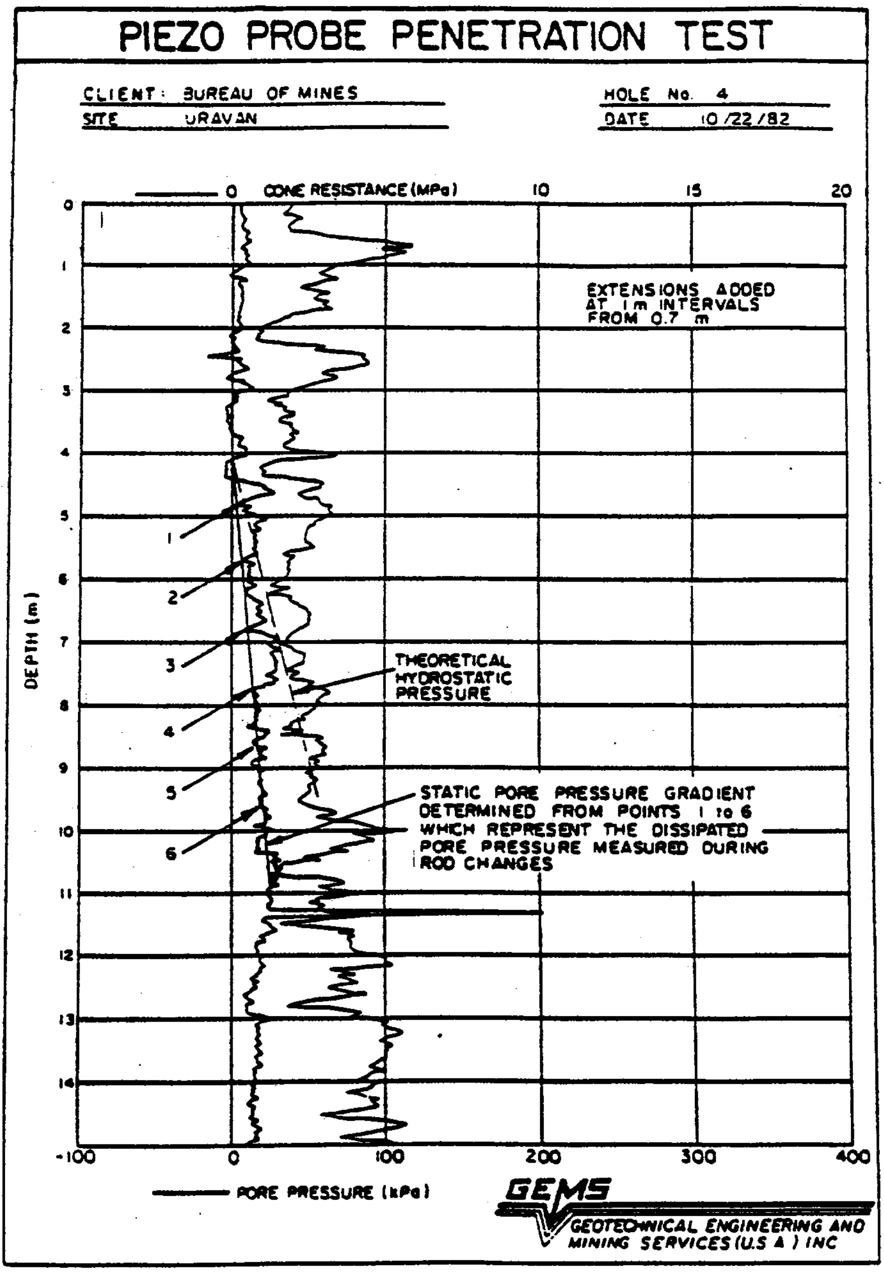


FIGURE 17. - Location of phreatic surface for hole P-4 from piezo probe results.

TABLE 7. - Estimation of top free surface location from piezo probe test results

Hole No.	Estimated depth (m)*
P-1	7.7
P-2	1.7
P-3	0.5
P-4	4.0
P-5	17.0
P-6	9.0
P-7	2.5

*From tailings surface

The dynamic pore pressure dissipation during rod additions, as shown in figure 17, may not have been complete, so some of the perched water table surface locations could be questionable.

Free water was present in some of the continuous sampling tubes when they were opened. On the basis of where water was observed, water levels identified as "C" were plotted on figure 16.

A review of figure 16 shows little consistency in the top free water surface.

The direction of seepage can be determined from the pore pressure distribution. A hydrostatic pore pressure distribution implies horizontal flow of ground water above a low permeability stratum. A pore pressure distribution at a gradient which is higher than hydrostatic is the result of upward flow conditions or under consolidated materials (13). Gradients less than hydrostatic are the result of downward flowing water.

Shown in figure 18 is a plot of all the pore water pressure measurements made at the location of hole P-3. The distribution of ambient pressure with depth is less than hydrostatic. This is due to downward flow of water through the tailings profile. The ambient pore pressure increases and decreases irregularly with depth in all the holes. In some instances the pore pressure becomes negative; for example, P-1 at 24 m to 26 m (see figure B.1.(b) in Appendix B). This indicates alternating zones of retarded and free vertical flow.

Some of the increases in water pressure approximate a hydrostatic pressure distribution. The levels where such hydrostatic (or almost hydrostatic) pressure distributions were observed are shown in figure 16. These levels are designated "D" and they all occur toward the base of the impoundment. In three of the holes (P-4, P-5, and P-6) two such levels were identified. Between these two levels the pore pressure returns almost to zero (P-4 at 23 m, figure B.7.(b)). These pressure drops are associated with changes from low permeability layers (soft or low cone tip resistances) to higher permeability layers (sands with higher cone tip resistances).

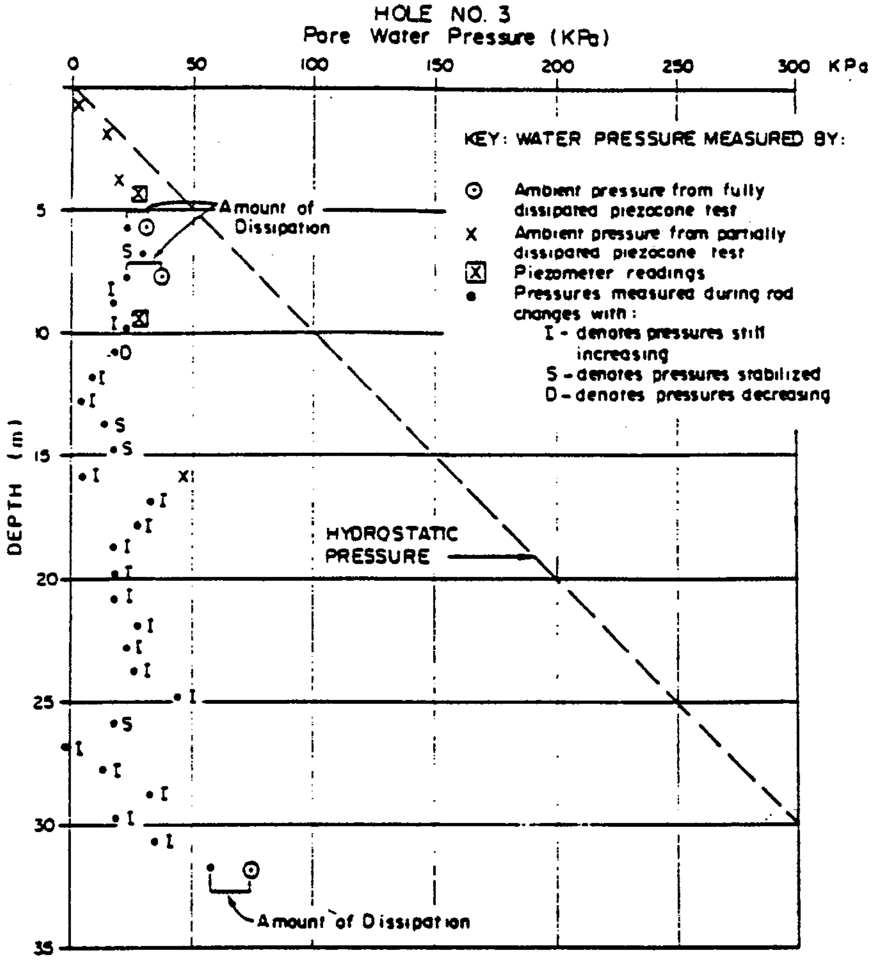


FIGURE 18 - Plot of all pore water pressure measurements at the location of hole P-3.

From inspection of adjacent exposures it is assumed that the foundation of the tailings impoundment consists of bedrock overlain by a sandy gravel soil. The soil cover represents a layer of high permeability over the bedrock. A high permeability preferential seepage layer or drain is, therefore, present under the tailings impoundment. Flow into this drain is probably being restricted by the low permeability slimes zones that occur toward the base of the impoundment.

Figure 16 and the piezocone results, therefore, indicate that a combination of nearly hydrostatic pressure conditions and lower than hydrostatic conditions exist in the Uravan tailings impoundment. The piezometric pressure conditions can be interpreted as a series of perched water tables on "leaky" lower permeability layers with almost vertical downward flow between them. The low pore pressures and slow dissipation rates measured as well as the method and history of impoundment construction suggest that most of the tailings are partially saturated.

The following model of flow in the impoundment is proposed (refer to figure 19): Water enters the impoundment from the pool. Since the tailings material has a low permeability in this area, considerable horizontal flow is caused by the layering. As a result, water seeps vertically and horizontally away from the pool area.

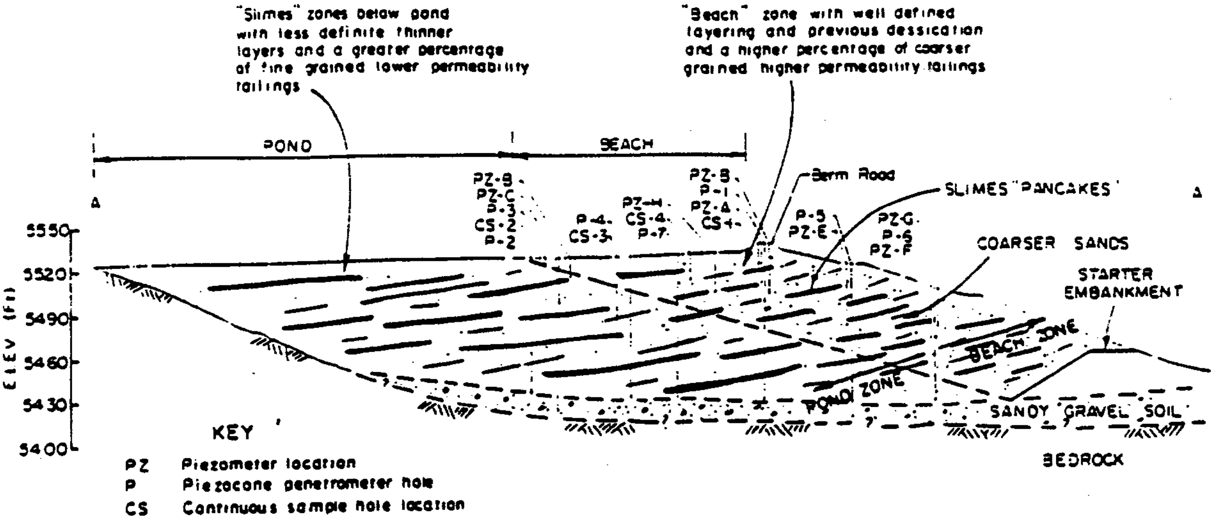


FIGURE 19. - Section through impoundment illustrating discontinuous layering.

The finer "slimes" layers are not continuous horizontally, so "cascades" develop when the seepage reaches the end of a finer layer. This process results in a series of perched water tables on leaky lower permeability layers with almost vertical flow in the more permeable intermediate layers. The general slope of the layering is parallel to the original beaches and is opposite to that of the phreatic surfaces. Recharge in the beach during rainfall and deposition also influences the presence of perched water tables. The tailings in the beach zone were dessicated following placement and it is unlikely that any of the layers in this zone would have become re-saturated. Because of the low pore water pressures (sometimes negative), it is probable that the layers of coarser, more permeable materials under the pond are also partially saturated.

The model described can be used to explain the flow regime over the whole section. Piezometers may register water levels but this does not mean that hydrostatic pore pressures exist below these levels.

The combination of piezocone and drive-in piezometer data made it possible to derive the flow model for the Uravan tailings impoundment. Such a model could not be derived from only a few standpipe piezometers.

Stratification of Tailings Material

The highly stratified nature of the tailings material at Uravan can be observed from the piezocone results, Appendix B, and the profiles of the continuous samples, Appendix C. In order to investigate the general trends in stratification, the cone results were all put on a cross-section of the impoundment as shown on figure 20.

The following general observations can be made:

(i) The material is in general weaker toward the pool (compare P-2 and P-3 to P-4).

(ii) It is not possible to distinguish layers with large strength variations in the upper 10 m of P-2 and P-3, while such layers are present in all the other piezocone holes.

(iii) The stratification in the beach zone can be interpreted to be continuous, as shown by the dashed lines.

(iv) Layering is observed for the full depth of the beach zone.

(v) Layers with consistently low cone resistance, indicating soft fine slimes layers, occur near the base of the impoundment in all holes. Penetration through these soft layers is often accompanied by a sharp reduction in pore water pressures.

These results are the consequences of the deposition history on the Uravan impoundment. Deposition took place through a few open point discharges located around the perimeter of the impoundment. The pool was large and has varied in size. Consequently, only a short beach existed along which segregation could occur. The coarse material was deposited on the beach while the fines settled in the pool area. Some segregation did occur along the beach close to the spigots, resulting in layers of coarser sand. However, much of the tailings reached the pool without significant segregation where it was deposited fairly uniformly. This explains the more uniform cone resistance obtained in the pool zone. Mass discharge from widely spaced spigots and the varying pool size resulted in back flashes of slimes onto the beach, leading to the highly stratified deposit observed in the beach zone. Dessication of the beach deposits also resulted in an increased density of the beach materials. Thus, variations in the dessication history of the various layers also affect the cone point resistance.

Material Identification

An important reason for carrying out penetration testing is to identify materials. In this study, both piezocone results and samples recovered by the continuous sampler were available for material identification. The material types identified using the piezocone results can be compared to the material types observed in the samples. One major limitation in applying this approach is the discontinuous stratification observed at Uravan. The piezocone and continuous

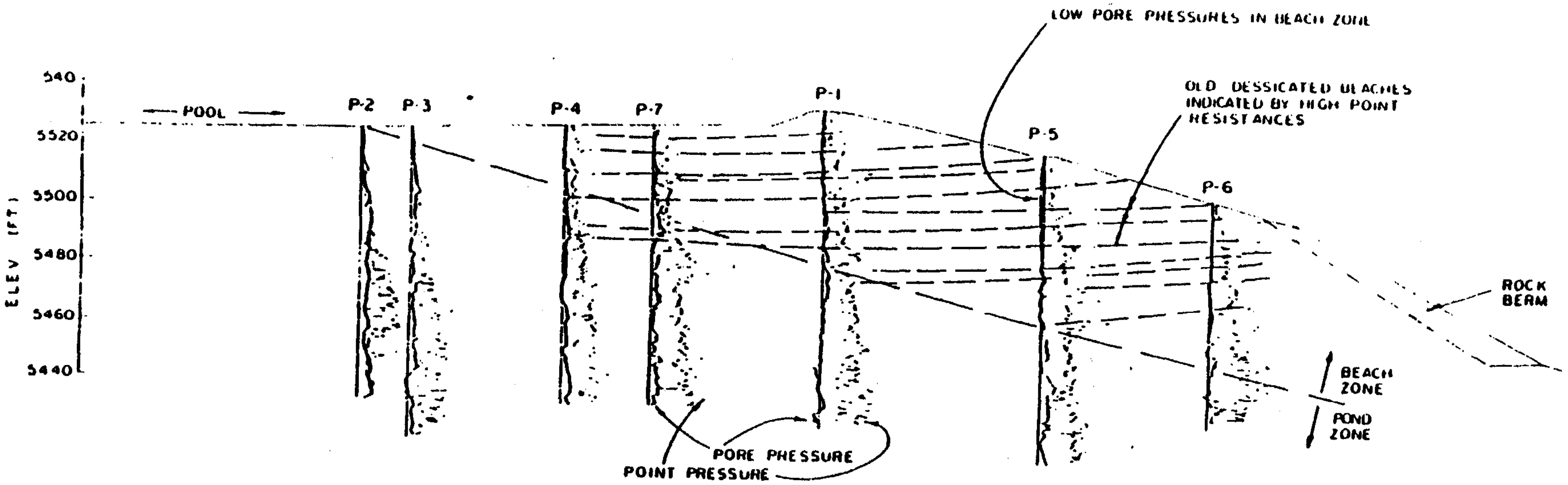


FIGURE 20. - Layering indicated by piezocone results.

sampler holes were not located directly next to each other so some discrepancies can be expected.

There are three methods that can be used for material identification:

(i) Relative strength as observed from cone resistance;

(ii) Cone resistance and dynamic pore pressure; and

(iii) Cone resistance and friction ratio.

The last two methods are based on empirically compiled charts and have been well-documented (3, 4, 5, 6, 14, 15). The charts have been compiled from testing in saturated soils. The application of all these methods to this project is doubtful because of the partly saturated nature of the tailings. Also, dessication induces stress effects and consolidation that is not accounted for in the published charts. These effects influence the cone resistance, dynamic pore pressure and the friction values measured. These values would probably be affected less in the probe holes underlying the pool than under the beach.

The exact nature of the material type and layering is not critical to the geohydrologic model for the impoundment, but, it does serve to develop a better understanding of the impoundment. The following evaluations were undertaken to determine if meaningful descriptions of the material types could be developed from the probe results, despite the conditions of partial saturation and previous dessication.

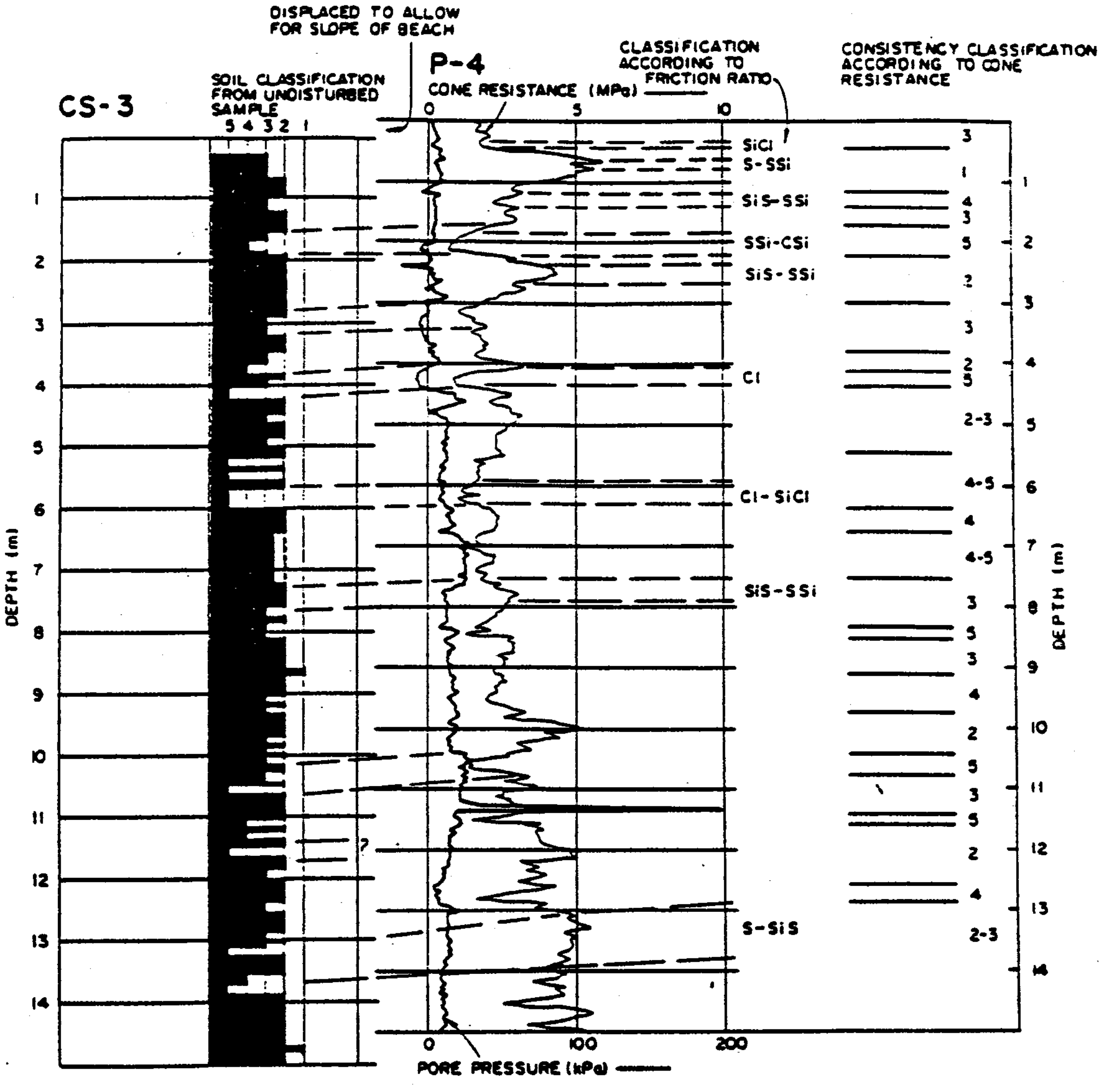
Material Identification Based on Cone Resistance

This approach is subjective because the relative cone resistance is used as a basis for the interpretation. An example of this interpretation for P-4 is given in figure 21. The consistency is expressed by numerical ranking from 1 to 5; 1 represents the strongest material (e.g. a dessicated dense sand) and 5 represents the weakest material (e.g. a wet silty or clayey layer). Also shown on figure 21 are the classifications based on laboratory testing and visual description of the undisturbed sample CS-3, located about 4 m from P-4. The classifications based on the friction ratio is also shown.

When the classifications determined from cone resistance are compared to the classification observed in the continuous sample, the following observations can be made:

(i) It appears that the interpretation based on cone resistance results are not sufficiently sensitive to material variations to record the intense variations observed in CS-3, e.g. at 2-3 m and 6-7 m. This is inevitable as generalizations were made in the interpretation.

(ii) Good correlation is observed at a few elevations, e.g. at 2 m and 4-4.3 m.



- For definition of symbols see Table 8

FIGURE 21. - Correlation of piezocone data with material classification by different methods.

(iii)A weaker material is interpreted than is observed at some elevations, e.g. 6.5-7.2 m.

(iv) At some locations material type 2 with thin layers of material type 3 was present in the continuous samples, while material types 4-5 were interpreted from cone resistance results. It can be concluded that the cone 'feels' the weaker material when such intense layering occurs.

During piezocone penetration about 200 data points are recorded per meter on floppy disks. In preparing a plot, such as figure 21, only a

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small number of these data points are used -- usually about 20 per meter. Figure 22 is a plot of all the data points recorded between 4 m and 5 m in hole P-4. This can be used to get more detailed insight into small variations of material characterstics. Comparison of this plot with figure 21 shows that the general trend in the data is nicely reflected in figure 21. The small, sharp deviations along the line are due to the limiting accuracy of the digitized data. Data were recorded as whole numbers so it is possible for small deviations in resistance to differ by a a full digit when recorded. A smoothing of the curves is therefore possible.

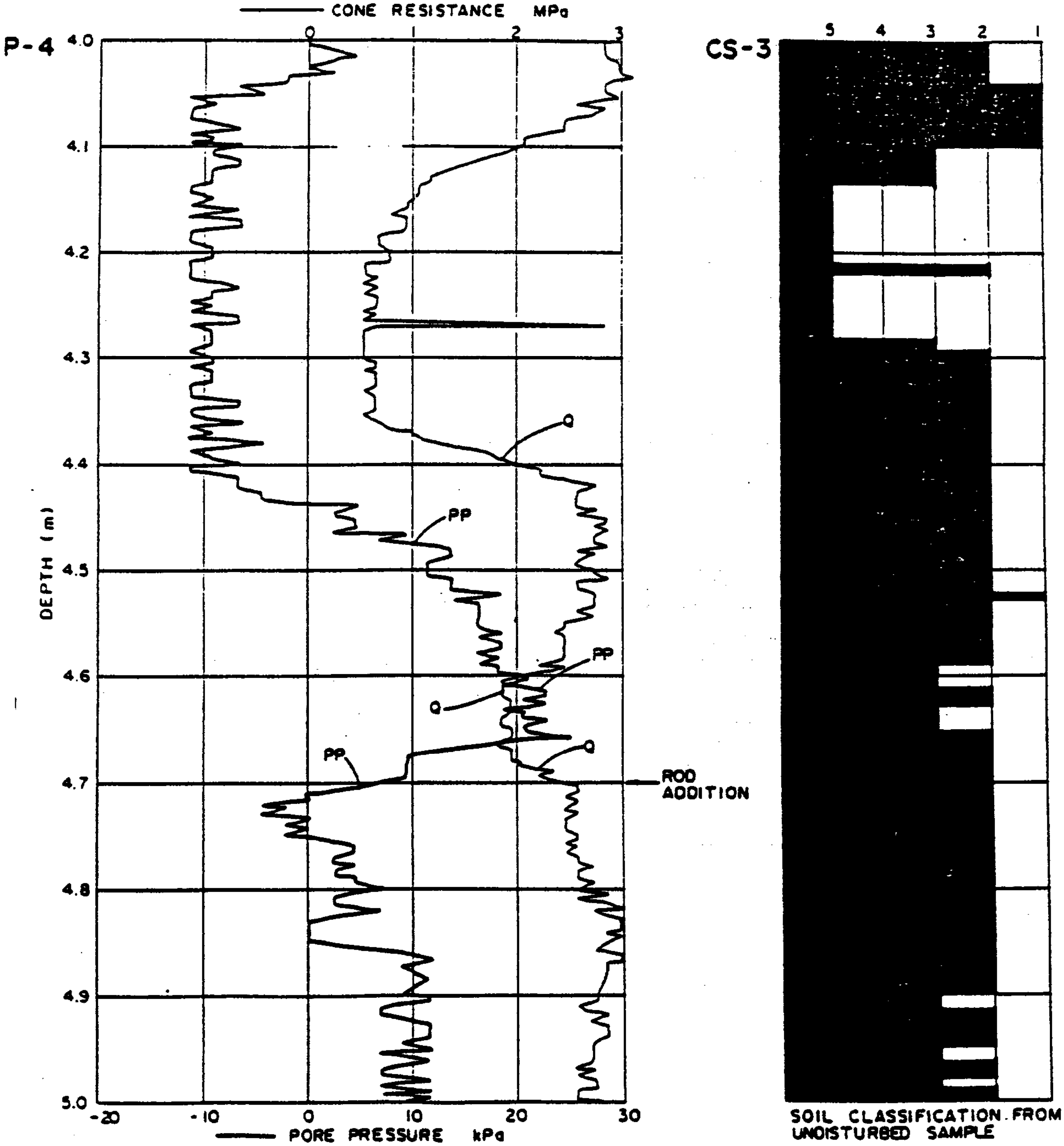


FIGURE 22. - Detailed comparison of piezocone results and soil classification from continuous sample.

Figure 22 does not significantly change the interpretation of layering as presented in figure 21. One exception is that a separate layer can be identified from 4.6 to 4.68 m, as material type 4. This is in good agreement with the continuous sample results at about this depth.

This analysis and previous interpretation experience indicates that cone resistance can be used for approximate material and layering identification, and is useful for preliminary analysis. It is subjective, however, and should not be used for detailed interpretations.

Material Identification Based on Cone Resistance and Dynamic Pore Pressure

Jones and Rust (6) proposed a material identification procedure which considers dynamic pore pressures, cone resistance, and overburden pressure. Figure 23 is their material identification chart. The chart shows empirically defined boundaries between different material types in terms of soil type (silt or sand) and consistency (soft, loose or dense). In general, positive dynamic pore pressure (u_e) is found in soils which contract during shearing (that is, loose sand and soft clay) and negative values of u_e are obtained in dilatant soils (that is, dense sands and stiff clays).

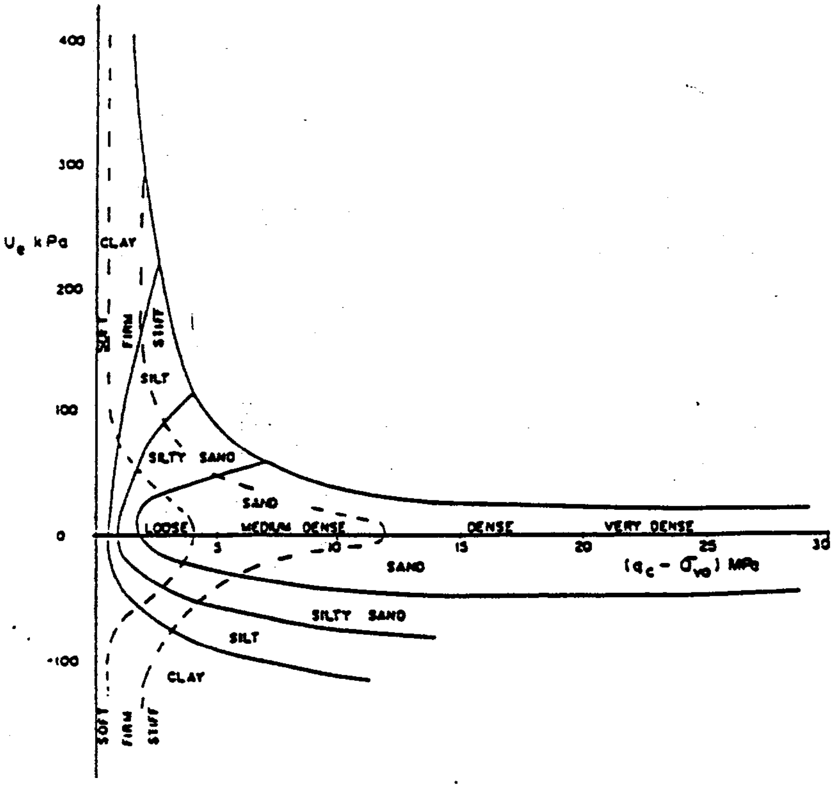


FIGURE 23. - Tailings based on cone resistance and dynamic pore pressure (Jones and Rust, 1982).

This interpretation includes overburden pressure and assumes that the material is fully saturated. It is difficult to derive a theoretical explanation for obtaining a negative pore pressure when penetrating a soft clay, but such data have been observed by Jones and Rust (6).

Although the descriptions on figure 23 are in terms of soil type and consistency, the overriding factor is the pore pressure behavior during shearing by the penetrometer. The pore pressure during shear is controlled by material permeability. Therefore, tailings classified as a given material (such as loose sand) exhibit similar coefficients of hydraulic conductivity whether u_e is positive or negative.

Applying the identification chart in figure 23 to piezocone results for hole P-4, for 4.0 to 11.0 m, gives the results in Table 8. All material classifies as a loose sand to very loose silty sand.

The material types obtained on the basis of the piezocone results and those observed in the samples from the nearby continuous sampler hole (CS-3) can be compared. Table 8 also presents the material type from CS-3.

There are substantial discrepancies between the material types identified on the basis of piezocone results and those observed in the continuous samples. Layers are interpreted from the piezocone data as being coarser and more free draining than they actually are. This is consistent with the previous conclusions: in partially saturated tailings the dynamic pore pressure developed during penetration would be considerably less than for saturated tailings. This underestimate of the saturated dynamic pore pressure results in the material being identified as a coarser than it actually is when using figure 23.

The above discussion indicates that soil identification based on the cone resistances and dynamic pore pressures obtained at Uravan was unsatisfactory. The poor correlation is attributed to the partially satured nature of the tailings and it is noted that reliable results have been obtained in saturated tailings deposits at other sites.

Material Identification Based on Cone Resistance and Friction Ratio

Material identification based on cone resistance and friction ratio was first proposed by Begemann (14). Since then a number of other studies have been published where this procedure has been used and refined. Douglas and Olsen (1981) (34) discuss this approach in some detail and figure 24 (obtained from Earth Technology Corporation) is one such empirical chart.

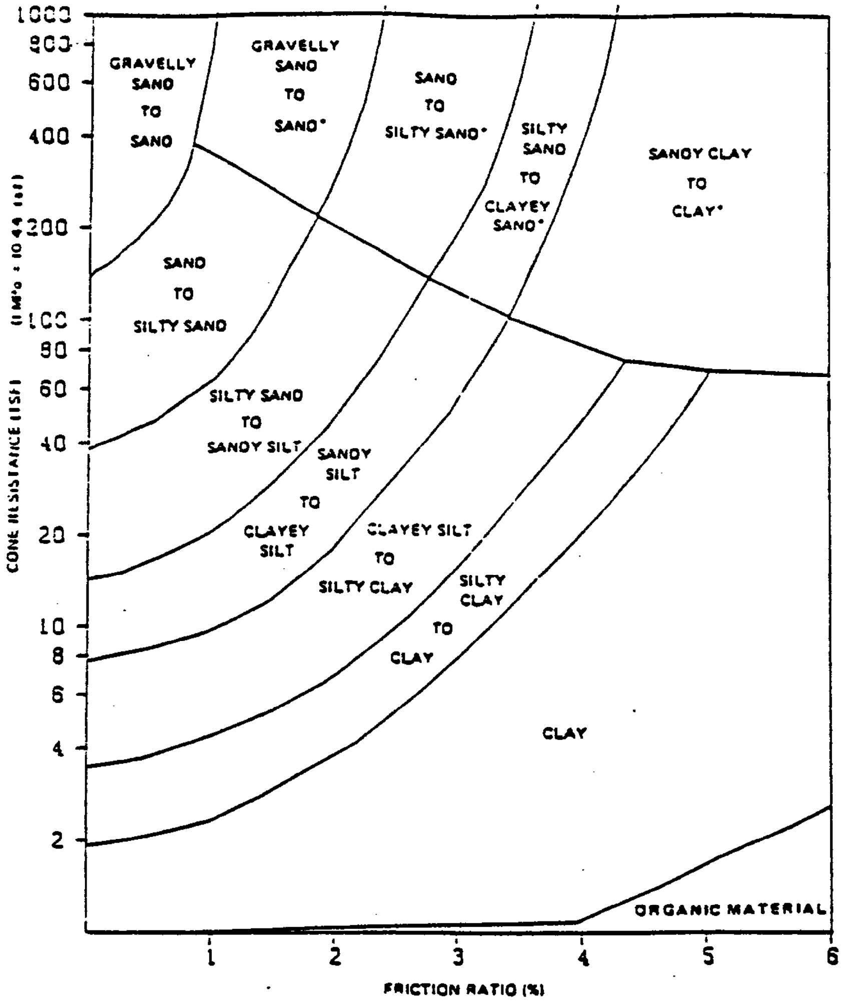
TABLE 8. - Material identification of piezo probe P-4

Depth (m)	q_c (MPa)	u_e (kPa)	Soil type[1,3]	Consistency[2,3]	Soil type from CS-3	Friction Ratio %	Soil type[4]
4.0	2.854	0	S	L	3	1	SiS-SSi
4.2	0.778	-9.164	SiS	VL	2	5	C
4.4	1.946	-6.873	S	L	2	1	SSi-CSi
4.6	2.076	20.619	S	L	2	0	SiS-SSi
4.8	2.595	6.873	S	L	2	1	SiS-SSi
5.0	2.724	9.164	S	L	2	1	SiS-SSi
5.2	2.076	11.455	S	L	2	0.5	SiS-SSi
5.4	1.946	9.164	S	L	2	0.5	SiS-SSi
5.6	1.427	11.455	S	L	2	2	CSi-SiC
5.8	1.297	4.582	S	L	5	0.5	SSi-CSi
6.0	1.427	4.582	S	L	2	2	CSi-SiC
6..2	1.038	2.291	S	L	2	4	C
6.4	1.686	13.75	S	L	3	1.5	SSi-CSi
6.6	2.076	18.328	S	L	2	1	SiS-SSi
6.8	1.557	18.328	S(SiS)	L(VL)	2	1	SSi-CSi
7.0	1.686	20.619	S(SiS)	L(VL)	2	1	SSi-CSi
7.2	2.076	22.91	S(SiS)	L(VL)	2	1	SiS-SSi
7.4	1.427	25.2	SiS	VL	2	2	CSi-SiC
7.6	2.076	22.91	S(SiS)	L(VL)	2	1	SiS-SSi
7.8	2.724	11.455	S	L	5	0.8	SiS-SSi
8.0	2.205	11.455	S	L	2	0.2	SiS-SSi
8.2	2.076	11.455	S	L	2	2	SSi-CSi
8.4	1.946	18.33	S	L	2	4	C
8.6	2.464	13.75	S	L	2	1	SiS-SSi
8.8	2.205	13.75	S	L	2	1.3	SiS-SSi
9.0	2.205	13.75	S	L	2	1	SiS-SSi
9.2	2.335	16.037	S	L	2	0.5	SiS-SSi
9.4	2.076	13.75	S	L	2	1	SiS-SSi
9.6	2.076	16.037	S	L	2	1	SiS-SSi
9.8	2.724	20.62	S	L	2	1.5	SiS-SSi
10.0	4.67	18.33	S	L	2	1	SiS-SSi
10.2	3.373	11.46	S	L	2	0.5	SiS-SSi
10.4	2.335	25.201	S	L	1	1	SiS-CSi
10.6	1.168	20.62	S	L	1	0	SSi-CSi
10.8	3.114	20.62	S	L	2	1	SiS-SSi
11.0	2.595	20.62	S	L	3	1	SiS-SSi

[1] S = sand   SiS = silty sand   SiC = silty clay   CSi = clayey silt   SSi = sandy silt   C   clay

[2] L = loose   VL = very loose

[3] Soil type based on cone resistance and dynamic pore pressure



* OVERCONSOLIDATED OR CEMENTED

FIGURE 24. - Material identification based on cone resistance and friction ratio (Earth Technology Corporation).

Interpretations based on this chart are also shown on Table 8. The material types determined from friction ratio compare reasonably well with the continuous sample results in the holes away from the pool. The upper 9 m of holes P-2 and P-3 are interpreted as clayey materials due to the high friction ratios (see figures B.3 and B.5 in Appendix B). This does not correspond well with the results from CS-2, although some thin fine layers are present.

There are several considerations that should be noted about the use of friction ratio to interpret material types in tailings. The friction sleeve is located behind the tip so there is a considerable offset in the observations. The friction sleeve has a length of 14 cm, (approximately 6 inches) this is longer than most of the layer thicknesses in the highly stratified tailings. The friction sleeve therefore 'feels' more than one layer at a time.

Material identification on the basis of piezocone results is still in the development stage, especially for highly stratified deposits.

The procedures used here have been reasonably successful in identifying significant layers (at least 10 cm thick). The procedures were not reliable when the tailings were highly stratified.

The results of this project suggest that for partially saturated and previously dessicated tailings, classification systems based on the friction ratio are more reliable than those based on the dynamic pore pressure. Moreover, these methods give only a very approximate indication of material type.

Estimation of Hydraulic Conductivity from Dissipation Tests

Estimates were made of the hydraulic conductivity for various layers of tailings based on the results of the dissipation tests. The methods used are described in Appendix E. The values obtained were one to two orders of magnitude lower than those obtained by laboratory testing. This difference is attributed to the effect of air bubbles in the partially saturated tailings. These air bubbles change volume when the tailings are stressed by the advancing cone. The volume change associated with these air bubbles during subsequent dissipation tests decreases the rate of pore pressure equilibration and this results in a reduced estimate of the hydraulic conductivity.

Dissipation tests are not a reliable measure of hydraulic conductivity in partially saturated tailings.

SELECTION OF PARAMETERS FOR THE GEOHYDROLOGICAL MODELLING OF THE IMPOUNDMENT

Introduction

This section discusses the piezometric pressure conditions and the hydraulic conductivities to be used for mathematical and numerical modelling the geohydrological conditions in the impoundment.

Hydraulic Conductivity

The hydraulic conductivities from the falling head tests in the piezometers (Table 3) are a measure of the average permeability of the material around the piezometer tip. This 'average' permeability is usually assumed to be the horizontal permeability. They fall within the range of values obtained from the laboratory tests (Table 6). These in situ tests may have been performed over more than one material type, due to the highly stratified nature of the tailings. The hydraulic conductivity values given in Table 2 are considered reliable average values for use as input parameters to horizontal flow for geohydrological analyses. They range from 2×10^{-6} cm/s to 2×10^{-4} cm/s.

The equivalent vertical and horizontal hydraulic conductivities of a layered system can be calculated if the permeability of the layers is available. In general, the equivalent vertical hydraulic conductivity of a horizontally layered system is close to the lower value, while the equivalent vertical hydraulic conductivity is close to the higher value. The layered system can, therefore, be replaced by an equivalent anisotropic medium. For such an equivalent anisotropic system at Uravan:

$$k_{hor} = 1 \times 10^{-4} \text{ cm/s}$$

$$k_{ver} = 1 \times 10^{-6} \text{ cm/s}$$

For an equivalent anisotropic medium, the average hydraulic conductivity is given approximately by:

$$k_{avg} = k_{hor} = k_{ver} = 1 \times 10^{-5} \text{ cm/sc}$$

Piezometric Heads

The seepage pattern in the Uravan tailings impoundment differs substantially from the classic seepage pattern through a water retaining embankment. It is controlled by recharge at the pond, intermittant recharge into the beach, and by drainage from the base of the impoundment into a natural base drain formed by the permeable subsoils overlying bedrock. The low permeability of the tailings underlying the pond limits seepage from the pond. Recharge through the beach has been considerably less in recent years as a result of reduced milling operations as well as the practice of limiting the amount of the water stored on this impoundment. With this reduced recharge the natural underdrain has been able to drain the tailings impoundment to the extent that a substantial water pressure mound no longer exists in the zone that was investigated.

Seepage occurs in the form of vertical flow, often in partly saturated conditions, in the more permeable coarser layers of tailings. When such seepage encounters a layer of lower permeability (slimes layer) it mounds and flows horizontally. Since these layers are inclined toward the interior of the impoundment there will be a slightly greater inward gradient locally. The slimes layers are not continuous and water reaching the end of a layer again moves vertically. These slimes layers have some permeability so some vertical flow does occur through them.

The extent to which the pore water mounds on these slimes layers or zones depends on the rate of seepage, relative permeability of the layers (slimes and sands) involved, and the lateral extent and thickness of the slimes layers. The flow paths which develop are complex and may include both saturated and partially saturated zones. A complex pressure head distribution results. This pressure head variation can be defined at each probe hole position, as for example in figure 18.

Conclusions Regarding Suitability for Modelling

One of the objectives of this study was to obtain the basic geohydrological data to enable the geohydrology of the impoundment to be modelled. The object of this modelling was to develop a tool for the design of horizontal drains in tailings impoundments. It was intended that horizontal drains would be installed to draw down the phreatic surface in the tailings impoundment and that this in turn would be modelled.

The difference in understanding of the geohydrology obtained as a result of this investigation graphically demonstrates the effectiveness of the specialized in situ testing techniques. It became apparent during this project that a phreatic surface, in the conventional sense, did not exist in the Uravan tailings impoundment at a location suitable for the testing of a horizontal drainage system. This conclusion could not have been reached based on previous geohydrological investigations or the existing piezometers. The previous investigations, based on the results obtained from conventional investigation methods, concluded that a high phreatic surface existed with hydrostatic pressure conditions below this.

This occurred because the existing piezometers, installed at a relatively high level in the embankment, indicated a fairly high phreatic surface.

The results of this investigation show that the section tested at the Uravan No. 3 tailings impoundment is not a suitable location for the horizontal drainage test. Moreover, the geohydrological conditions which exist at the Uravan No. 3 impoundment are not typical of the conditions under which horizontal drains are effective. It is therefore not a suitable site to use for the development of a design tool for horizontal drains.

Data from this investigation, such as the hydraulic conductivities and impoundment geometry, could be used to develop a hypothetical model, in which a saturated region and typical phreatic surface is assumed.

ASSESSMENT OF THE USE OF SPECIALIZED INVESTIGATION EQUIPMENT IN THE CHARACTERIZATION OF TAILINGS IMPOUNDMENTS

Introduction

The objective of this research was to evaluate the geohydrological characteristics of a tailings impoundment using specialized geotechnical equipment, that is not normally used in the United States for impoundment investigations. Listed below are the advantages and disadvantages of the equipment as identified by this research. This equipment is compared with traditional geotechnical equipment and investigation techniques (truck-mounted drill rig, Shelby tube sampling, and drilling and installing piezometers).

Advantages

Jones Piezocone

The cone pushing unit is trailer-mounted and easily transported on tailings beaches and embankments. In areas where access preparation is required, less preparation is required for the pushing unit than for standard truck mounted drill rigs. The piezocone obtained continuous data on strength (tip and friction resistance) and pore water pressures (pore pressure readings).

In tailings, the continuous readout is especially important because the piezocone is the most cost-effective and easiest way to measure a pore pressure profile in a highly layered, partially saturated, complex flow profile. In addition, these two parameters, through accepted correlations, provide information about consolidation and permeability, material type, and, if needed, shear strength and relative density. Continuous readout and data capture make the cone information ideal for the definition of layers and zones of similar characteristics.

Piezocone testing is fast and cost-effective. More sampling (meters of material tested) can be done and more information can be obtained per day and per dollar than traditional drilling.

Delft Continuous Sampler

The Delft continuous sampler recovers continuous samples to depths of 20 m (66 ft). Continuous samples are very important in evaluating tailings characteristics because of the layering and variability in material type.

The Delft continuous sampler provides the least disturbed sample of any sampler in soft, very sloppy, saturated materials. The authors have found no other equipment or methods that can sample these kinds of materials as well as the Delft continuous sampler.

In the appropriate materials, and for sufficiently large sampling volumes, is more efficient and cost-effective than traditional drilling and sampling equipment.

GEMS Tailings Drill

The GEMS tailings drill can be hand carried and operated in areas not accessible to conventional drilling equipment. It provides disturbed samples in dry to partially saturated tailings. It is a cost-effective way of drilling and sampling in tailings.

Cambridge Drive-in Piezometers

The Cambridge drive-in piezometer can be installed without the use of a drilling rig. Installation does not disrupt the hydraulic characteristics of surrounding material as much as traditional drilling and piezometer installation.

Disadvantages

Jones Piezocone

The Jones piezocone can only be used for soft to medium hard materials. Soils with gravels or cobbles are not suitable for piezocone probing. In partially saturated, previously dessicated materials, the dynamic pore pressure measurements have little meaning. They cannot be used reliably for the quantitative estimation of permeability, consolidation characteristics or for the identification of material types.

Delft Continuous Sampler

The Delft continuous sampler is suitable for soft, saturated materials. Dry to medium to coarse sands, such as those encountered in CS-1 and CS-4, are not suitable for the sampler. Initial preparation of the sampling equipment is fairly time-consuming. Its use would be fairly expensive if only one or two holes were to be probed.

GEMS Tailings Drill

The GEMS tailings drill works best in loose dry tailings. The drill will penetrate only one to two meters below the water table before the hole caves. It recovers only disturbed samples.

Cambridge Drive-In Piezometers

There is a limit to the depth the piezometers can be driven, depending on the consistency of the tailings. Greater depths can be reached only with the aid of a tailings drill or other drilling device. The size of the filter element is fairly small, limiting the zone being tested.

Costs and Comparisons

The following is an estimate of typical costs involved in the use of the specialized equipment and some comparisons. The costs are based on the actual costs incurred for this project and on rates charged for conventional equipment on other types of geotechnical projects. The field drilling and testing performed for this investigation was done during a 6-day field program by a crew of 3. This consisted of:

7 piezo probe holes - 206 meters

4 Delft continuous sampler holes - 46 m of sample

8 Cambridge drive-in piezometer installations

10 tailings drill starter holes plus 30 m of tailings drill sampling

Jones Piezocone

The Jones piezocone equipment consists of a three-man crew (engineer and two technicians), a 20-ton Goudsche pushing unit pulled by a four-wheel drive truck and the piezocone with electronic equipment. The daily cost for these personnel and equipment is $1,350.00, excluding per diem, travel time and mobilization. Production rates for this project averaged 60 meters per day. It should be noted that several dissipation tests were made during each probe sounding, and because this was a research project with the same crew performing other field testing, production rate was not at its maximum.

Piezocone - Cost per meter $1,350/60 m = $22.50/meter.

In comparison, the cost for drilling and continuous sampling using a truck mounted drilling rig (Mobile 41 or CME 55) with a two-man crew is approximately $1,000/day without crew travel time, per diem or mobilization. It has been our experience that an experienced crew will be able to drill and sample 15 meters (45 ft) per day of tailings with 60-75 percent sample recovery.

Drilling and continuous sample cost per meter - $1,200/15 m = $80/m.

Delft Continuous Sampler

Delft continuous sampling was performed using the same pushing unit and crew as the piezocone. Equipment rental rates are about $500 per day and expendable supplies cost about $10 per meter.

Compared to the cost of drilling and continuous sampling (estimated at $80/m above), the Delft continuous sampler is $5/meter ($1.67/foot) cheaper.

PART II - A TEST OF HORIZONTAL VACUUM DRAINAGE

INTRODUCTION

The horizontal vacuum drainage tests were conducted on the northeast corner of the No. 3 addition to the tailings impoundment at Union Carbide's Gas Hills mill in Natrona county, Wyoming. The geohydrological characteristics of the site had been investigated and described in a study by Water, Waste and Land Inc. (29).

The purpose of this investigation was twofold:

- to determine the effectiveness of gravity horizontal drains for draining saturated uranium tailings, and
- to evaluate the benefit of vacuum-augmentation relative to gravity drains

Two 91 m (300 ft) long horizontal drains were drilled with an (upward) inclination of 2 degrees at the collars. The horizontal drains were allowed to flow under gravity for a two week period after which a vacuum was applied to the system for three and four day test periods. The drawdown was measured by a nest of nine piezometers installed from the top of the impoundment.

PROJECT OBJECTIVES

The principal objective of the tests was to determine the influence that horizontal drains have on pore pressures and the location of the phreatic surface.

These results, plus the site characterization information are to be employed by the Bureau to develop a computer model that will simulate the effect of horizontal drains in a tailings environment. Specific objectives of the project were:

- To confirm that a reduction in the piezometric head could be achieved in stratified tailings.
- To determine the effectiveness and areal influence of horizontal drains.
- To determine if pore pressure dissipation and areal influence can be enhanced by means of vacuum-augmented drains.
- To determine whether a satisfactory vacuum can be maintained in a tailings environment.
- To ascertain what advantages vacuum-assisted drains have over gravity drains.

HORIZONTAL DRAINS AND THEIR APPLICATIONS

Applications of Horizontal Drains

Horizontal drains were first used in about 1939 by the California Division of Highways to stabilize highway slopes. Most of the early horizontal drains were installed with perforated or slotted iron pipe. Because of its advantages in cost, corrosion, sediment transport and plugging, slotted PVC pipe has been preferred in recent years.

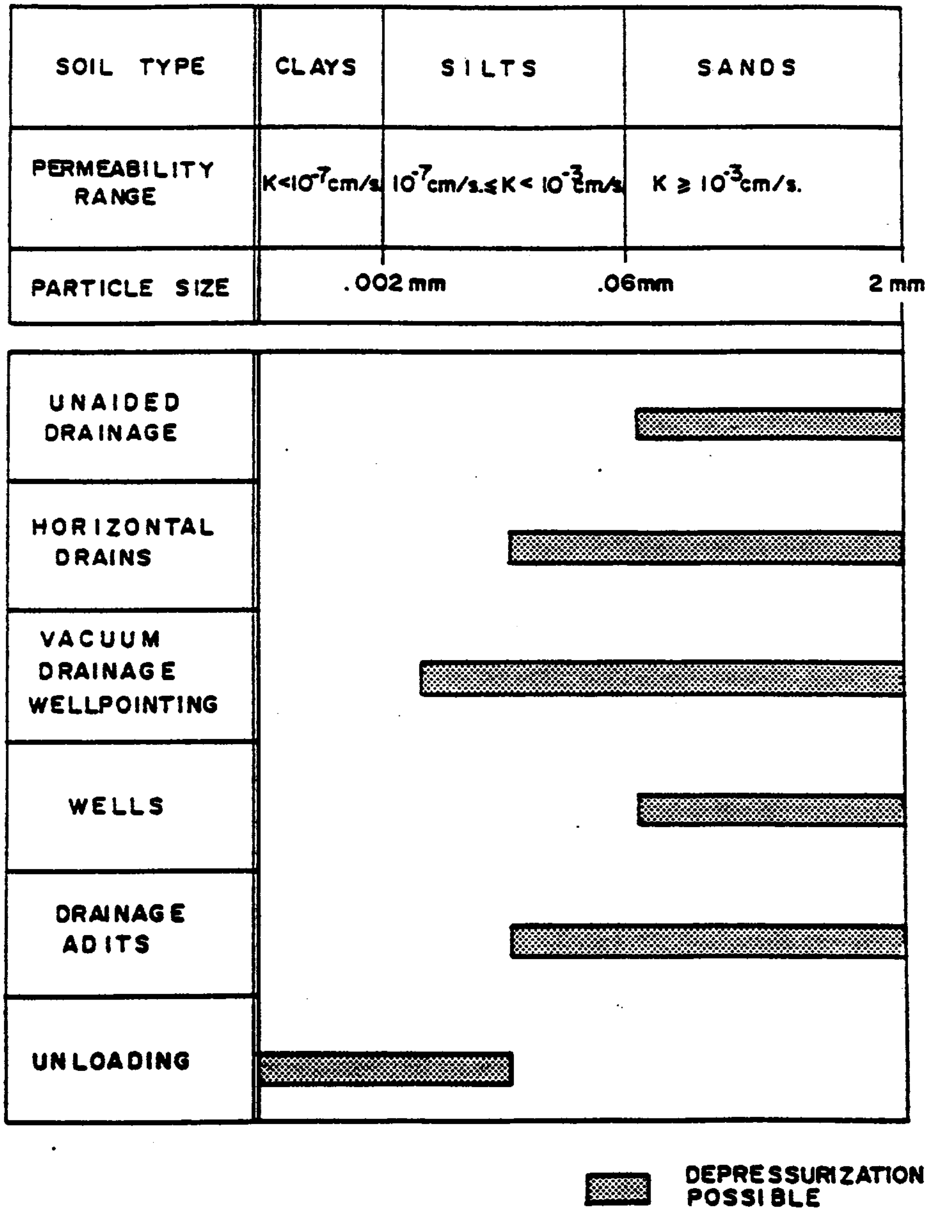


FIGURE 25. - Recommended depressurization techniques for various mass permeabilities After Brown (32) and Glossop and Skempton (31)

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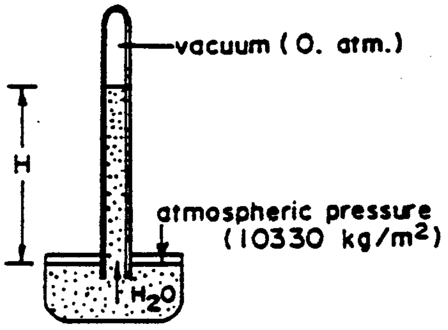
Horizontal drains can effectively lower the piezometric head in soils that have an effective grain size (D_{10}) that is greater than 0.05 mm (30). The capillary attraction in finer grained soils inhibits the release of water under gravity drainage. Glossop and Skempton (31) suggest that a total silt and clay content of about 60% is the upper limit for gravity drainage to be effective. Figure 25 illustrates the range of effectiveness of some alternative drainage measures.

Experience with vertical dewatering wells has shown that the application of a vacuum has frequently improved the drainage in soils too fine-grained to be dewatered by gravity drainage. Vacuum well-point systems have been used for many years to remove water from excavations and slopes (32). The horizontal vacuum system tested was developed by C.O. Brawner and R. Pakalnis. The patent number is 430549 (U.S./CAN.) and is retained by C.O. Brawner, R. Pakalnis and G. Sweeney of Soil Sampling Services, Inc.

Theory of Horizontal Vacuum Drains

The theory of horizontal vacuum drains is documented in a paper by Brawner and Pakalnis (33). The following is a brief description.

An enclosed column of water open to a vacuum (0 atm pressure) will rise to 10.3 meters (at mean sea level) due to the atmospheric pressure that acts on the water surface outside of the column (Figure 26). When a vacuum is applied to a horizontal drain, the drop in pressure in the drain increases the hydraulic gradient between the drain and the phreatic surface. The increased hydraulic gradient (Figure 27) will theoretically increase drainage rates and effectively drain lower permeability materials. In addition, drainage from below the drain level is possible due to the vacuum principles demonstrated in Figure 26.



WHEREBY:

H = height of water column

$$H = \frac{\text{atmospheric pressure (10330 kg/m}^2\text{)}}{\text{density of water (1000 kg/m}^2\text{)}}$$

$$= 10.3 \text{ m (at mean sea level)}$$

FIGURE 26. - Vacuum principle

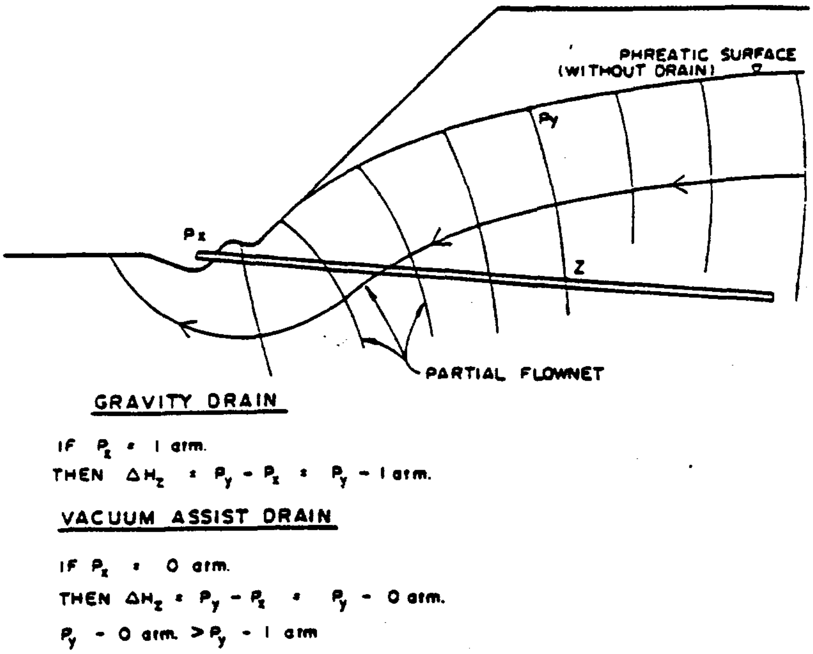


FIGURE 27. - Effect of vacuum drainage on hydraulic gradient

INSTALLATION

Test Site

A description of the site and its geohydrology is given in reference 29.

The test site is shown in Figures 28 and 29. In August 1983, nine piezometers had been installed at the locations shown. The piezometers were located so as to:

- determine the phreatic surface profile parallel (Section A-A') and perpendicular (Section B-B') to the drain installation; and
- determine the areal influence of the horizontal drains.

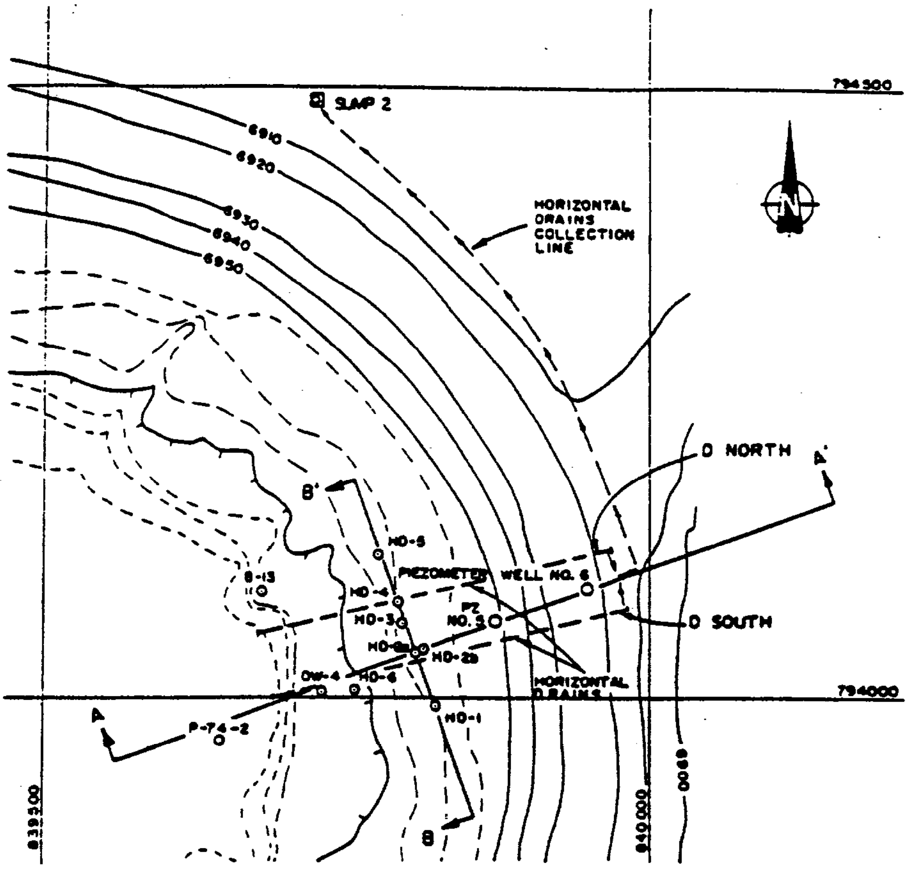


FIGURE 28. - Horizontal drains and collection system

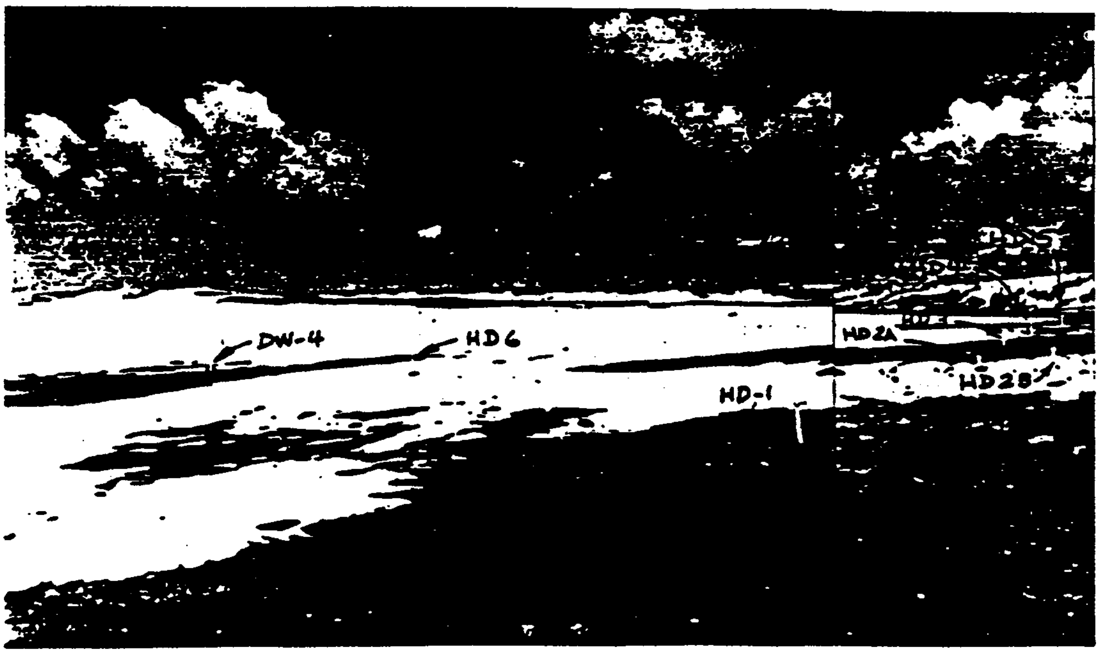


FIGURE 29. - Piezometer layout on impoundment

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The depths of the piezometers are given in Table 9.

TABLE 9. - Piezometer depths

Piezometer number	Depth of piezometer* in m (ft)
HD-1 (pneumatic).	9.1 (30.0) estimated
HD-2a (pneumatic)	8.1 (26.7)
HD-2b (pneumatic)	9.8 (32.0)
HD-3 (pneumatic).	9.5 (31.0)
HD-4 (pneumatic).	9.5 (31.0)
HD-5 (pneumatic).	10.7 (35.0)
HD-6 (pneumatic).	9.4 (30.7)
OW-4 (stand pipe)	10.4 (34.0)
PZ-5 (stand pipe)	9.1 (30.0) estimated

*Ground elevation 6950 ft

A typical soil profile in the tailings is shown in Figure 30 which also illustrates the installation of one of the standpipe piezometers. A 30 (100 ft) thick embankment of mine waste had been constructed to contain the spigoted tailings. This embankment was composed of a compacted coarse sandy silt containing cobble size material.

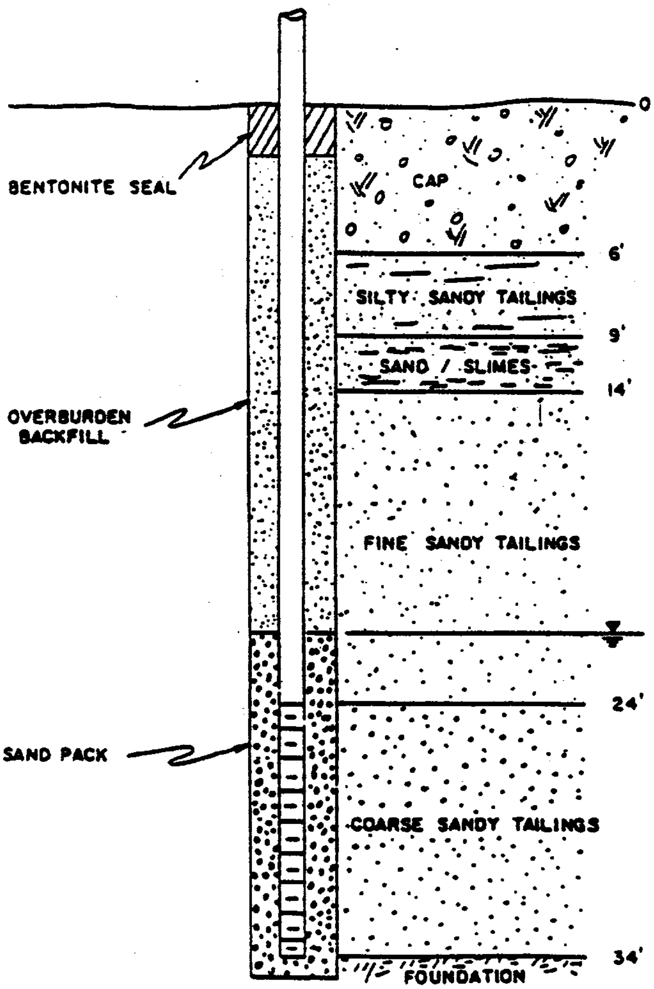
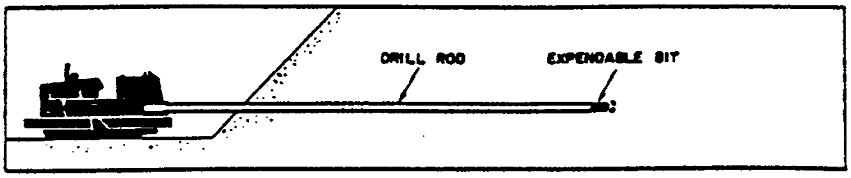


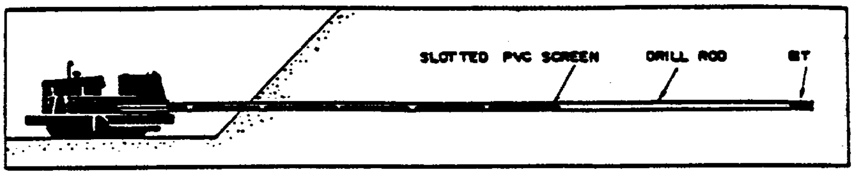
FIGURE 30. - Typical profile in Gas Hills tailings impoundment and schematic of standpipe piezometer installation

Drain Installation

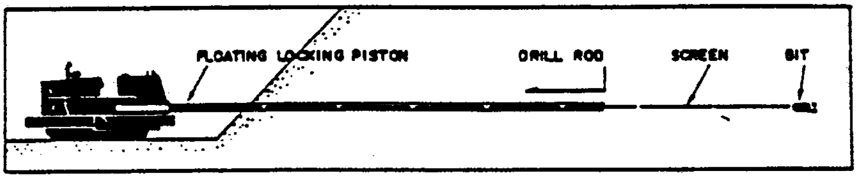
The horizontal drains were installed in May 1984. Each drain had a length of 91 m (300 ft) and was inclined at 2 degrees (upward) at the collar, with an azimuth of 250 degrees and spaced 15 m (50 ft) apart. The procedure for installation is summarized in Figure 31.



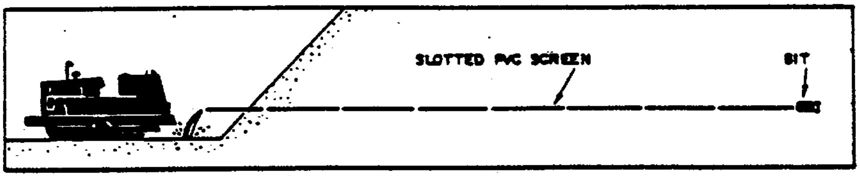
Horizontal hole is drilled by conventional rotary method.



Upon completion of the boring, P.V.C. well screens are inserted inside the drill rod to the full length of the hole.



Floating locking piston is inserted, holding the screens in place by hydraulic pressure while the drill rod is withdrawn.



Completed drain installation. Screens of fine slot size prevent clogging and formational mining. Collector lines are installed.

FIGURE 31. - Drain installation

The first 15 m (50 ft) and 12.2 m (40 ft) for the north and south drains, respectively, were cased by tri-coning a 149 mm (5 7/8 inch) diameter hole and inserting a 140 mm (5 1/2 inch) O.D. pipe as shown in Figure 32. The casing was subsequently grouted with an expanding grout and allowed to set for 12 hours. The grout mixture used was as follows:

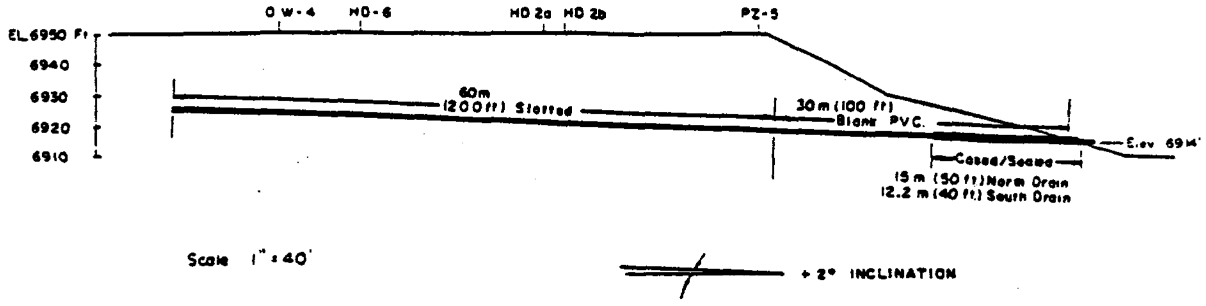
- 1 pint aluminum (paint grade)
- 90 lb of Portland cement
- 60 gallons water
- 1 pint calcium chloride

FIGURE 32. - Driving 5 1/2" O.D. casing into previously tri-coned 5 7/8" hole

This grout was required to seal the anulus between the casing and the surrounding soil, thereby maximizing the vacuum that can be developed. Figure 33 shows the packer placed at the end of the cased hole. It is subsequently inflated thereby allowing pressure grouting around the casing. The packer was deflated and removed after the grout had set. Drilling of the remainder of the drain hole then proceeded.

FIGURE 33. - Grouting - placement of packer

Figure 34 is a cross-section depicting the intended drain installation. The first 30.5 m (100 feet) of drain pipe was blank since this was the estimated thickenss (length) of the embankment material. The remaining 61 m (200 ft) were slotted. The following is a brief log of the drilling procedure and results:



Drain Hole	4 3/4 in. Dia., Cased Section 5 7/8 in. Dia.
Blank Pipe	1½ in. (10) Schedule 80 PVC Pipe 1.9 in. (OD)
Slotted Pipe	Slot size 0.01 in. with slots spaced 1/4" apart providing open area of 0.440 square inches per linear foot
Cased Section	5½ in. (OD) Pipe

FIGURE 34. - Drain hole specifications

South Drain

- o Tungsten finger bit employed to drill beyond the cased section.
- o

0-46 m (0-150 ft)	waste embankment material-sandy silt containing cobbles
46-52 m (150-170 ft)	waste embankment and tailings
52-72 m (170-235 ft)	tailings
72-72.6 m (235-237 ft)	cobbles
72.6-91 m (237-300 ft)	tailings

- o No leakage occurred around the outside of the casings
- o Average advance rate was 3 m (10 ft) per minute.

North Drain

- o

0-30 m (0-100 ft)	waste embankment
30-43 m (100-140 ft)	tailings
43-46 m (140-150 ft)	cobbles
46-91 m (150-300 ft)	tailings

- Average advance rate was 3 m (10 ft) per minute.
- No leakage around anulus of casing

After installation the drain pipes were surveyd to precisely define their location. The survey was undertaken by NL Sperry-Sun Inc. using a Sperry-Sun borehole camera. This survey indicated little deviation of the drains in the horizontal plane with installed orientations of 255 degrees and 257 degrees for the north and south drains respectively. There was significant deviation of the drains in the vertical plane as indicated by the measured profiles shown on Figure 35. Blockage of the drain holes at 33.2 m (109 ft) and 34.1 m (112 ft) in drain holes north and south (respectively) prevented the surveys penetrating to the full depth of the drains.

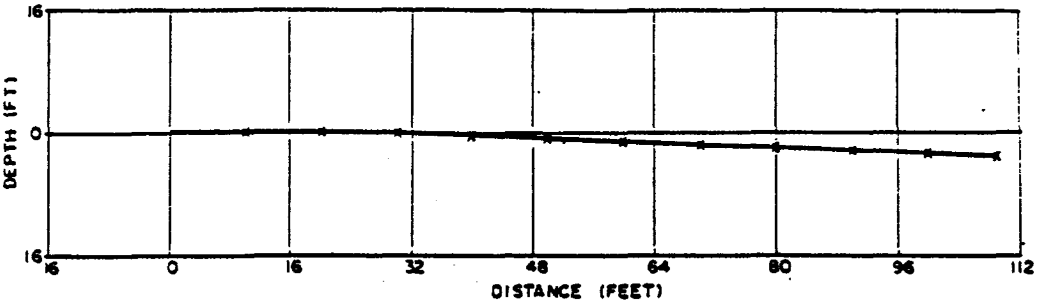


FIGURE 35(a). - Vertical profile of drainhole north

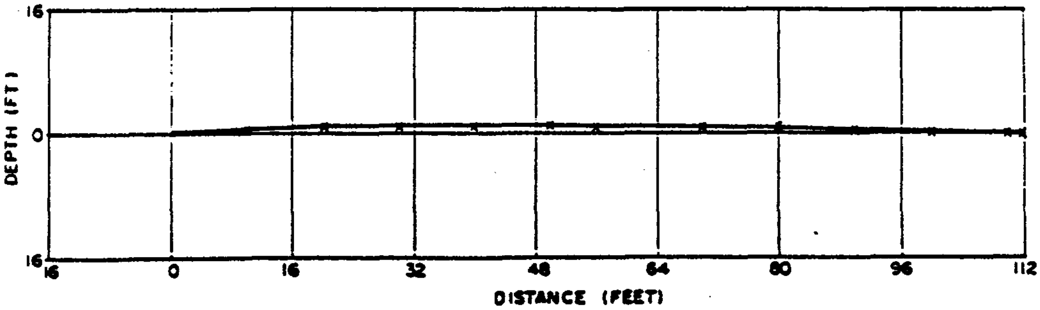


FIGURE 35(b). - Vertical profile of drainhole south

Vacuum Installation

A model 220 SF vacuum pump manufactured by Moretrench America, capable of exhausting 1.4 m /min (50 cfm) of air at 1 atm (29.99 inches of mercury) was connected to the drains. The system is shown in Figure 36. The amount of vacuum achieved was indicated by a gauge mounted on the pump. The number of drains one pump may service is a function of the amount of vacuum that can be maintained in a system. Normally, about six drains can be connected to one pump in a horizontal vacuum augmented drainage system.

FIGURE 36. - Vacuum installation

RESULTS OF DRAINAGE TESTS

Testing Schedule

The following summarizes the monitoring and testing schedule:

- Feb. 14/84 - May 3/84 - Piezometer readings recorded weekly.
- May 1-2/84 - Drain casings installed and grouted.
- May 3/84 (9:30 a.m. - 2:00 p.m.) - Drains drilled and installed.
- May 3/84 (2:00 p.m.) - May 15 (12:45 p.m.) - Drains allowed to flow under gravity; piezometers and flows monitored daily.
- May 15 (12:45 p.m.) - May 18 (2:30 p.m.) - Vacuum test 1 - monitoring of vacuum pressure piezometers and flows twice a day.
- May 18 (2:30 p.m.) - May 21 (8:30 a.m.) - Gravity drainage, no monitoring.
- May 21 (8:30 a.m.) - May 25 (2:30 p.m.) - Vacuum test 2 - monitoring of vacuum pressures, piezometers and flows daily.
- May 25 (2:30 p.m.) - (pump removed)-gravity drainage, monitoring of flows and piezometers weekly.

Vacuum Pressures

The test site is located at 2100 m (6900 ft) above sea level for which a maximum vacuum of 584 mm (23 inches) of mercury is attainable (1 ATM = 584 mm at 2100 m A.S.L.).

Table 10 summarizes the vacuum pressures attained during the study.

TABLE 10. - Vacuum measurements

Period	Mercury Suction head D north mm (inches)	Mercury Suction head D north mm (inches)	Mercury Suction head D north mm (inches)
May 15 (12:45 pm) - May 18 (2:30 pm)		508 ± 38 (20) (1.5)	467 ± 20 (18.4) (0.8)
May 15 (12:45 pm) - May 16 (2:30 pm)	457 (10)		
May 21 (8:30 am) - May 25 (2:30 pm)	254 (10)	559 ± 25 (22) (1)	432 ± 36 (17) (1.4)

These tests show that it is possible to maintain a satisfactory vacuum for horizontal drains in tailings.

Flow Rates

The flows measured during gravity and vacuum testing are shown on Figure 37 and summarized in Table 11. Maximum vacuum flows are approximately double those of gravity drainage. The north drain was dry under gravity flow. The south drain, located 15 m (50 ft) away, flowed continuously.

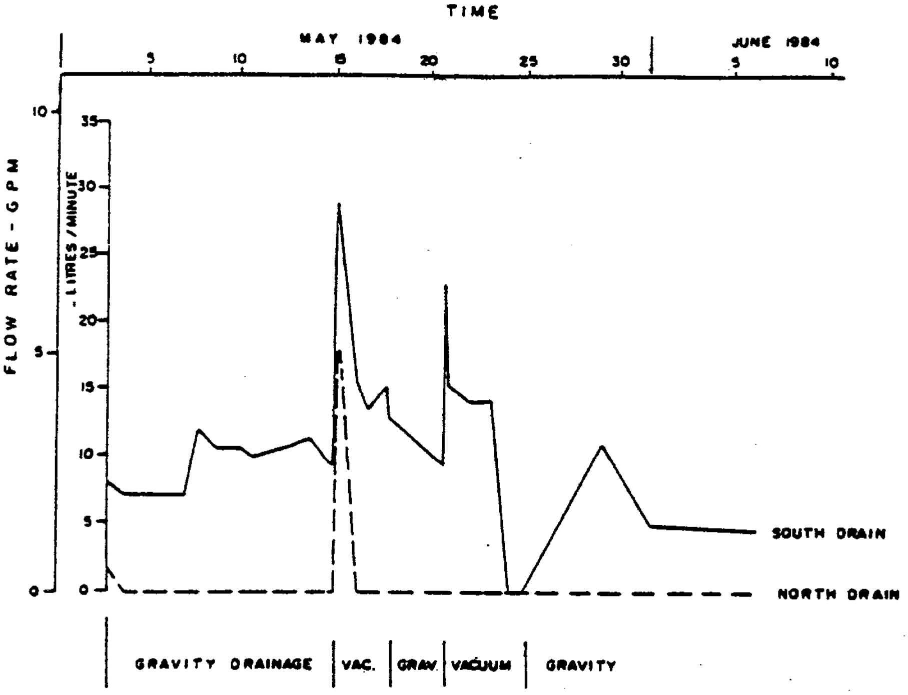


FIGURE 37. - Drainage flow rates

TABLE 11. - Flow measurements

Period	System	Total flow l/min (gpm)
May 3 (5 pm) - May 15 (12:45 pm)	Gravity	9.7 (2.7) ± 1.4 (0.4)
May 15 (12:45 pm) - May 18 (2:30 pm)	Vacuum	21.2 (5.9) ± 8.6 (2.4)
May 18 (2:30 pm) - May 21 (8 am)	Gravity	9.4 (2.6)
May 21 (8:30 am) - May 24 (2:30 pm)	Vacuum	17.3 (4.8) ± 2.9 (0.8)
May 24 (2:30 pm) - May 25 (2:30 pm)	Vacuum	0

Figure 38 shows the results of a brief test conducted on May 4 when vacuum was applied and then removed from each of the drains. The resulting gravity flow was greater after the application of vacuum. This suggests that the vacuum created new flow channels to the drain and consequently a greater permeability. The flows were of short duration. However, the tests were repeated and similar results obtained.

The pH of the water varied from 4.0 to 5.0.

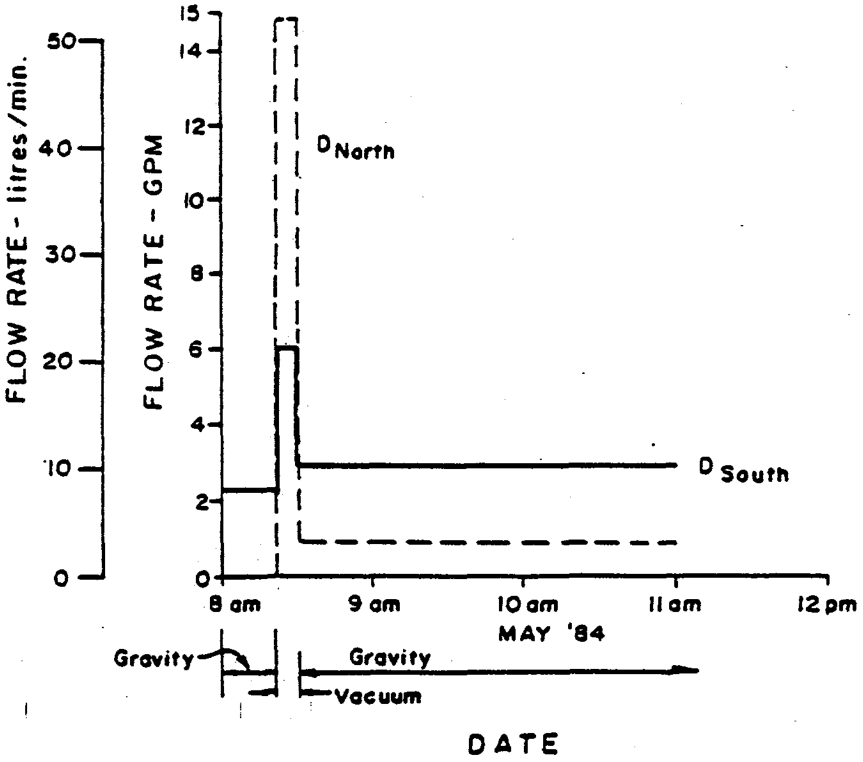


FIGURE 38. - Short term effect of vacuum drainage

Piezometer Monitoring

Figures 39(a) and 39(b) indicate the drawdown of the individual piezometers as a function of time. Figure 39(a) contains the piezometers located along Section A-A', whereas Figure 39(b) contains pieozometers along Section B-B' of Figure 28.

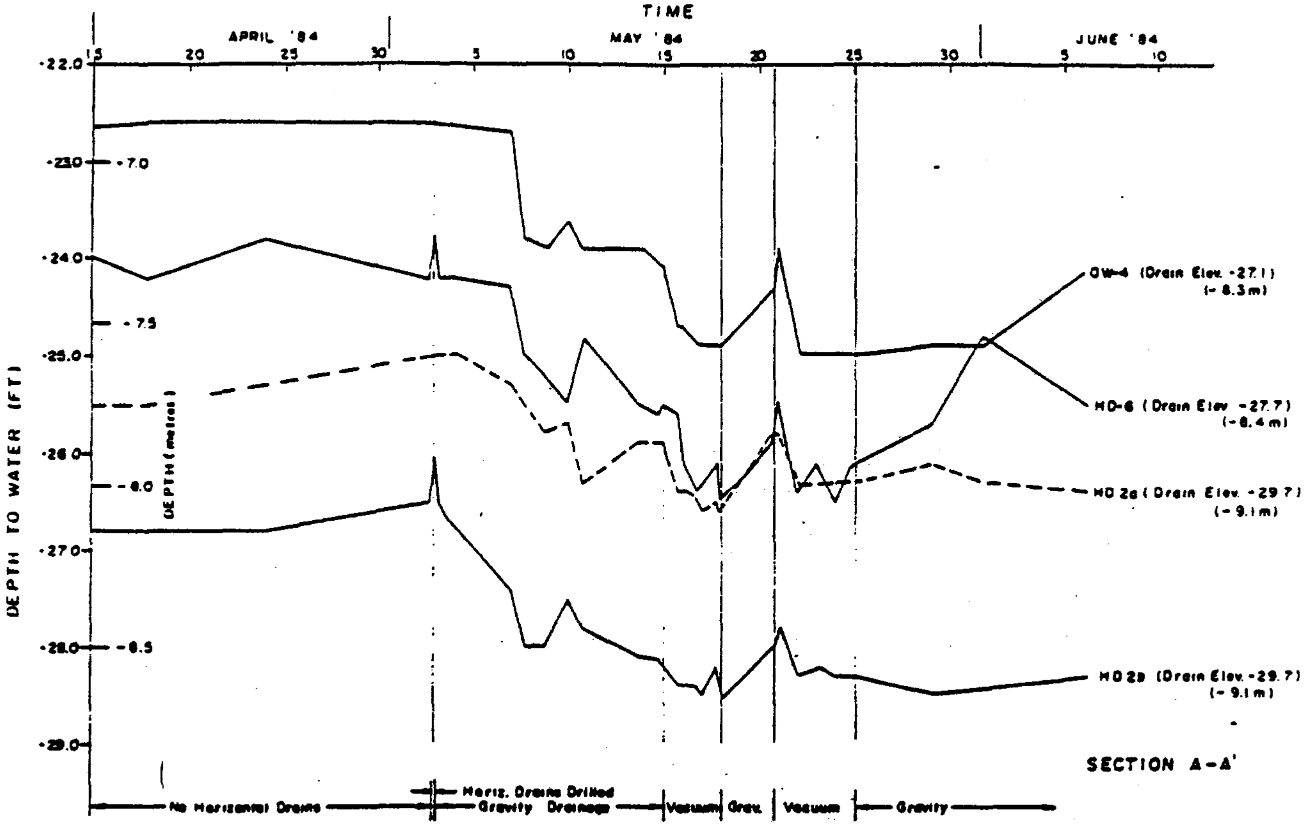


FIGURE 39(a). - Drawdown vs. time

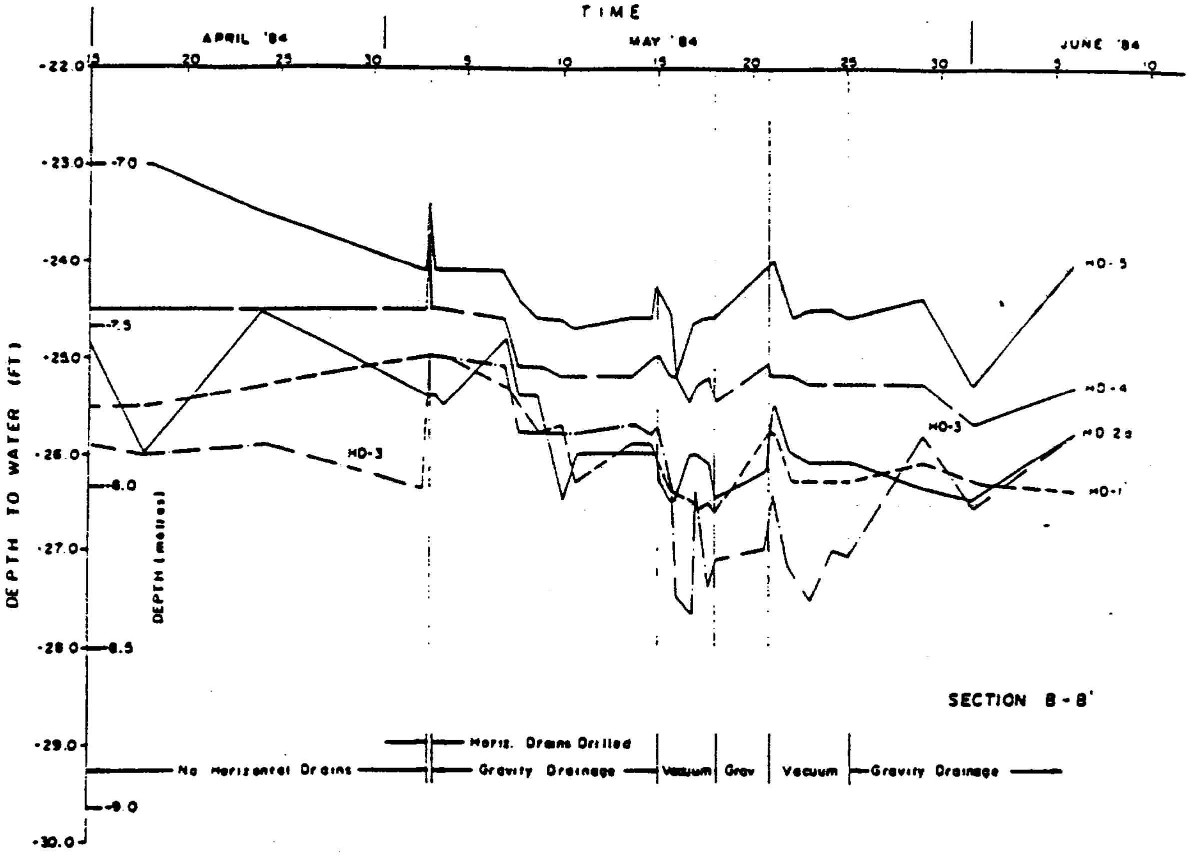


FIGURE 39(b). - Drawdown vs. time

Table 12 summarizes the water levels measured.

Figures 40(a) and (b) are profiles showing the phreatic surface relative to the drain elevation drawn along Section A-A' in figure 28 whereas Figures 41(a) and (b) are a profile drawn along Section B-B'.

The following observations apply:

- Water table was generally 4-5 m above the drain cover.
- Drawdown under gravity drainage was approximately 0.3 m (1 ft) or an 8% drawdown in the water table relative to the drain level.
- Drawdown under vacuum drainage was approximately 0.6 m (2 ft) or a 16% drawdown in the water table relative to the drain level.
- The pneumatic piezometers have an inherent accuracy of + 0.3 psi or 0.2 m (.7 ft) which is relatively large considering the water pressures ranged from 0.05 psi (0.03 m or 0.1 ft) to 4.5 psi (3 m or 10.4 ft). This may

explain the erratic behavior of the pneumatic piezometers in certain instances.

- Drawdown with vacuum drainage was approximately double that attained through gravity drainage. This result has also been found in previous research conducted on a laboratory size soil slope (33).

TABLE 12. - Drawdown measurements (based on extrapolated lows figure 39)

Piezometer*	Depth to Drain m (ft)	Base RDG m (ft)	Gravity Drainage m (ft)	Vacuum m (ft)	% Increase Vacuum over Gravity**
OW-4	-11.6 DS*** (-38.1)	-6.8 (-22.6)	-7.3 (-23.9)	-7.6 (-25)	+85%
HD-6	-11.4 DS (-37.4)	-7.4 (-24.2)	-7.8 (-25.6)	-8.1 (-26.5)	+64%
HD-2a	-11.2 DS (-36.8)	-7.6 (-25.0)	-8.0 (-26.2)	-8.1 (-26.6)	+33%
HD-2b	-11.2 DS (-36.8)	-8.1 (-26.5)	-8.5 (-28.0)	-8.7 (-28.5)	+33%
HD-5	-12.6 DN*** (-41.3)	-7.4 (-24.2)	-7.5 (-24.7)	-7.7 (-25.2)	+100%
HD-4	-12.6 DN (-41.3)	-7.5 (-24.5)	-7.7 (-25.2)	-7.8 (-25.5)	+43%
HD-3	-12.6 DN (-41.3)	-7.6 (-25.0)	-7.9 (-25.8)	-8.4 (-27.7)	+238%

*Values measured relative to surface.

** $\% = \frac{(/Vacuum/ - /Base/) - (/Gravity/ - /Base/)}{(/Gravity/ - /Base/)}$

***DS or DN refers to drain in vicinity.

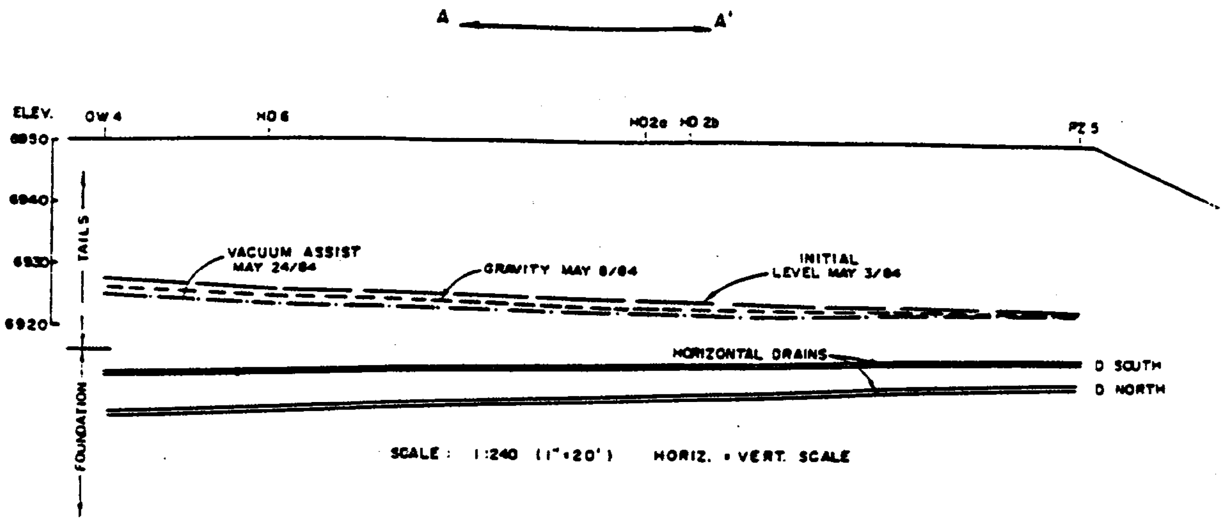


FIGURE 40(a). - Phreatic surface section A-A'

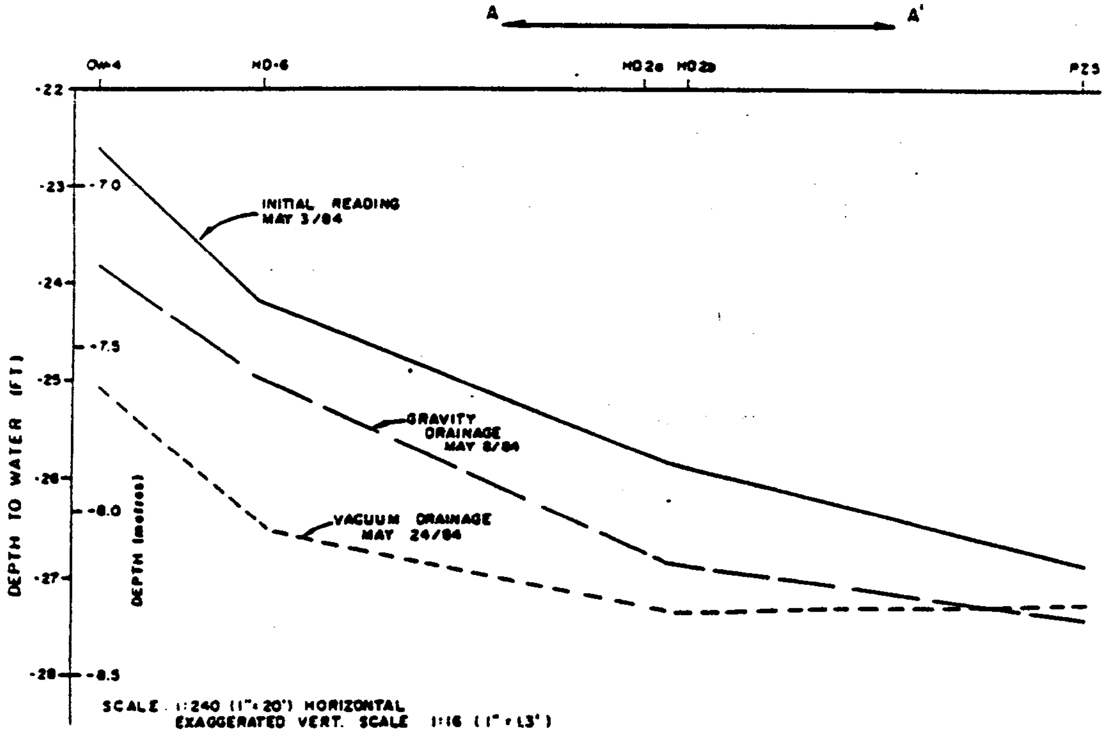


FIGURE 40(b). - Drawdown vs. time - section A-A' (exaggerated scale)

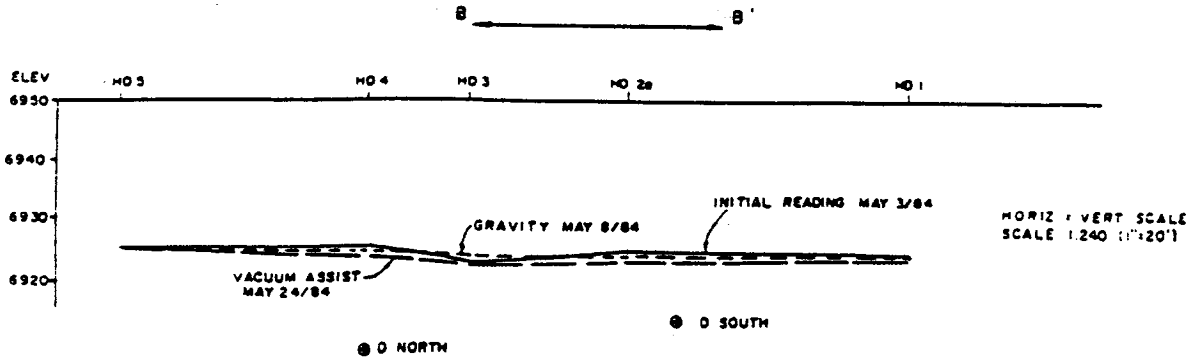


FIGURE 41(a). - Phreatic surface - profile B-B'

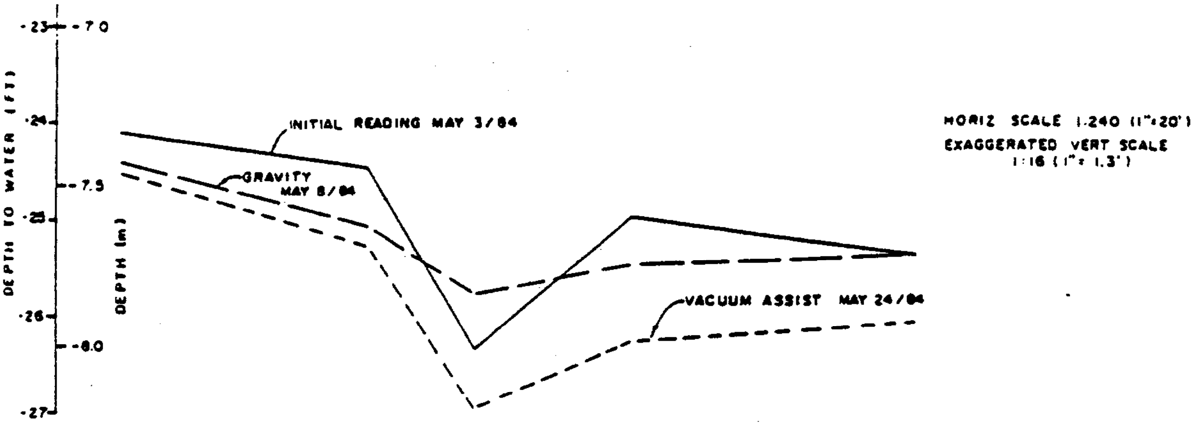


FIGURE 41(b). - Phreatic surface - profile B-B' (exaggerated scale)

COSTS

Typical cost for a large scale horizontal drilling program carried out in similar environment to Gas Hills would be as follows:

- $6-$8/ft (U.S.) of horizontal drain installed. This is an all inclusive cost, i.e., materials plus manpower.
- Cost of mobilization/demobilization of drill rig and personnel to and from the site.
- $1500/mo. (U.S.) for rental of vacuum pump, plus diesel fuel ($30/day) and maintenance.

CONCLUSIONS

The following conclusions apply to the horizontal vacuum drainage system installed at Gas Hills:

- Horizontal drains effectively dewatered and depressurized the tailings.

- High vacuums were achieved.
- Vacuum augmented drains increased the effectiveness of the dewatering system:
  - flow rates doubled
  - increased drawdown (doubled)
- The 12-15 m (40-50 ft) seals were adequate
- Silting of the drains, due to application of the vacuum, did not occur and the drains were functional after the vacuum was removed.
- Vacuum assisted drainage induced flow in drains that exhibited no flow under gravity conditions.
- The system functioned well in an acidic environment, pH = 4.

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APPENDIX A - DETAILED DESCRIPTION OF EQUIPMENT AND TESTING EQUIPMENT AND TEST PROCEDURES

Piezocone System

Jones Piezocone

The dutch cone penetrometer was developed in the 1930s. Its history and that of the electric piezometer probe version are well documented (3, 4, 5). The cone was originally developed for in situ testing in the soft and loose sands and clays that underlie much of the Netherlands. It has since been used in similar soft soils elsewhere. The piezocone used for this project was developed by Messrs. Eben Rust and Gary Jones of Steffen Robertson and Kirsten (Pretoria) South Africa (6) where it has been extensively used to investigate tailings deposits.

The Jones piezocone complies with recommendations of the European Subcommittee (7). The 60 degree cone has a diameter of 37.7 mm; a friction sleeve with an area of 150 cm is located immediately behind the cone (see Figure 6). Between the cone and the friction sleeve is a 5 mm thick, porous, plastic filter disc which transmits pore pressure from the surrounding soil to the chamber which contains the pore pressure transducer. In the cone are voltage regulators, signal conditioners, and amplifiers for the tip and sleeve load cells, and pore water pressure transducers.

Goudsche Pushing Unit

The Goudsche pushing unit was supplied by SRK-DELFT Geotechnics (Canada) Inc. The unit was used to advance both the piezocone and the Delft continuous sampler.

The development of the Goudsche pushing unit paralleled the development of the Dutch cone. The unit used (see Photo A-1) is trailer mounted; has a maximum pushing force of 20 tons provided by hydraulic rams which, in turn, are driven by a diesel engine powered hydraulic pump. The hydraulics are designed to provide a constant pushing head speed of 2 cm/s through varying densities of soil.

Reaction to the pushing force is provided by anchoring the unit with four soil augers; one at each of the corners. A hydraulic "spanner", powered by the pushing unit's hydraulic pump, is used to install the anchors. Because the unit is anchored, the mass of the pushing unit is low, 1300 kg (2860 lbs), but still provides a 20 ton reaction force. The low mass makes it possible to move the unit on fairly soft tailings -- a significant advantage over more conventional equipment.

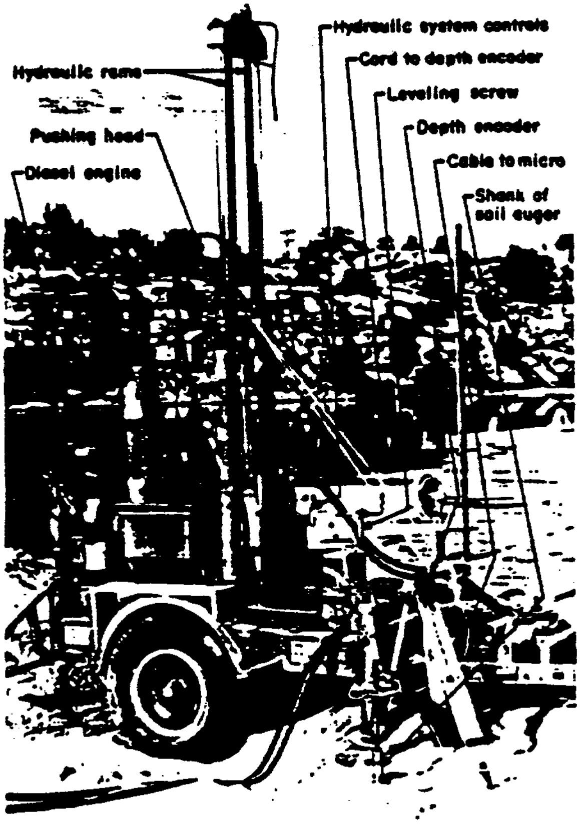


PHOTO A-1. - Goudsche pushing unit

Depth Encoder

The depth encoder was designed and built by Steffen Robertson and Kirsten. It monitors the depth of the piezocone and supplies the information to the control box which routes the information to the strip chart recorder and Sharp Microcomputer. The depth encoder consists of an optical linear encoder connected to the pushing head via a system of cord and pulleys. The encoder rotates at a speed proportional to the rate of downward movement of the cone rods and produces an electrical signal compatible with the electronic strip chart recorder and microcomputer.

Control Box and A.C. Generator

The control box provides electronic connection and conditioning for electronic data capture. Data from the piezocone tip and sleeve load cells, as well as pore pressure transducer, are fed to the control box. Calibration sensitivities for the data can be set on the control box. The data are relayed to the microcomputer for processing, display and disc storage. Electronic signals from the depth encoder are also fed into the control box. This signal is split and routed to the strip chart recorder and Sharp Microcomputer. The control box contains power convertors and voltage regulators for the piezocone.

The A.C. power supplied is converted to D.C. and regulated for the load cells and pressure transducer located in the piezocone.

The power requirements for the whole system are supplied by a lightweight, portable, gasoline driven, A.C. generator.

TOA Strip Chart Recorder

The strip chart recorder used is a two pen model manufactured by TOA Instruments, Japan. It is powered by a 12-volt D.C. source and is used to display, in real time analog, data from the tip load cell and the pore water pressure transducer. The rate of advance of the strip chart is controlled and is proportional to the rate of penetration of the cone measured by the depth encoder.

Sharp Microcomputer

The Sharp Model MZ808 Microcomputer is the central processing unit for the Jones piezocone system. The Sharp Microcomputer is an 8 byte, interactive system with built-in cassette mass storage and full screen monitor, and is programmed in BASIC. It was modified to accept five analog signals and to convert these to digital signals.

The data storage and data handling rates of the Sharp were expanded with the addition of a dual floppy disc drive unit which reads programs on one disc and stores data on the other. The floppy disc storage uses six-inch diameter single density discs, with an access time of 126 bytes/sec. The floppy disc unit is controlled by the Sharp Microcomputer.

Field Testing Procedures

Pushing Unit Set-up

The pushing unit is pulled to sites behind a four-wheel drive pick-up. Once in position, the pushing unit is leveled and anchors are installed at each corner by two men using the hydraulic "spanner" (see Photo A-2). The pushing unit's hydraulic pump powers the hydraulic motor on the "spanner". After set-up, the hydraulic head is checked to make sure it is adjusted to the 2 cm/s downward speed. Set-up of the pushing unit and installation of the anchors takes approximately 45 minutes per probe site.

Electronic System Set-up

While the pushing unit is being anchored, a technician hooks up the electronics. The depth encoder is connected to the ram on the pushing unit by a system of cord and pulleys. The depth encoder is bolted to a surveying tripod and set off to the side of the pushing unit.

PHOTO A-2. - Hydraulic spanner being used for anchor installation

The end of the electric cable from the piezocone is connected to the control box which holds the connections for the power line from the generator and the hookup from the depth encoder and Sharp Microcomputer. All electronic systems are kept in the back of the support vehicle. Once the electronics are connected, the recording technician verifies that the cone is working, initializes the floppy disc with the pertinent data (data, project name and number, probe number) and takes initial readings.

Sounding Procedure

Once the equipment is set up, probing begins. The steps involved are:

- The probe is attached to a cone connection rod. The rod is 0.75 m long so that when the probe is added, the total length is 1 m. In addition, the connecting rod has a 5 mm wide by 5 mm thick ring welded above the piezocone portion. This ring causes an enlargement of the probe hole above the piezocone, thereby reducing the friction of the soil on the rods.

- The porous plastic filter ring is saturated by boiling for 10 minutes and stored in de-aired water. It is installed on the probe by unscrewing the conical tip and placing the filter behind the tip. To prevent air entrapment in the probe the probe is placed in a bucket of de-aired water and a syringe is used to force de-aired water into the cavity and passages. The filter ring is positioned and the conical tip screwed into position. New filter rings are used for each probing.

- The lead section of rod is then placed under the head of the pushing unit. The pushing unit, operated by a two man crew, pushes the lead section at the specified rate of 2 cm/s.

- Rods are added by screwing the bottom of the upper rod into the top of the lower rod. It takes 50 seconds to push the rod one meter and approximately 30-45 seconds to add the next rod. The electric cable is threaded through the rods (see Photo A-3), which are placed on a rack ready for adding as the test progresses.

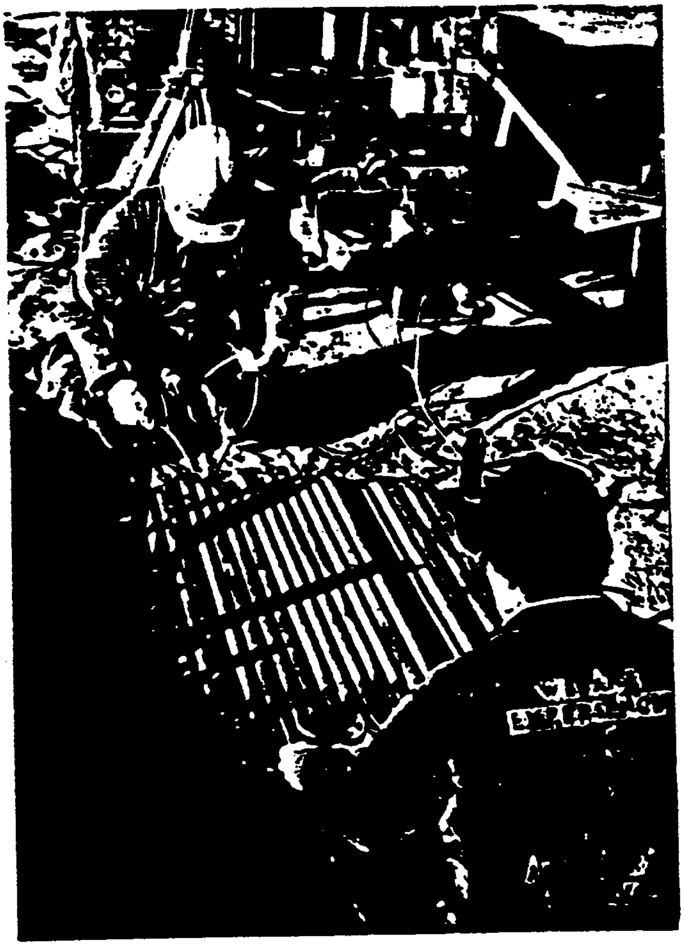


PHOTO A-3. - Piezometer extension rods with threaded cable

- During probing, the recording technician monitors the electronic signals. The computer software is designed to interact with the operator and after each meter of penetration, the microcomputer prompts the operator about probing information. The technician monitors the real time display of data on the microcomputer monitor and strip chart in order to develop an understanding of the material type and consistency of the materials being probed. Depths at which dissipation tests are conducted are selected after examination of these data.

- Once the gravels of the foundation soils are encountered, the probing is terminated and the rods retracted one by one with the aid of a "pulling dog" attached to the hydraulic head. The "pulling dog" slips over the rods without interfering with the electric cable.

- The electronic recording devices are left on during the removal of the rods so that a final set of readings can be taken once the probe is back on the surface. This final set of readings are compared with the initial set to check for electronic drift in the load cells and transducer. Corrections for drift are made when necessary.

- Once the probe is back on the surface and final readings have been taken, the equipment is moved to the next location. The time required to set up the equipment, probe 30 m (without dissipation tests), remove rods, and get ready to move is approximately 2.5 hours.

Delft 66 mm Continuous Sampler

The Delft continuous sampler was supplied by the Delft Soil Mechanics Laboratory, Delft, Netherlands, through SRK-DELFT Geotechnics of Calgary, Alberta. The equipment was operated by a senior field technician from Delft Laboratories.

The sampler (see Figure 6b) was developed because of the difficulties Delft Laboratories had with traditional samplers (Osterberg, Swedish Foil, Shelby tube, etc.) (8). The soils of the Netherlands are recent geologic deposits of sands and silts with the water table at, or just below, the ground surface in most of western Netherlands. Traditional geotechnical drilling and sampling introduced excessive sample disturbance and poor recovery.

These difficulties in sampling wet, loose, recent sedimentary soils is very similar to the problems encountered when drilling and sampling in tailings.

The mechanics and operating principles and procedures of the Delft 66 mm Continuous Sampler is next described.

- The sampler is advanced by pushing with the Goudsche pushing unit. The sample enters the cutting shoe on the bottom of the sampler.

- Once the sample has entered the sampler, it is encased in a pre-coated nylon stocking. The stocking is designed to expand diametrically but not along its length. The stocking is also impermeable to prevent the flow of moisture in or out of the sample.

- The soil encased in the stocking is surrounded by a lubricating fluid. This fluid has two purposes: to lubricate the movement of the stocking against the P.V.C. liner and to provide a restraining horizontal pressure on the soil. The lubricating fluid is a mixture of water, bentonite, barite, and lime, with a unit weight that matches that of the tailings (approximately 16 kN/m3). The lubricating fluid is introduced at the surface into the annulus between the steel outer casing and the P.V.C. liner. The fluid flows out through a number of holes at the base of the tube and enters the narrow gap between the nylon stocking and the P.V.C. liner. The width of the gap is so small that it comes within the tolerance of 0.5 to 1 percent of the sample radius recommended internationally for taking undisturbed samples.

- The top of the nylon stocking is connected by a thin wire cable through the center of the tubes, to a spring measuring scale which connects to the frame of the pushing unit. The wire and scale monitor the tension in the nylon stocking. Readings on the scale of over 25 kg indicate excessive friction between the nylon stocking and P.V.C. liner and sampling is then stopped. This prevents damage to the nylon stocking and also induced stresses and deformation of the sample.

- The pushing unit drives the sampler into the soil by pushing down on the outer steel casing which is extendable by one meter lengths. Inside the steel casing is the P.V.C. liner insert which also extends in 1 m lengths.

- Initial retraction of the sampler causes "cam-like fingers" to automatically pinch the P.V.C. liner just above the sampler head and prevents loss of the sample. The "fingers" are approximately 50 cm from the bottom of the sampler.

- Extraction of the samples is achieved by lifting the casing in one-meter increments and unscrewing and removing the outer steel casing to expose the inner P.V.C. liner. The P.V.C. liners are unscrewed, the stocking and soil cut at the joint, and protective end caps screwed on.

- The tubes are stored and transported in the vertical position.

GEMS Tailings Drill

The Tailings Drill is a portable, hydraulically driven specialty drill rig. It is divided into three portable parts (see Photo A-4). These are:

- Gas engine and hydraulic motor;
- Drilling head; and
- Lifting mechanism.

PHOTO A-4. - GEMS tailing drill

A 10 H.P. gasoline engine provides the energy for the hydraulic pump. This unit has handles at both ends for carrying.

The hydraulic pump drives the hydraulic motor on the hand-held drilling head. The drilling head rotates the auger. The auger consists of two parts, an inner auger that draws materials up into the 1.5 inch diameter casing and the casing which protects the sampled material. Unique aspects of the system are that the inner auger and the outer casing rotate in opposite directions so that there is little torque on the hand-held drilling head. Rotation of the casing also reduces friction on the casing, facilitating penetration.

Drilling and sampling are done in one meter increments. The auger is withdrawn from the hole after each one meter advance and the tailings are extruded, logged and samples taken and labelled. Lifting and lowering of the light weight aluminum rods is achieved with a set of six-inch diameter hydraulically driven hard rubber wheels through which the rods are inserted. With this mechanism it is possible to pull up to ninety feet of rods in less than three minutes.

Cambridge Drive-in Piezometers

The installation process of the Cambridge drive-in piezometers (see figure 6c and photo A-5) involved the following steps:

PHOTO A-5. - Cambridge drive-in piezometer

- o The strata into which the piezometer is to be installed, and consequently the "tip" depth, are determined from the piezocone logs. These logs served both to identify the strata in which significant pore pressures exist and the nature of the materials in the various strata.

- If necessary, a hole is pre-drilled using a tailings drill to a depth of 3 m (10 ft) above the proposed "tip" depth.
- The Cambridge drive-in piezometer with 19 mm (3/4 in) diameter galvanized pipe additions is driven to the desired depth with a fence post driver.
- After installation, the piezometer tube is filled with water and an inner mandrel rod 12 mm (1/2 in) diameter rod in 1.5 or 3 m (5 or 10 ft) sections is inserted. The mandrel rod is gently driven exactly 150 mm; this pushes the piezometer tip shield down to expose the 150 mm long by 18 mm diameter porous plastic filter. The mandrel rods are removed and piezometers left to stabilize.

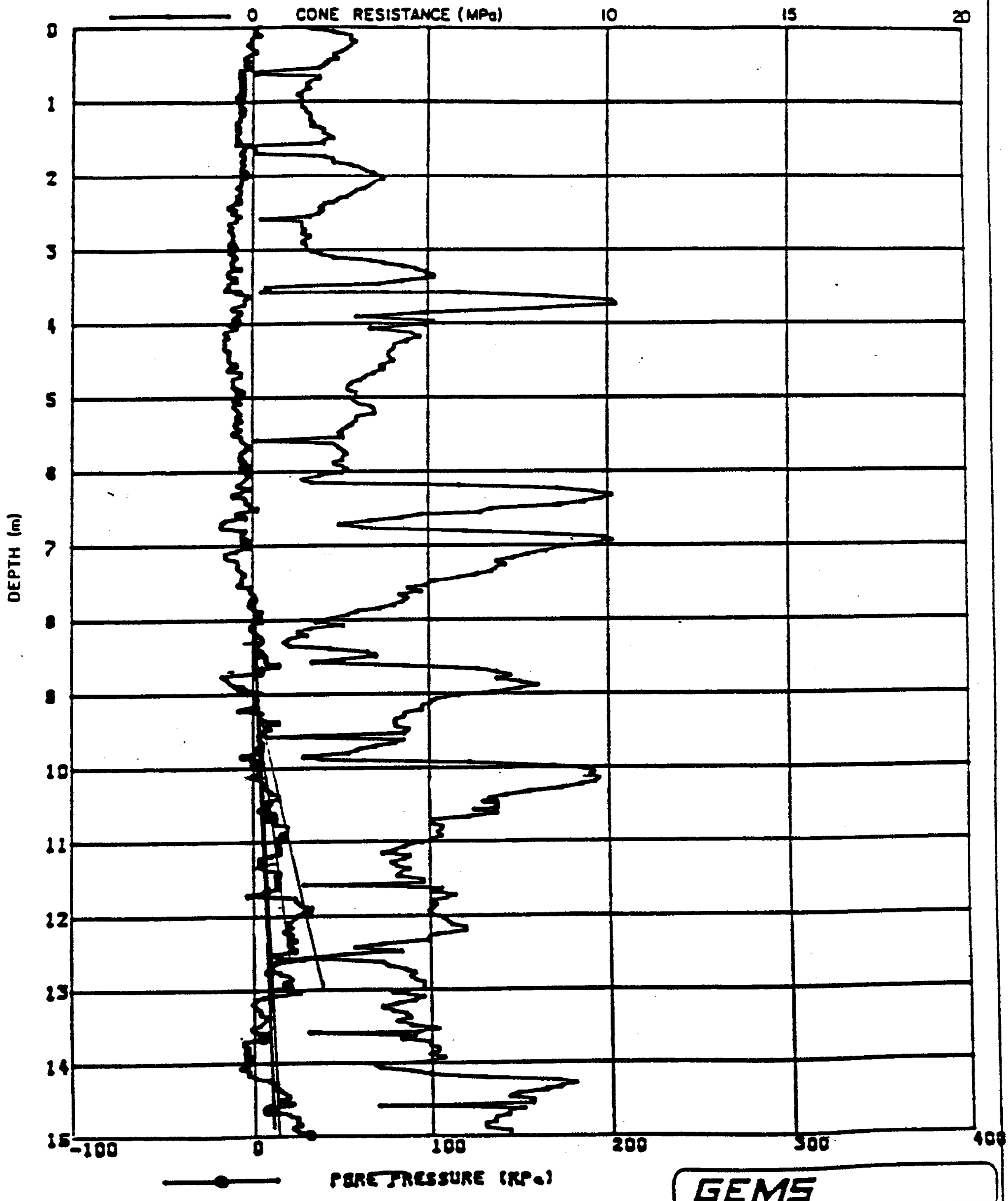
APPENDIX B

COMPLETE PIEZOCONE TEST RESULTS

PIEZO PROBE PENETRATION TEST

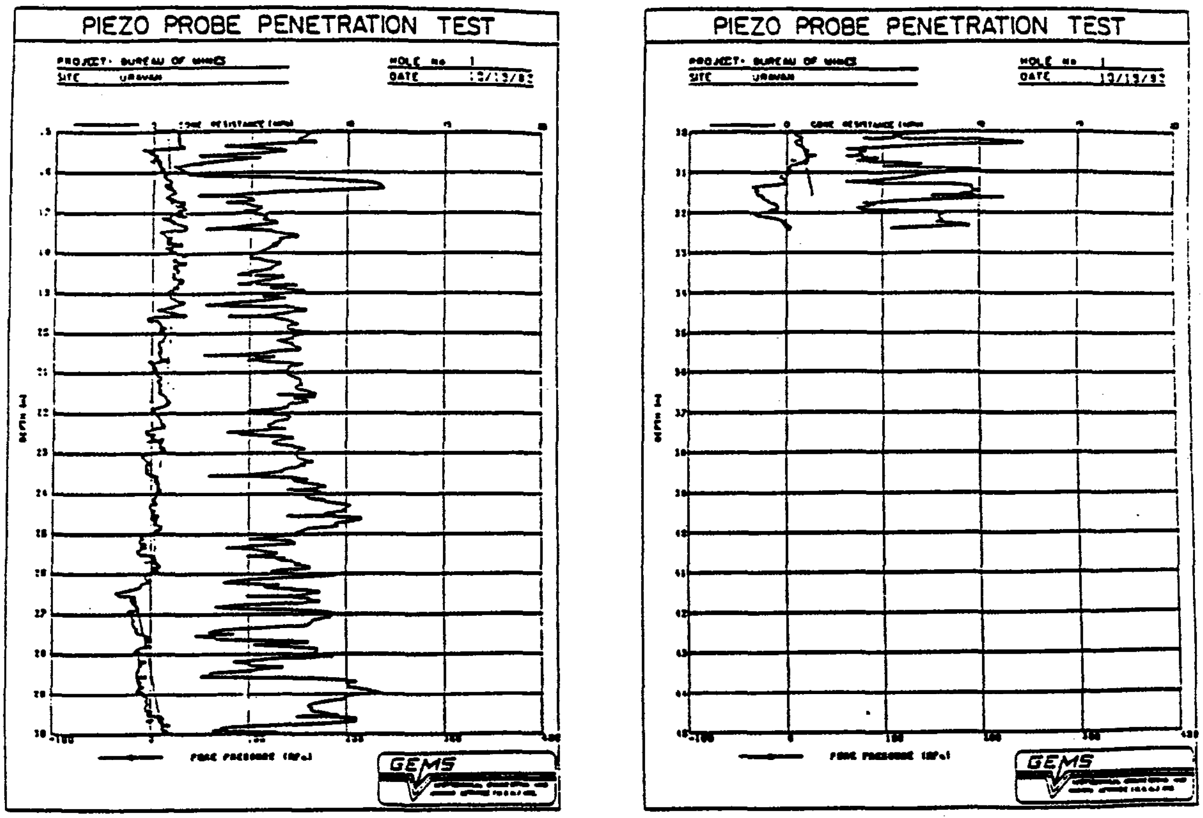
PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 1
DATE 10/13/82



B1(a). - Detail of first 15 m of piezoprobe test P-1 showing cone point resistance and pore pressure

GEMS
GEOTECHNICAL ENGINEERING AND MINING SERVICE (U.S.A.) INC.

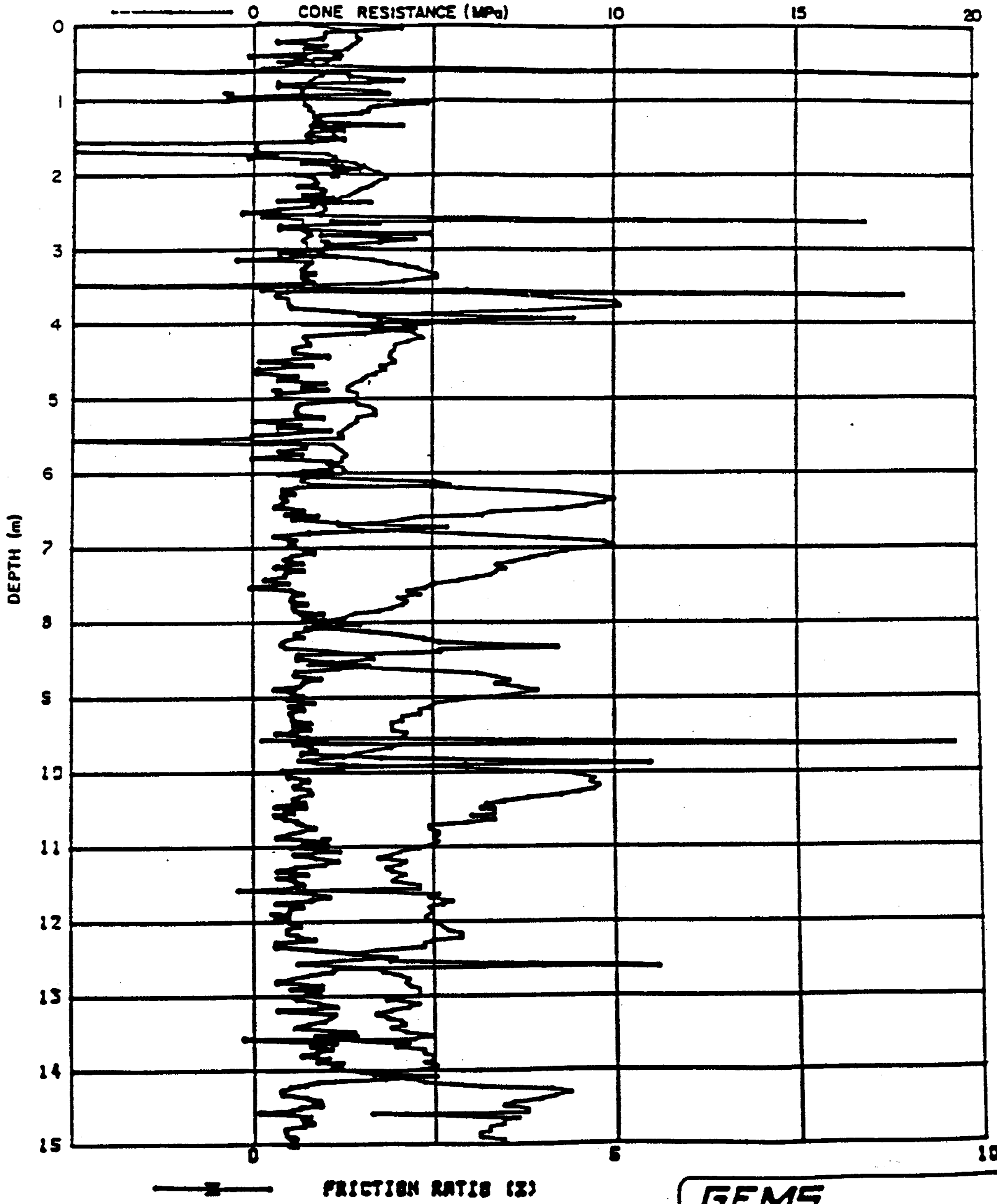


B1(b). - Piezoprobe test P-1 showing cone resistance and pore pressure

PIEZO PROBE PENETRATION TEST

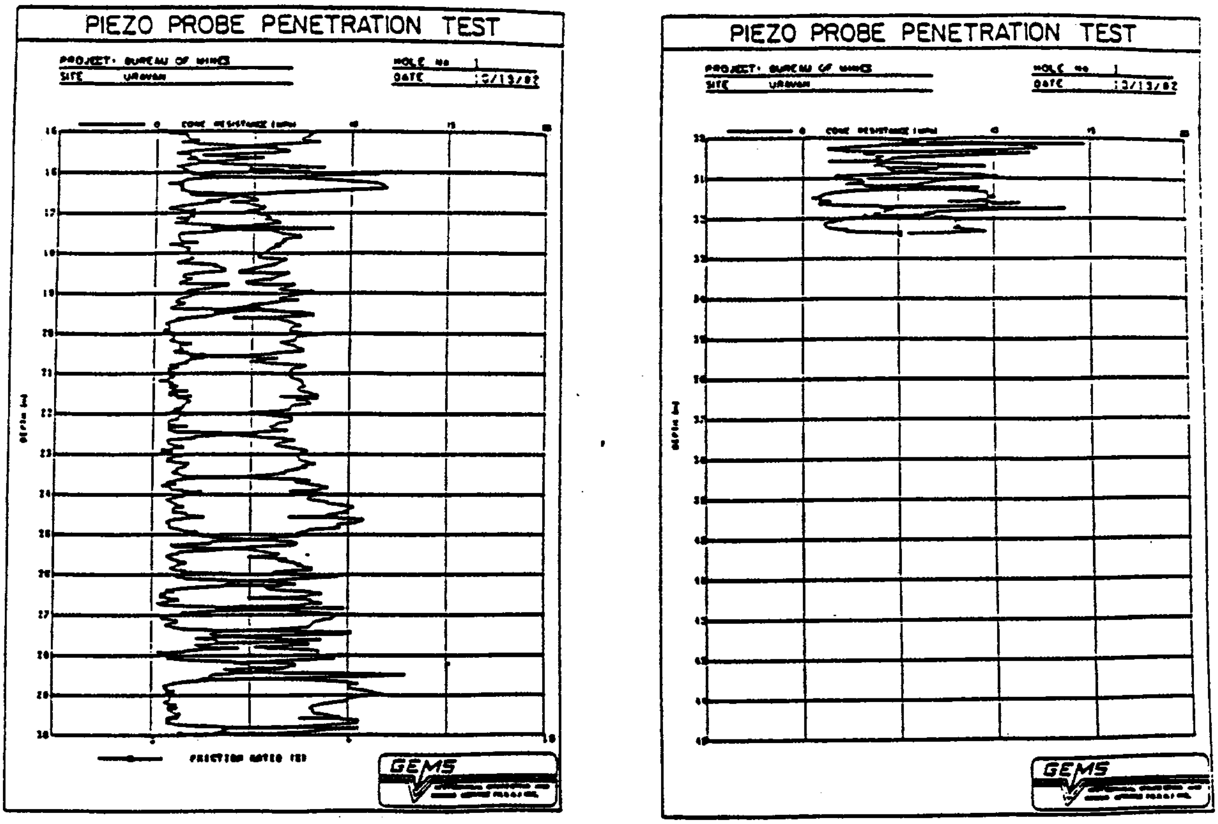
PROJECT: BUREAU OF MINES
SITE URAVAN

HOLE No. 1
DATE 10/19/82

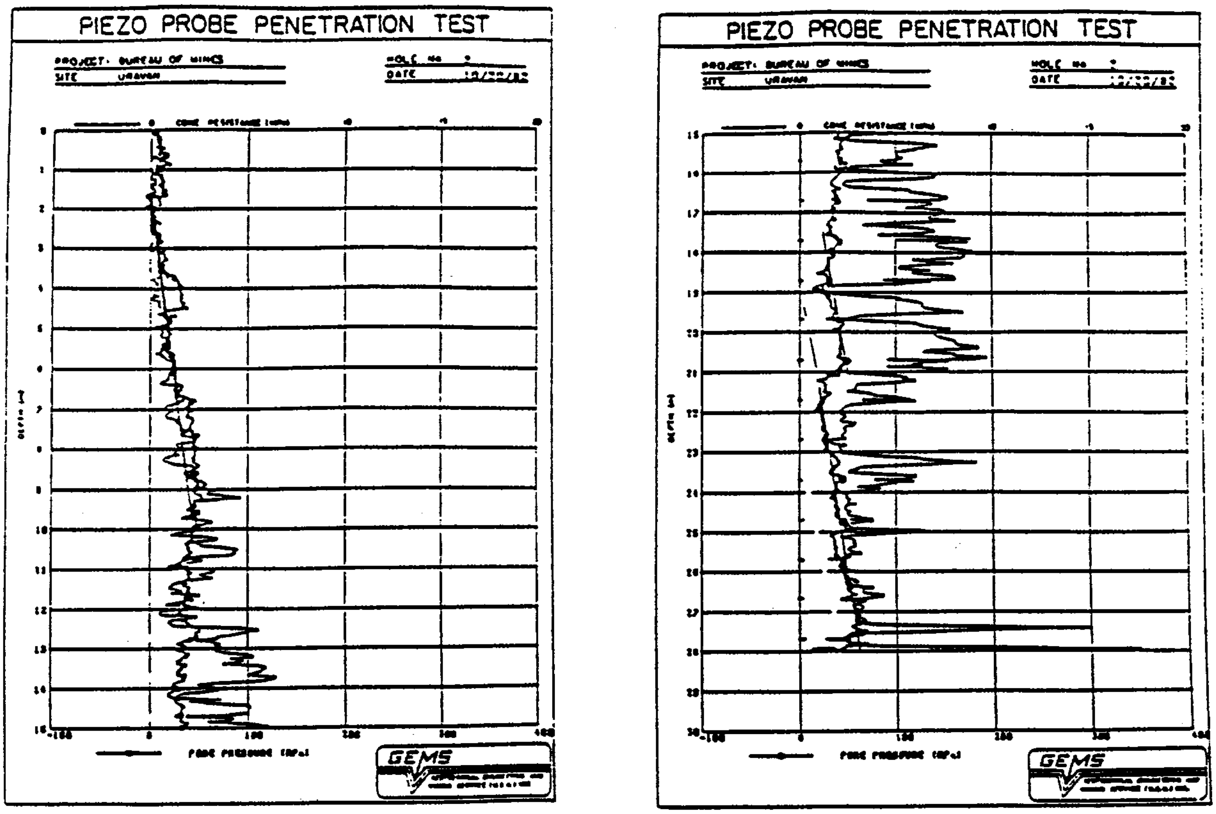


B2(a). - Detail of first 15 m of piezoprobe test P-1 showing cone point resistance and friction ratio

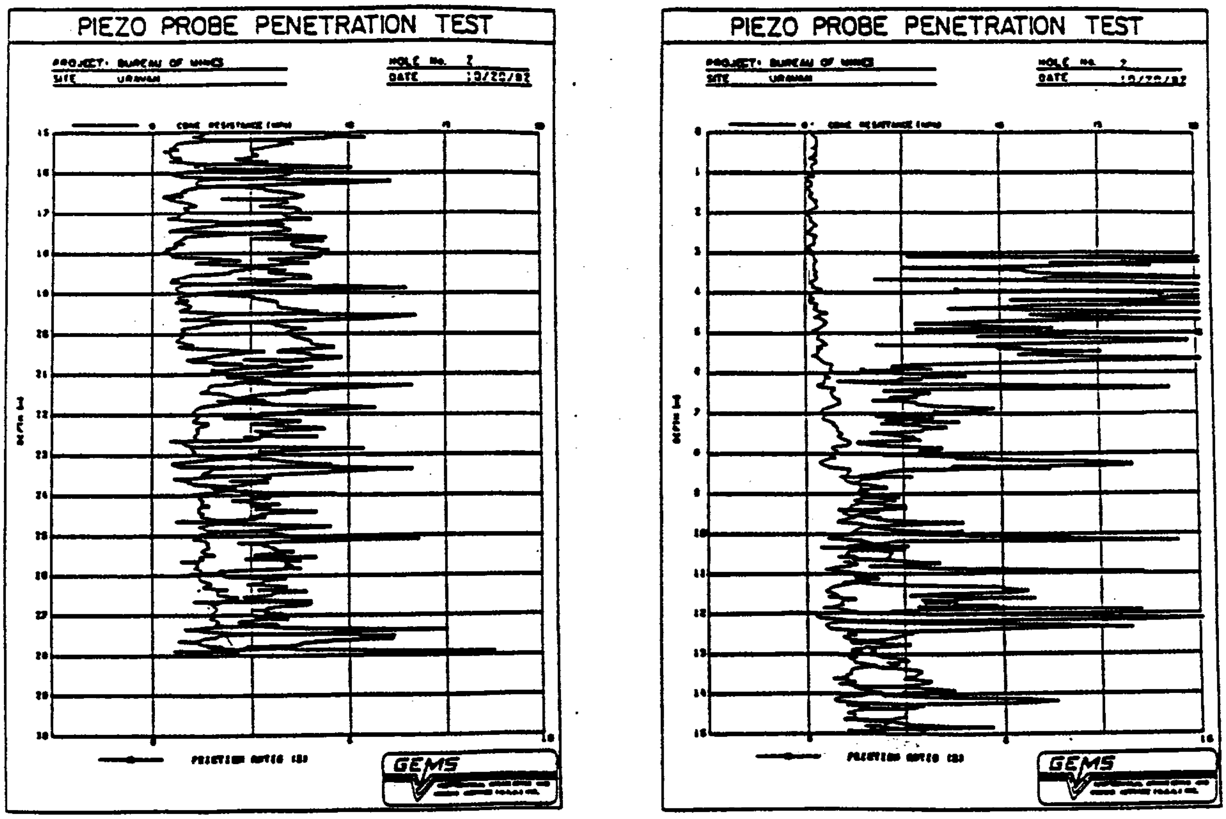
GEMS
GEOTECHNICAL ENGINEERING AND MINING SERVICE (U.S.A.) INC.



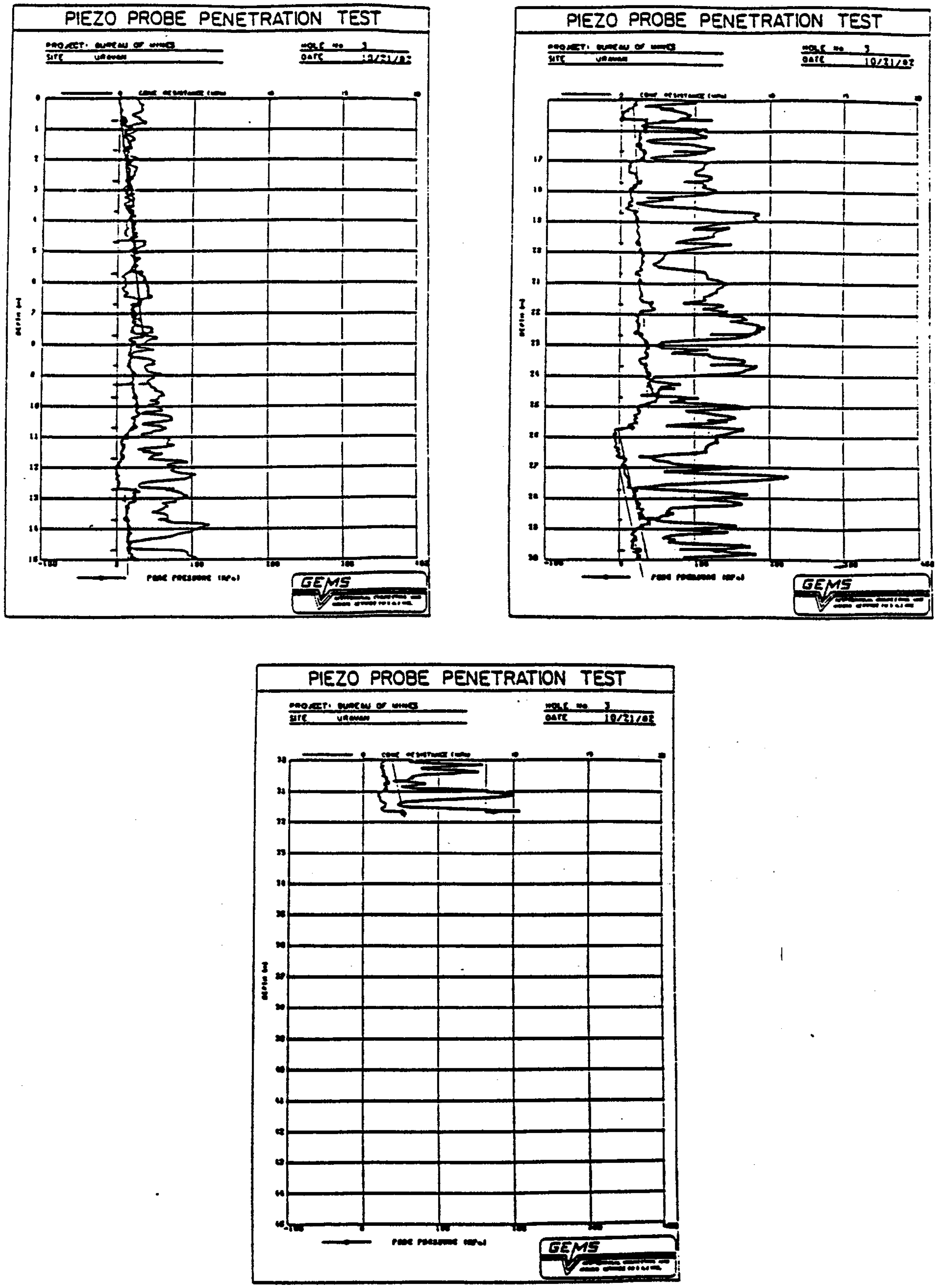
B2(b). - Piezoprobe test P-1 showing cone resistance and friction ratio



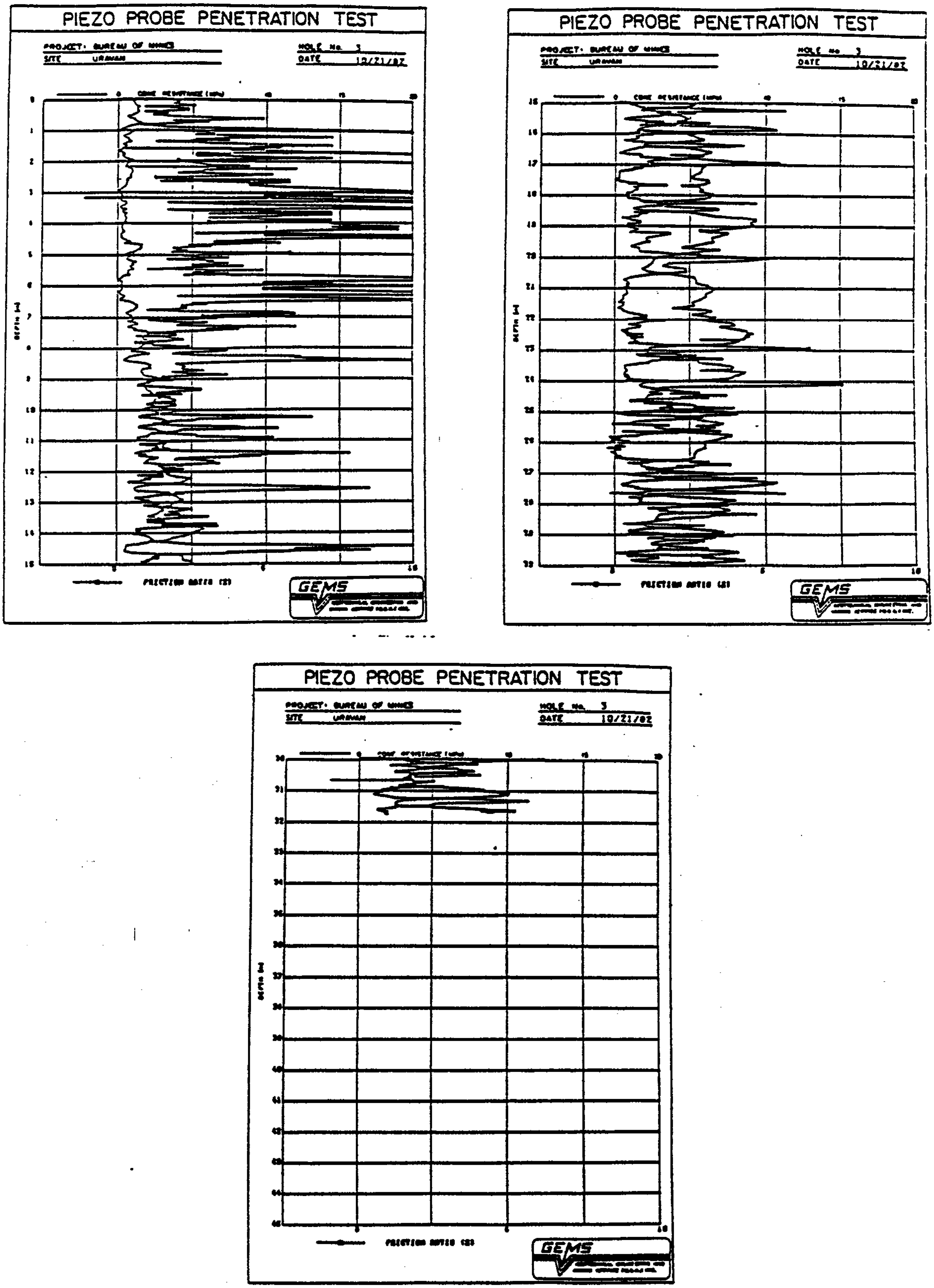
B3. - Piezoprobe test P-2 showing cone resistance and pore pressure



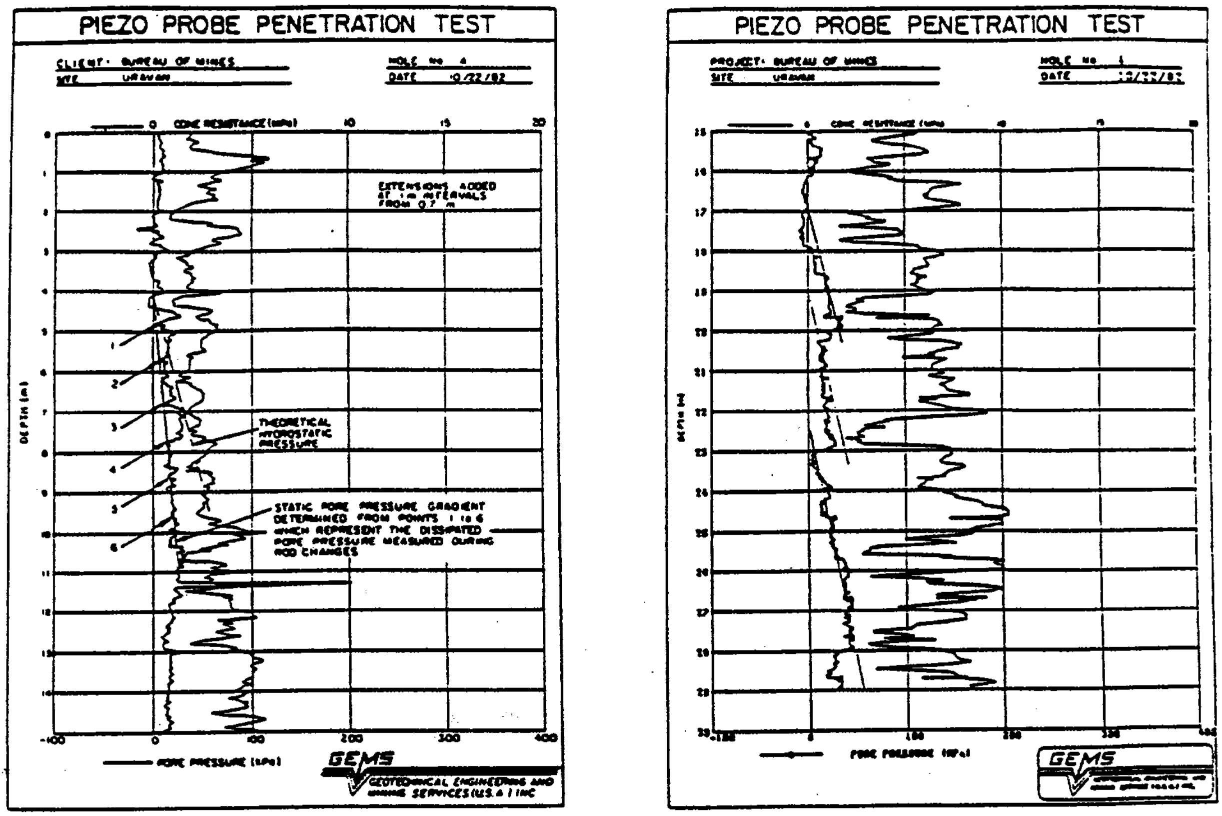
B4. - Piezoprobe test P-2 showing cone resistance and friction ratio



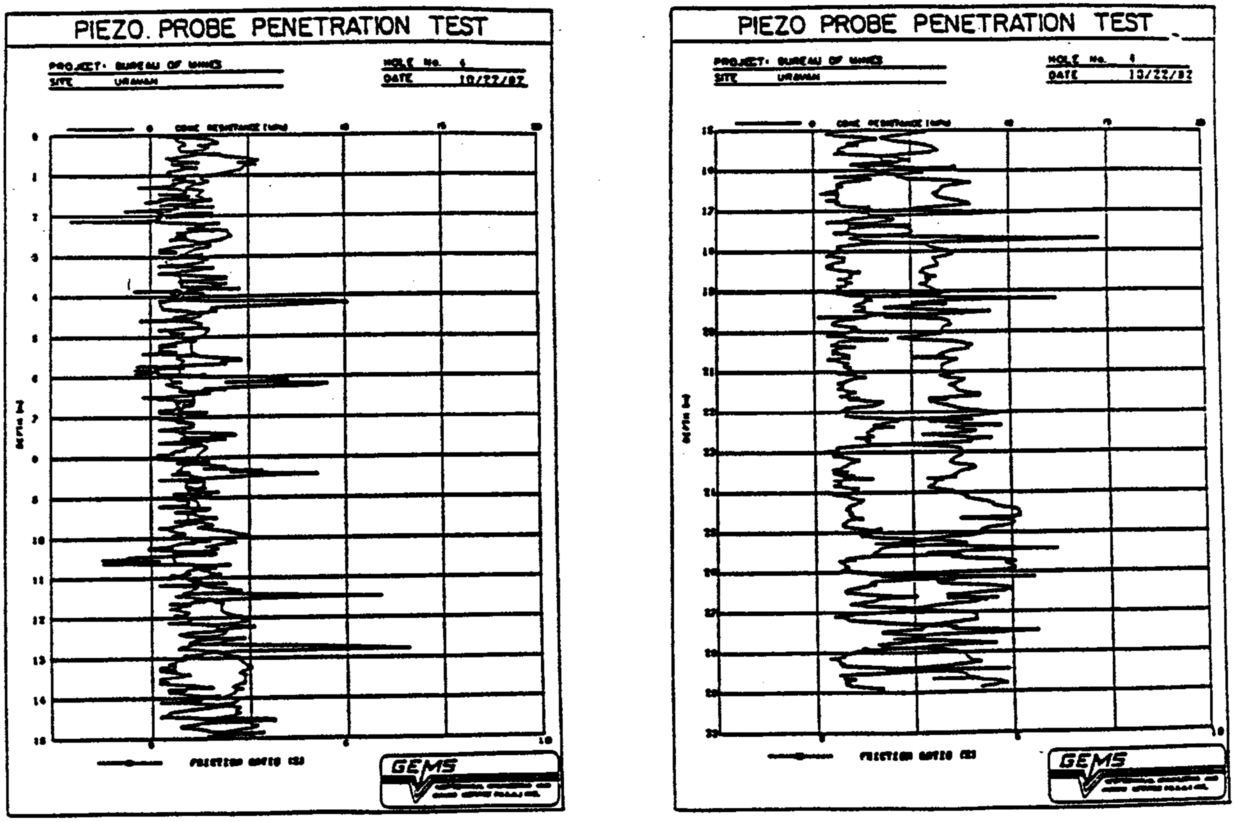
B5. - Piezoprobe test P-3 showing cone resistance and pore pressure



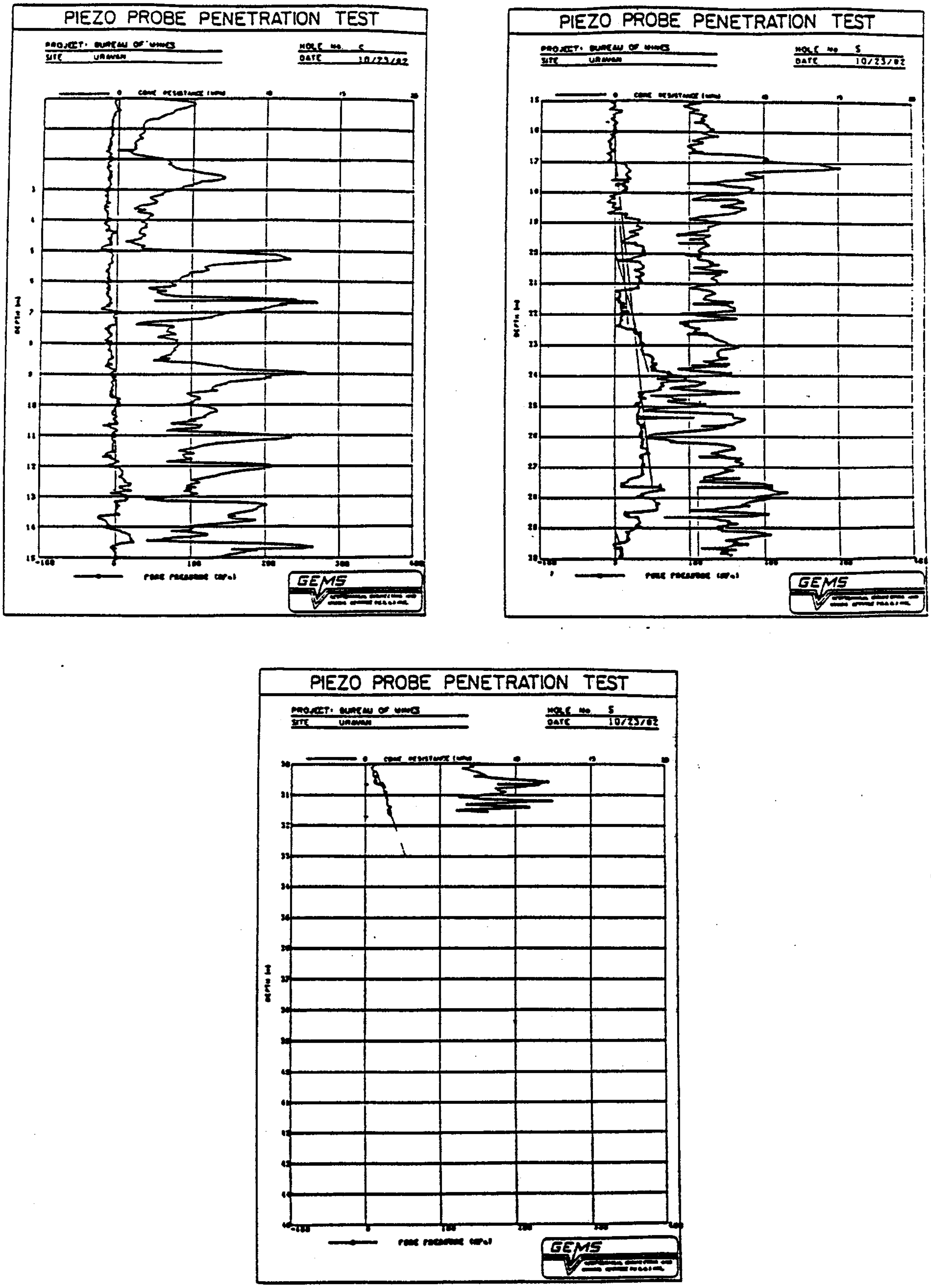
B6. - Piezoprobe test P-3 showing cone resistance and friction ratio



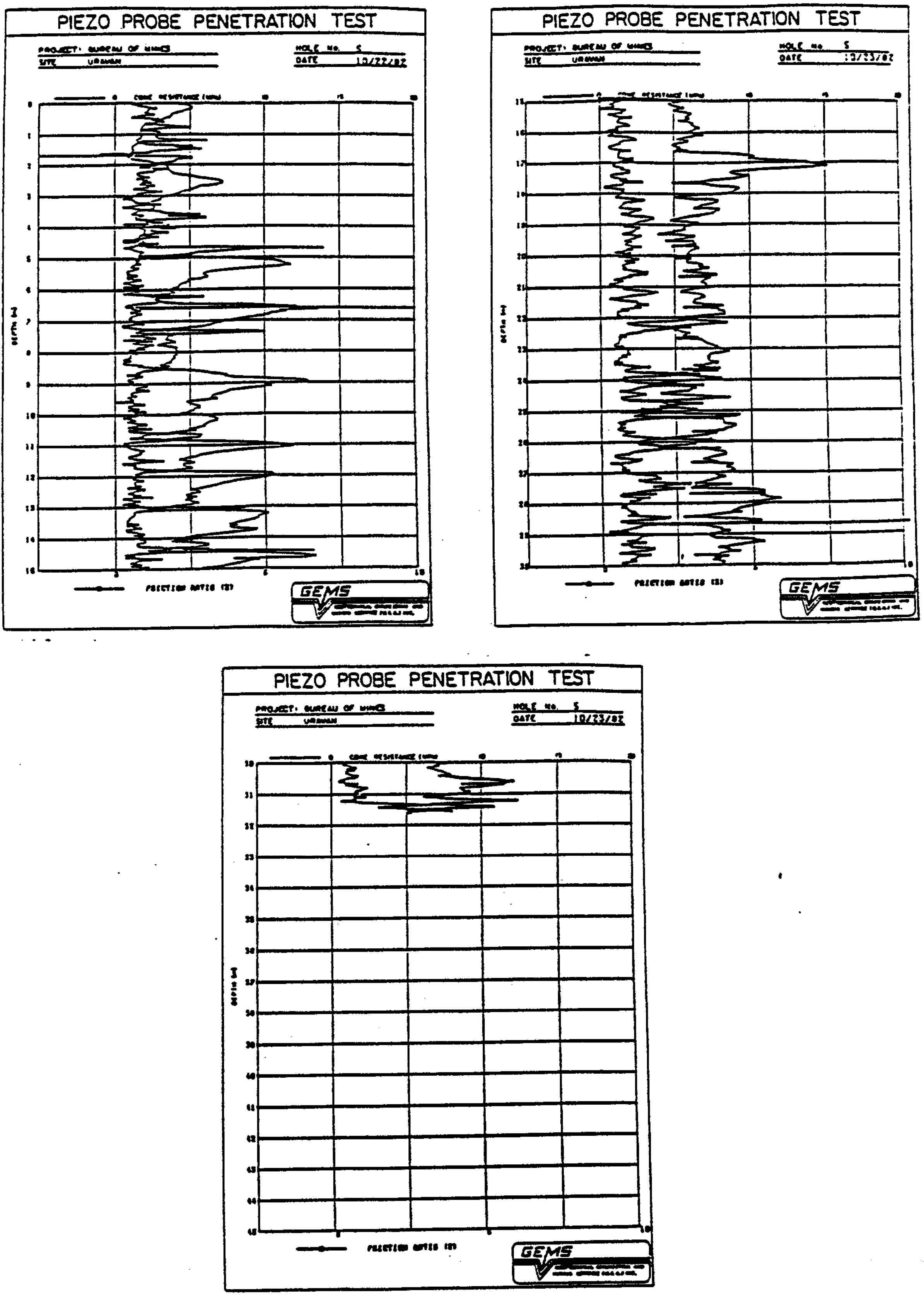
B7. - Piezoprobe test P-4 showing cone resistance and pore pressure



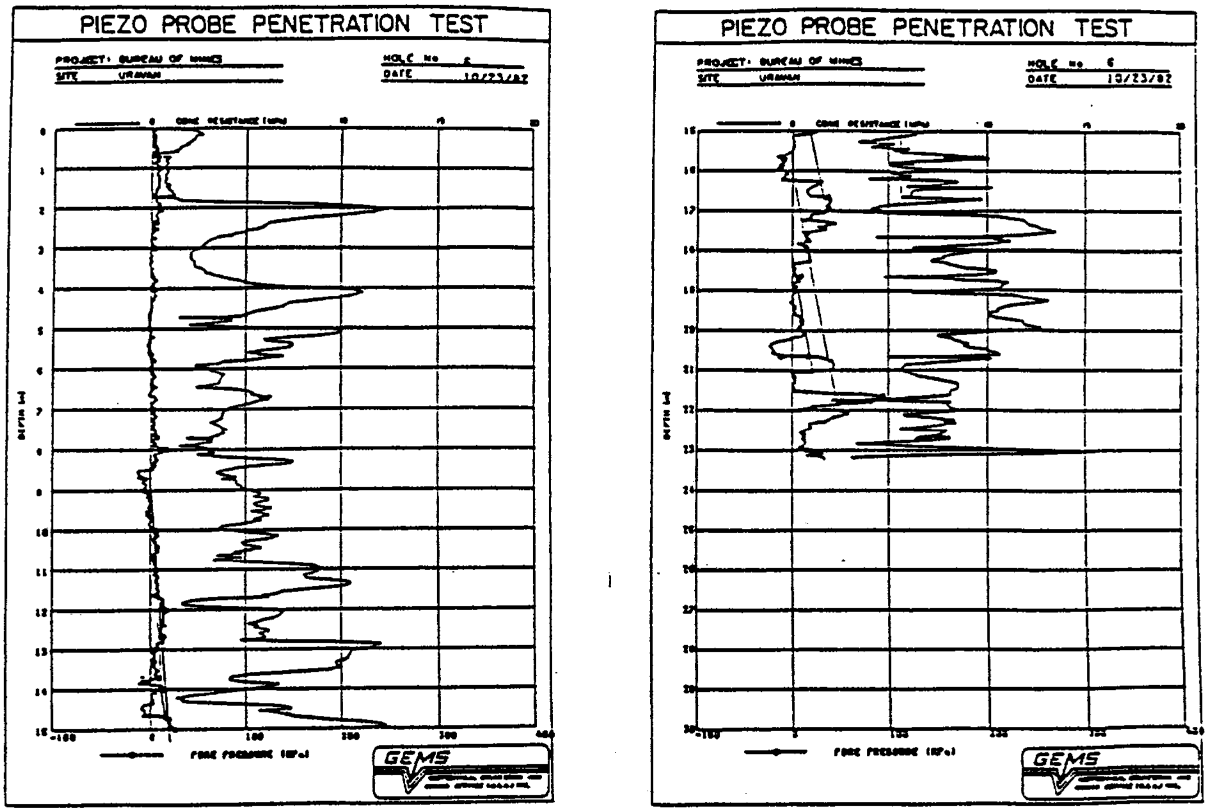
B8. - Piezoprobe test P-4 showing cone resistance and friction ratio



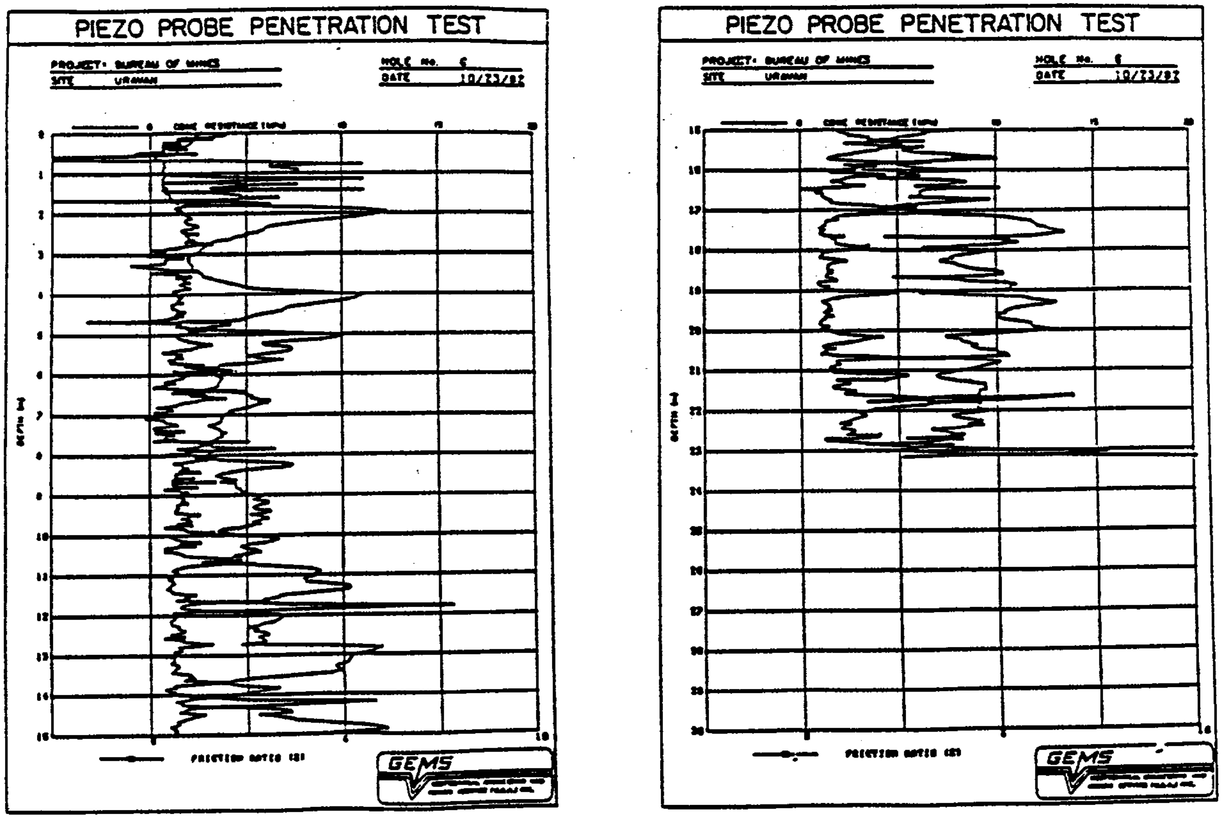
B9. - Piezoprobe test P-5 showing cone resistance and pore pressure



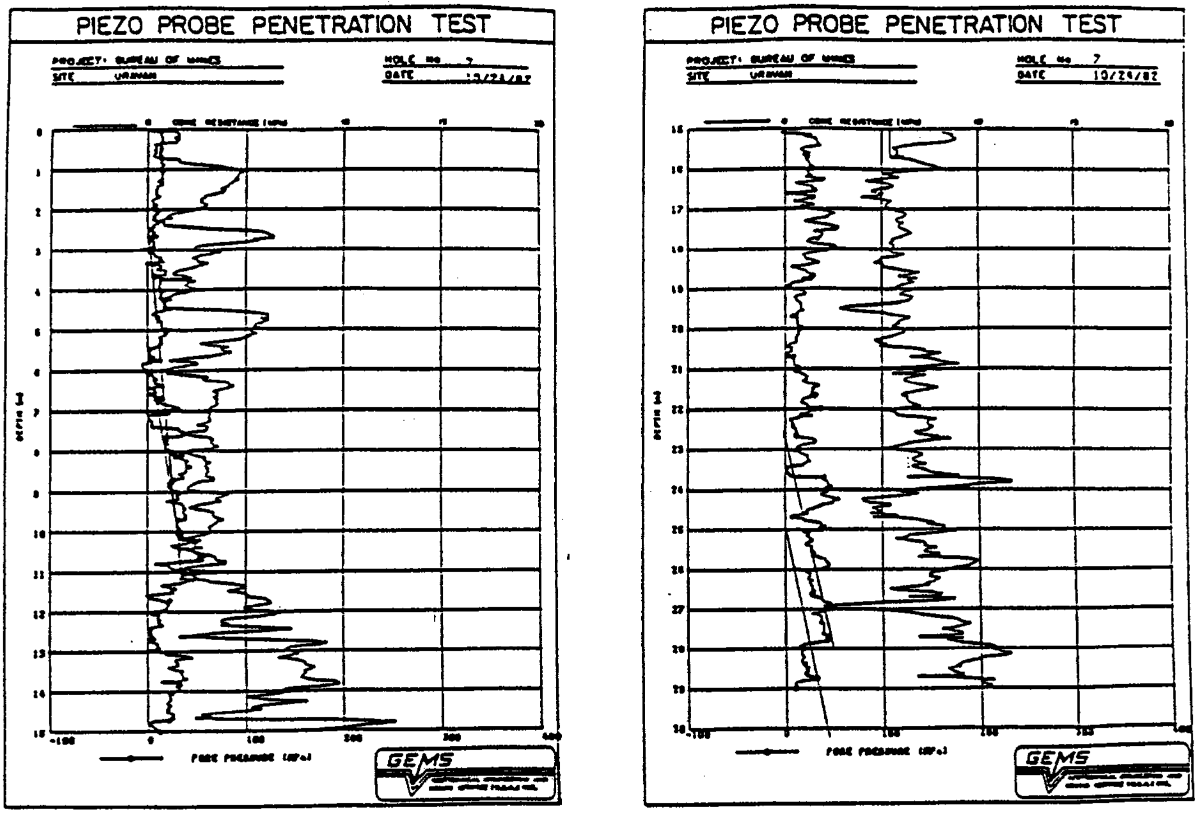
B10. - Piezoprobe test P-5 showing cone resistance and friction ratio



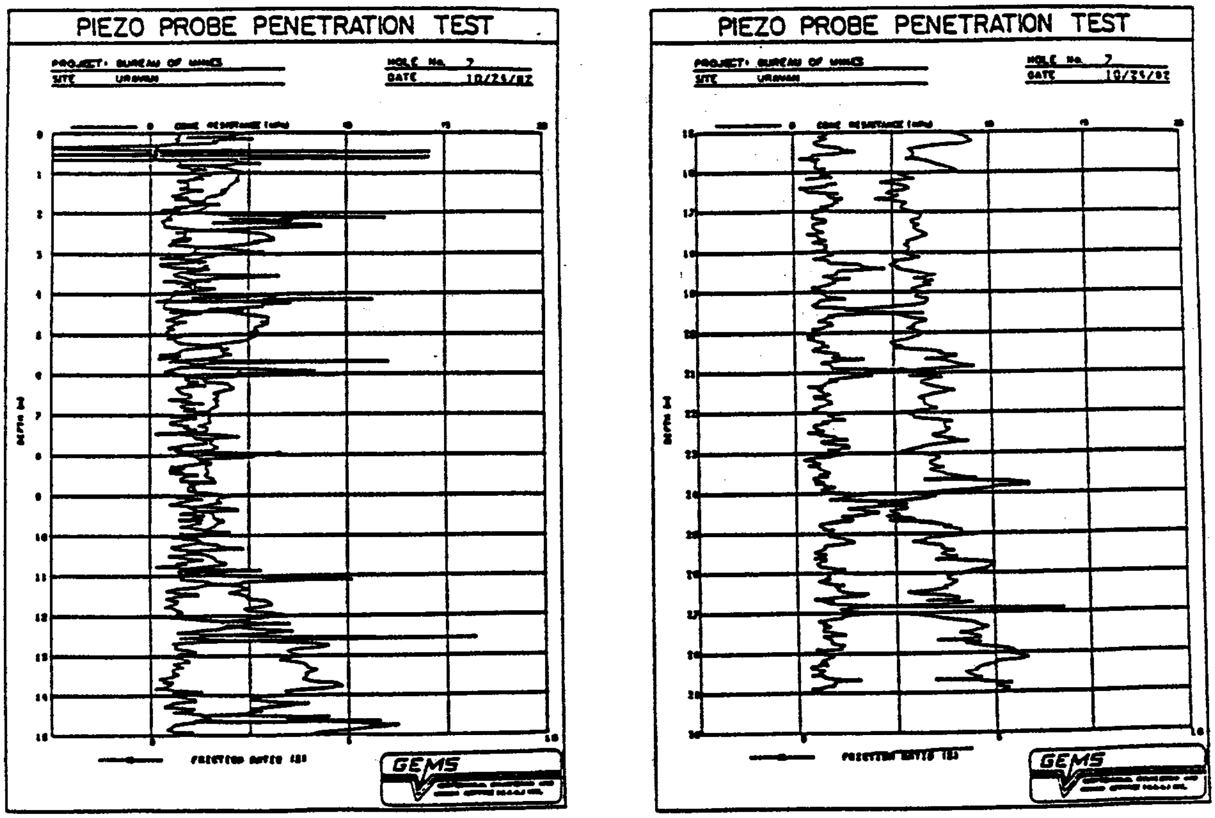
B11. - Piezoprobe test P-6 showing cone resistance and pore pressure



B12. - Piezoprobe test P-6 showing cone resistance and friction ratio



B13. - Piezoprobe test P-7 showing cone resistance and pore pressure



B14. - Piezoprobe test P-7 showing cone resistance and friction ratio

PHOTOGRAPHS OF CONTINUOUS SAMPLER CORE

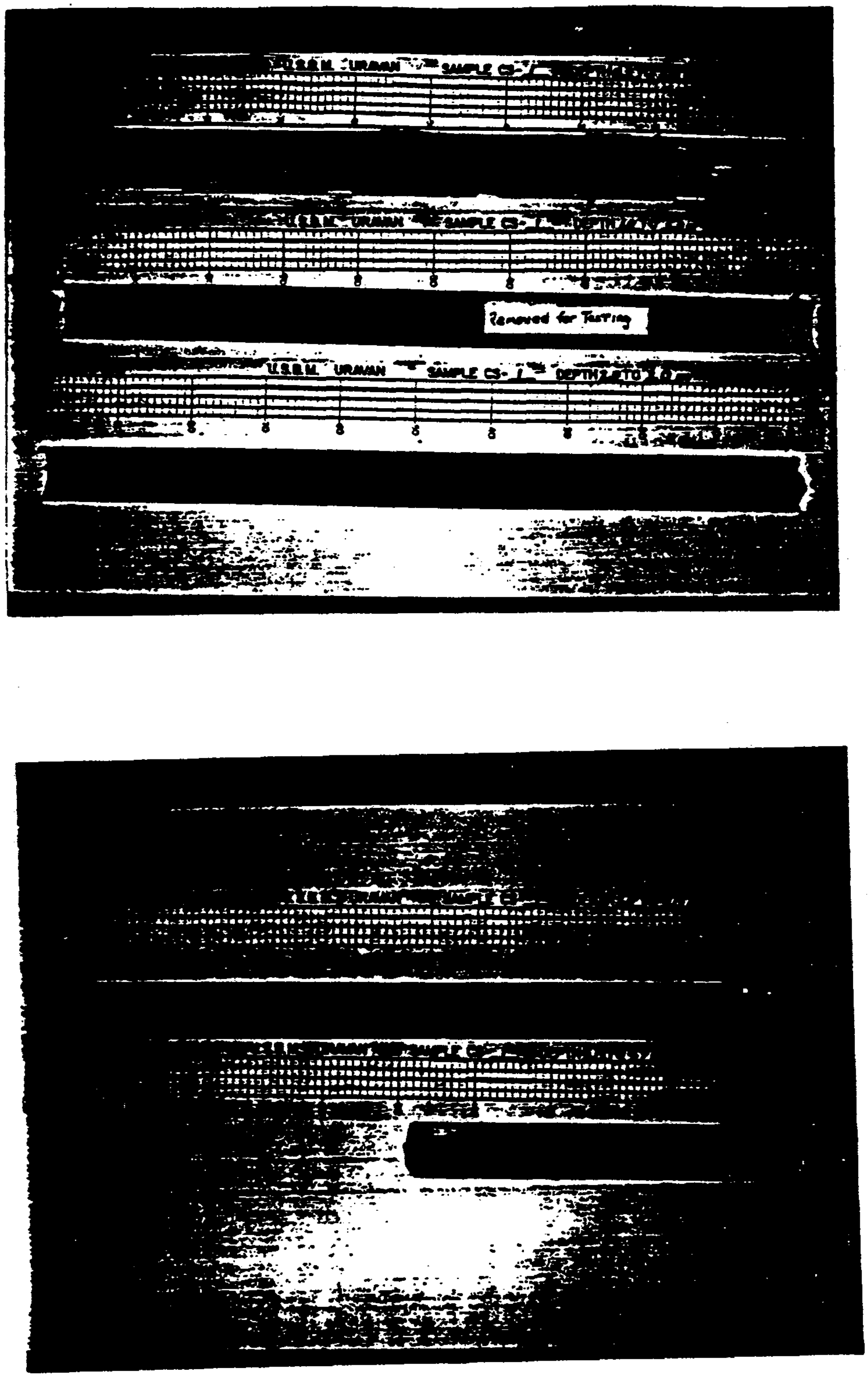


Photo C-1 Continuous sample CS-1 from 0 to 4.7 m.

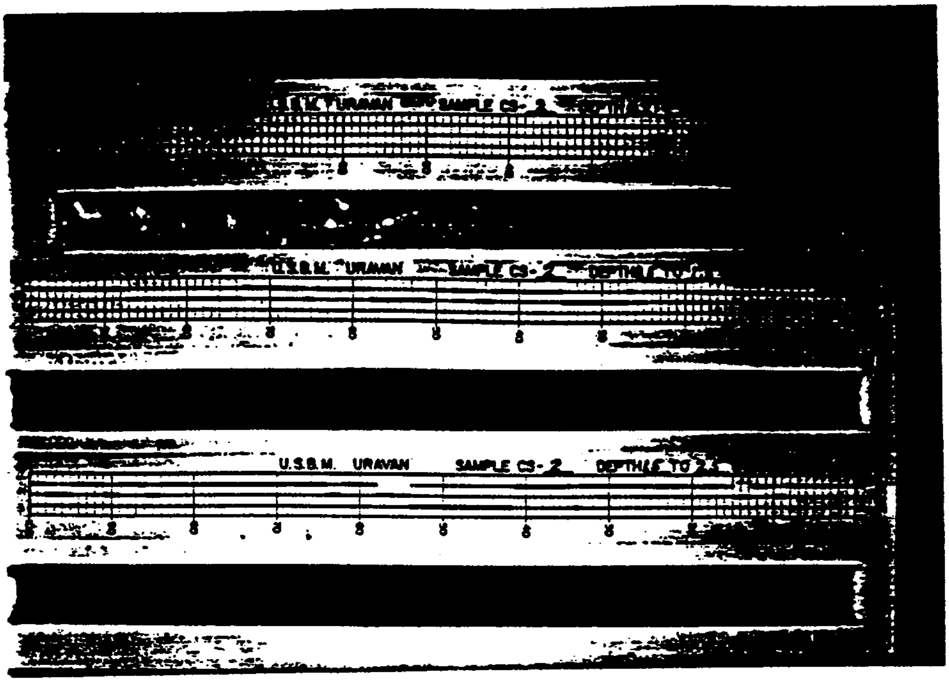


PHOTO TO BE ADDED

Photo C-2 Continuous sample CS-2 from 0 to 5.5 m.

PHOTO TO BE ADDED

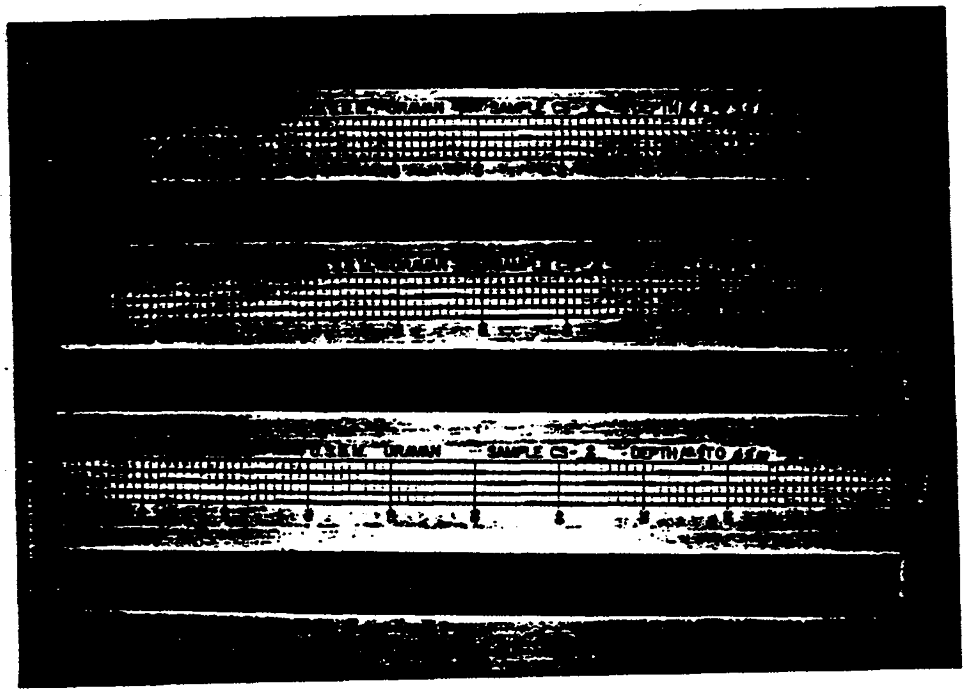


Photo C-3 Continuous sample CS-2 from 5.5 to 11.5 m.

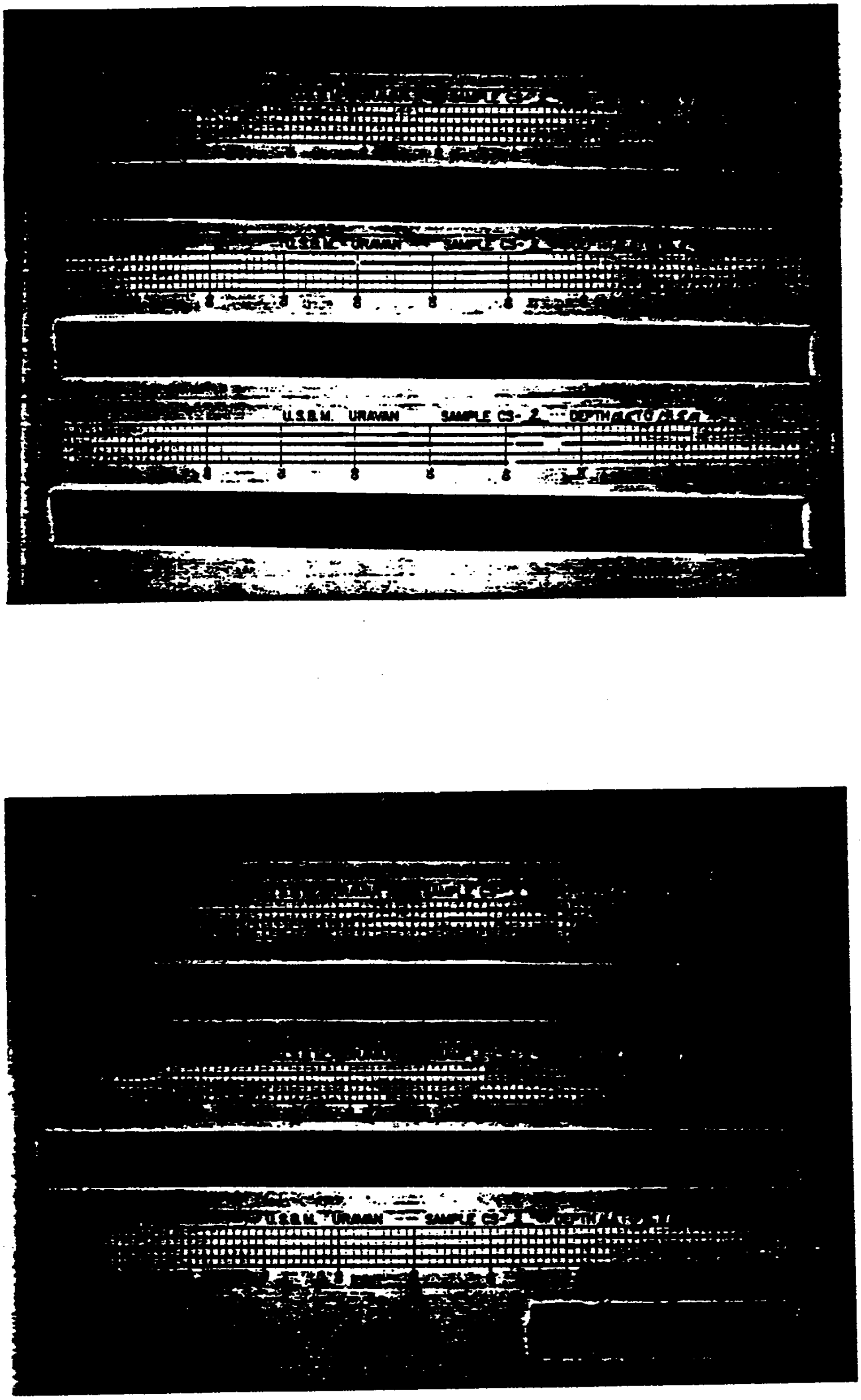


Photo C-4 Continuous sample CS-2 from 11.5 to 16.8 m.

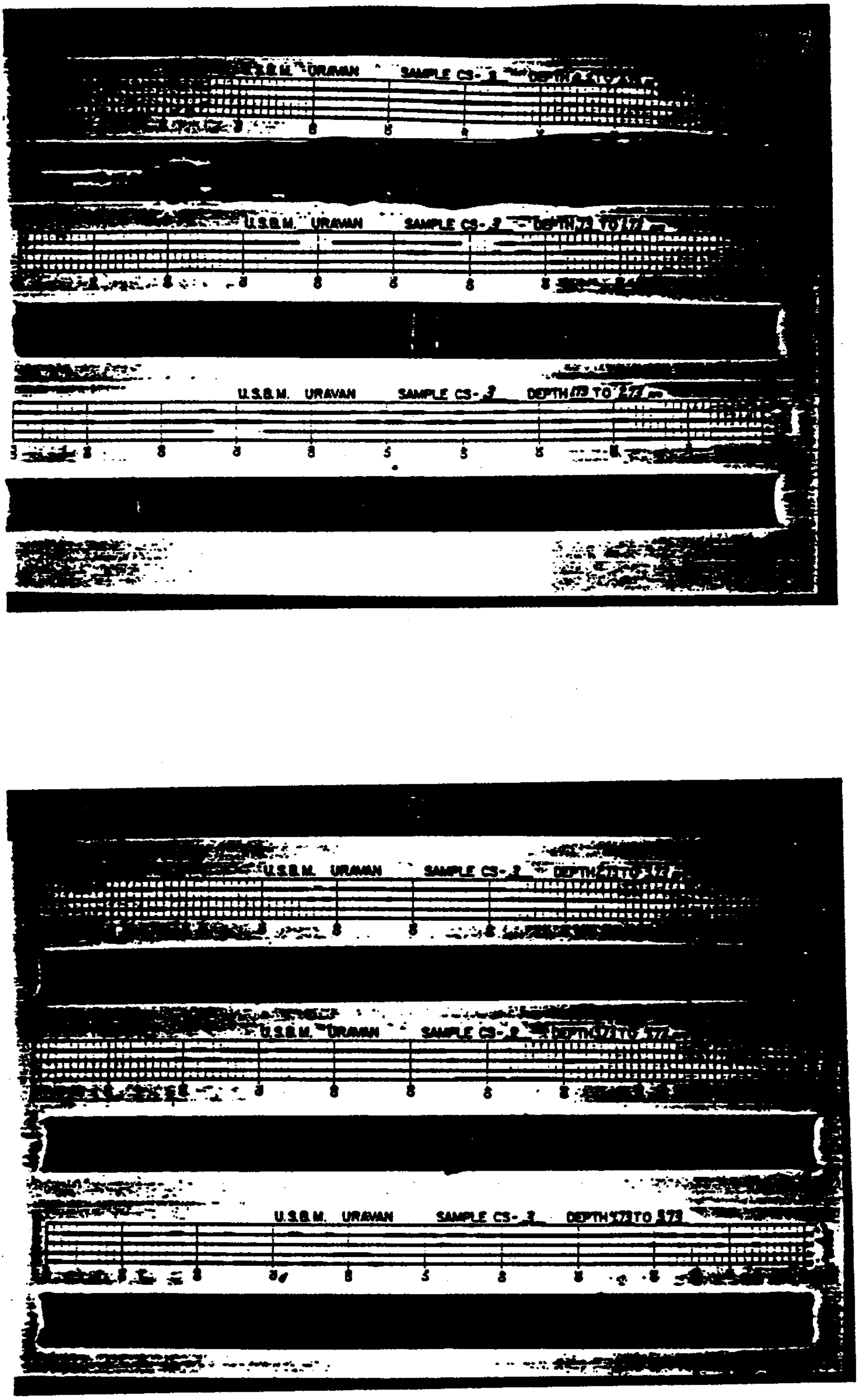


Photo C-5 Continuous sample CS-3 from 0 to 5.73 m.

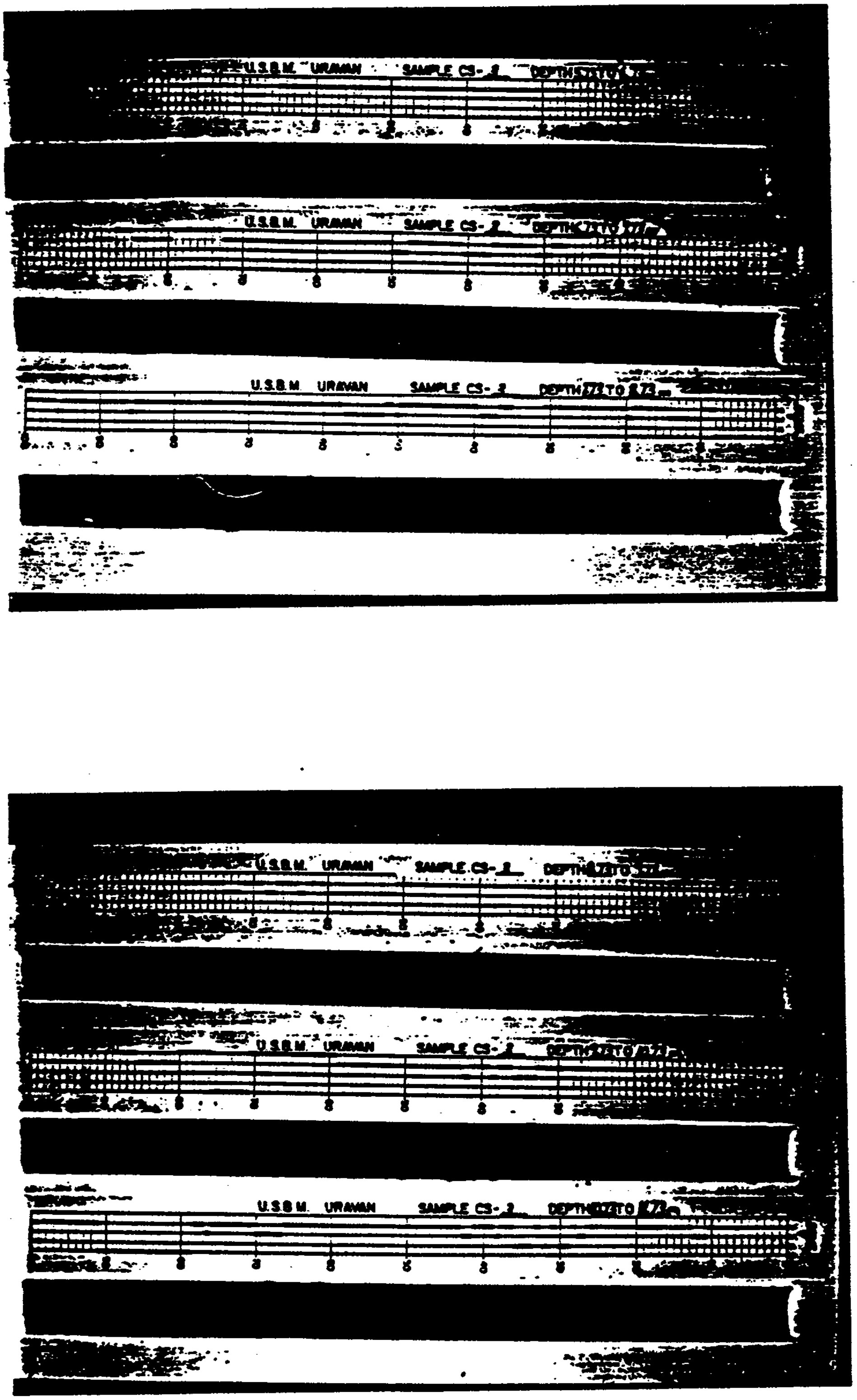
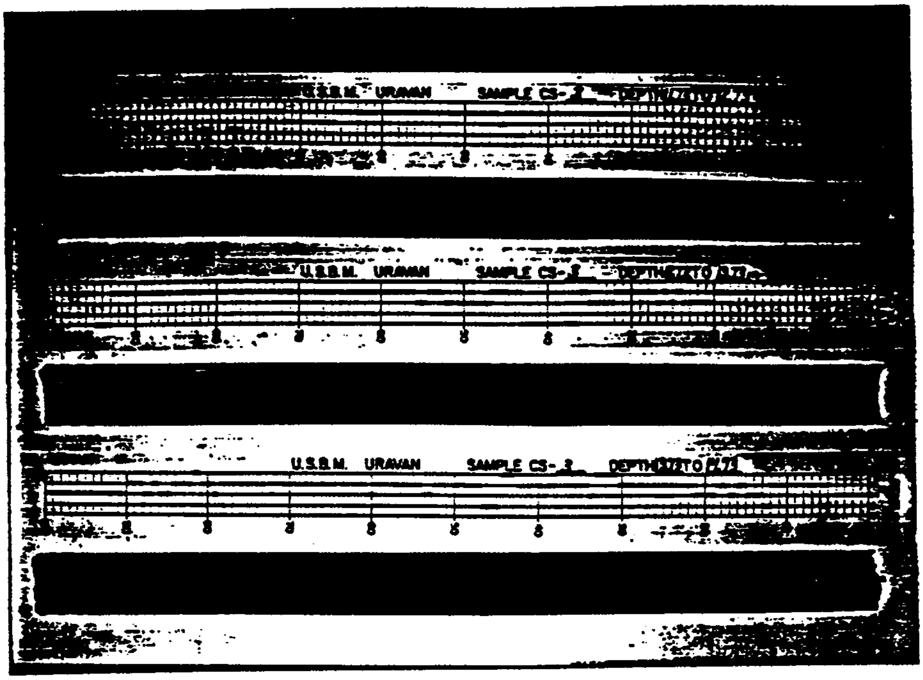


Photo C-6 Continuous sample CS-3 from 5.73 to 11.73 m.



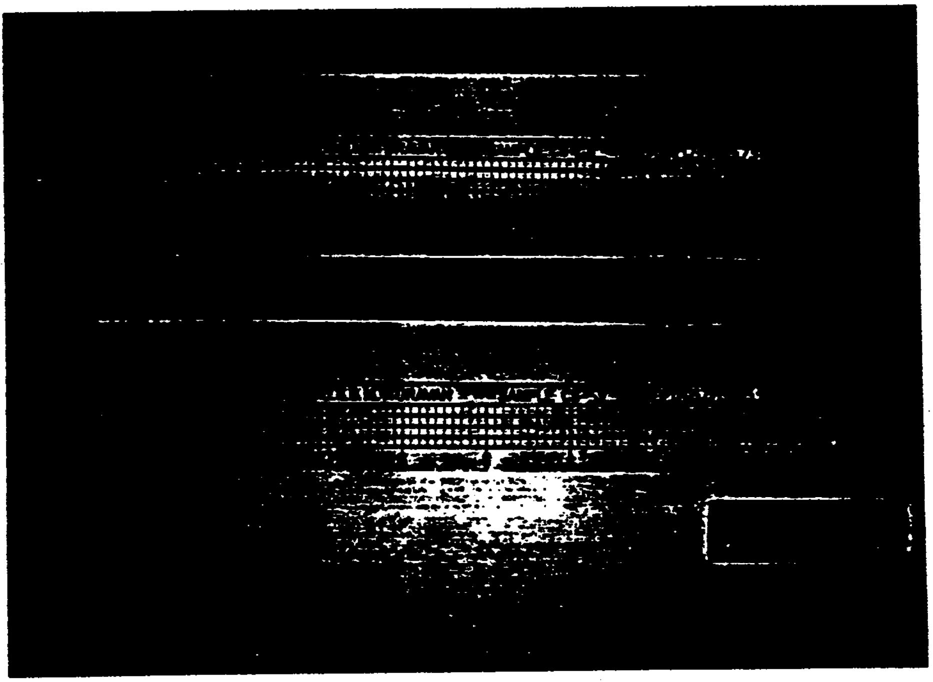


Photo C-7 Continuous sample CS-3 from 11.73 to 15.93 m.

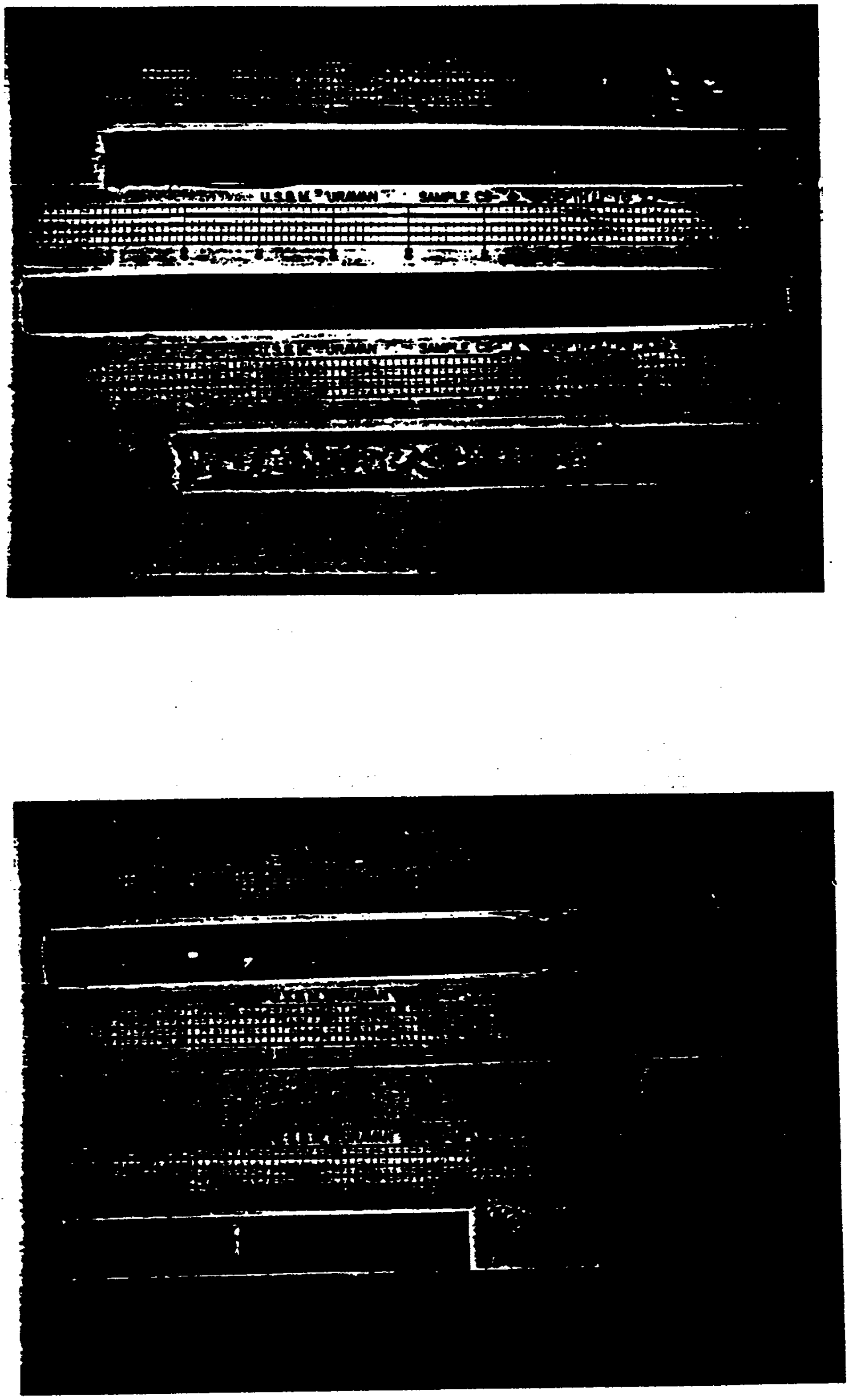


Photo C-8 Continuous sample CS-4 from 0 to 4.98 m.

APPENDIX D

COMPLETE LABORATORY TEST RESULTS

TABLE OF CONTENTS

Tests by University of Colorado

Tests By SRK-Denver

TABLE D1. - Water contents and in situ effective stress

Sample	w_o (%)	w_f (%)	σ' (kN/m^2)
Test No. 1, Material Type 4, CS-2, 11.715-11.745 m	37.4	46	104.8
Test No. 2, Material Type 5, CS-2, 11.135-11.220 m	50.7	54.3	85
Test No. 3, Material Type 5, CS-3, 13.095-13.160 m	29.0	43.7	149

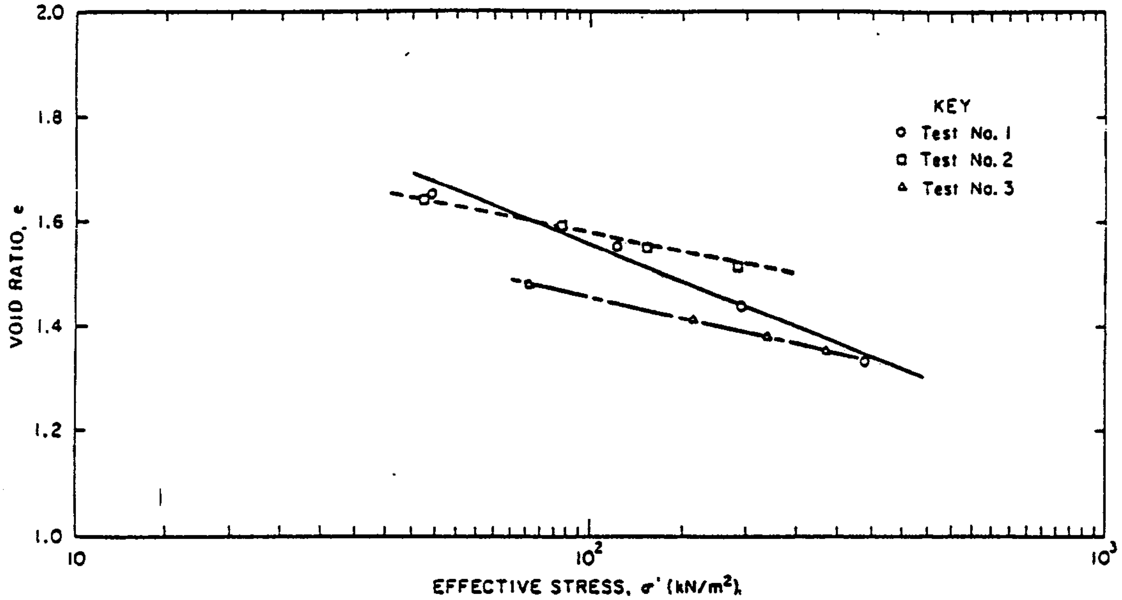


FIGURE D1. - Variation of void ratio with consolidation stress

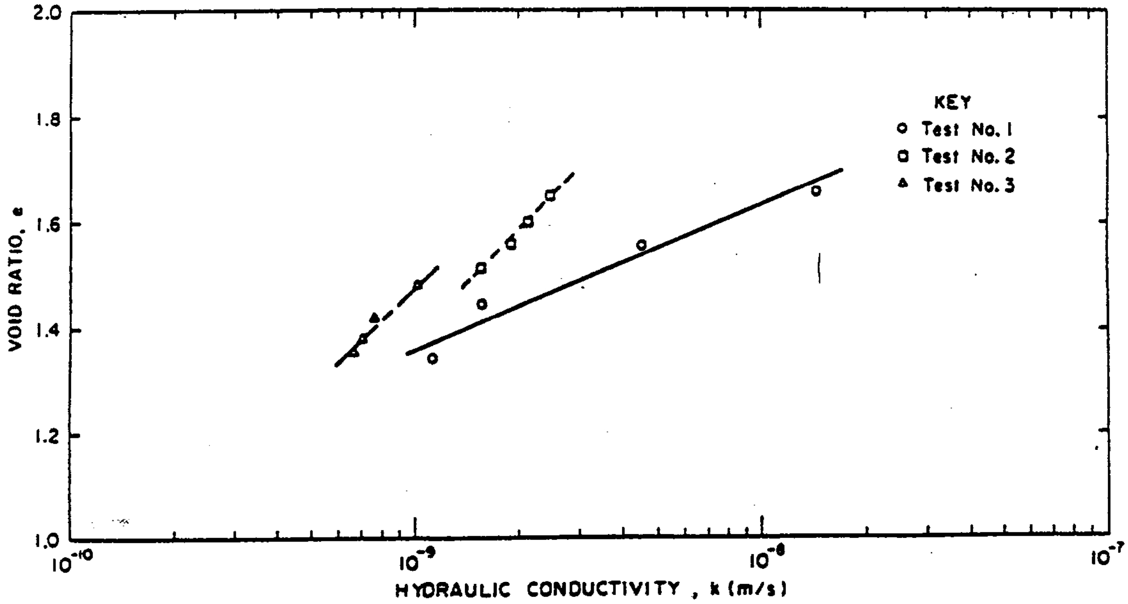


FIGURE D2. - Variation of hydraulic conductivity with void ratio

TABLE D2. - Consolidation and permeability test results

Sample	Void Ratio (e)	Effective Stress σ' (kN/m^2)	Coefficient of Permeability k (m/s)
Test No. 1, Material Type 4, CS-2, 11.715-11.745 m	1.64	49.10	1.46×10^{-8}
	1.55	110.50	4.52×10^{-9}
	1.44	192.25	1.57×10^{-9}
	1.34	335.40	1.12×10^{-9}
Test No. 2, Material Type 5, CS-2, 11.135-11.220 m	1.64	47.13	2.45×10^{-9}
	1.59	86.80	2.11×10^{-9}
	1.55	128.93	1.93×10^{-9}
	1.51	190.28	1.57×10^{-9}
Test No. 3, Material Type 5, CS-3, 13.095-13.160 m	1.48	75.84	1.01×10^{-9}
	1.42	157.64	7.85×10^{-10}
	1.38	218.99	7.07×10^{-10}
	1.36	280.34	6.70×10^{-10}

TABLE D3. - Permeability, natural moisture content and density results

Sample	Depth (m)	Permeability (cm/sec)	Dry Density kg/m^3 (pcf)	% Moisture Content	
				Initial	Final
CS-2	0.77-0.845	6.8×10^{-4}	1443 (90.2)	15.4	30.5
CS-3	2.39-2.57	5.6×10^{-3}	1479 (92.3)	21.5	NA
CS-2	8.2-8.3	2.5×10^{-6}	1112 (69.5)	45.0	75.0
CS-3	1.64-1.71	2.4×10^{-7}	1445 (90.3)	17.7	28.7

TABLE D4. - Specific gravity

Material Type	Sample	Depth (m)	Specific Gravity
2	CS-3	3.13-3.18	2.73
4	CS-2	8.2-8.3	3.09
4	CS-2	11.39-11.425	2.90

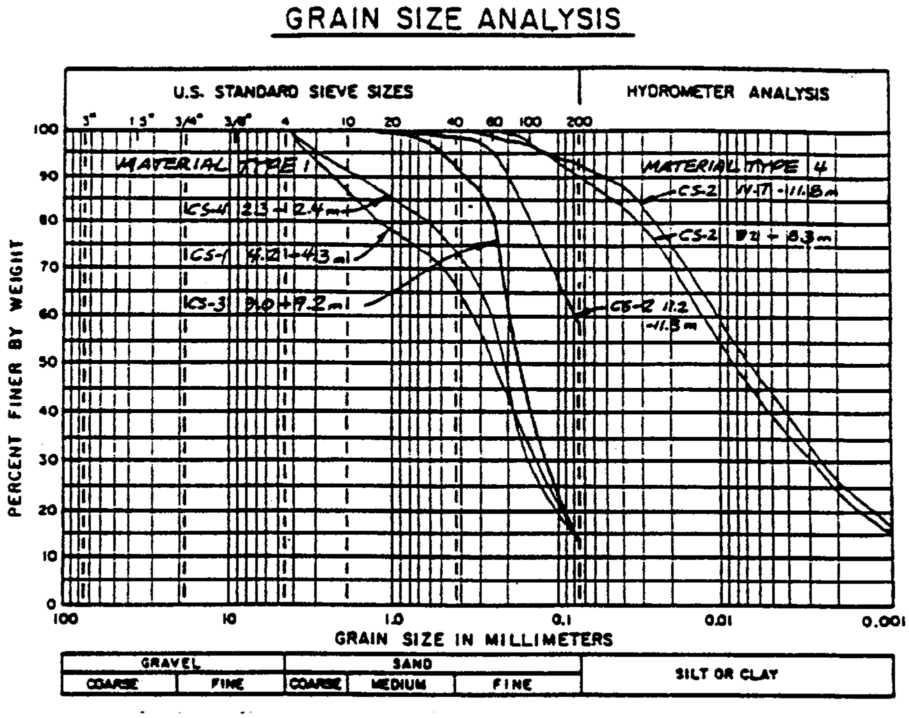


FIGURE D3. - Grain size analyses; material types 1 and 4

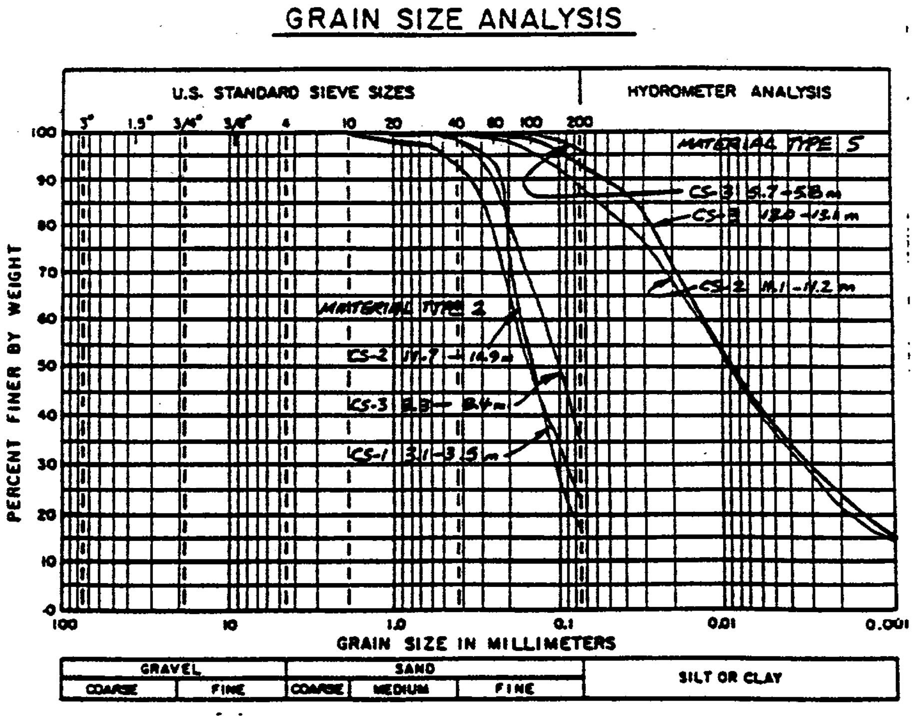


FIGURE D4. - Grain size analyses; material types 2 and 5

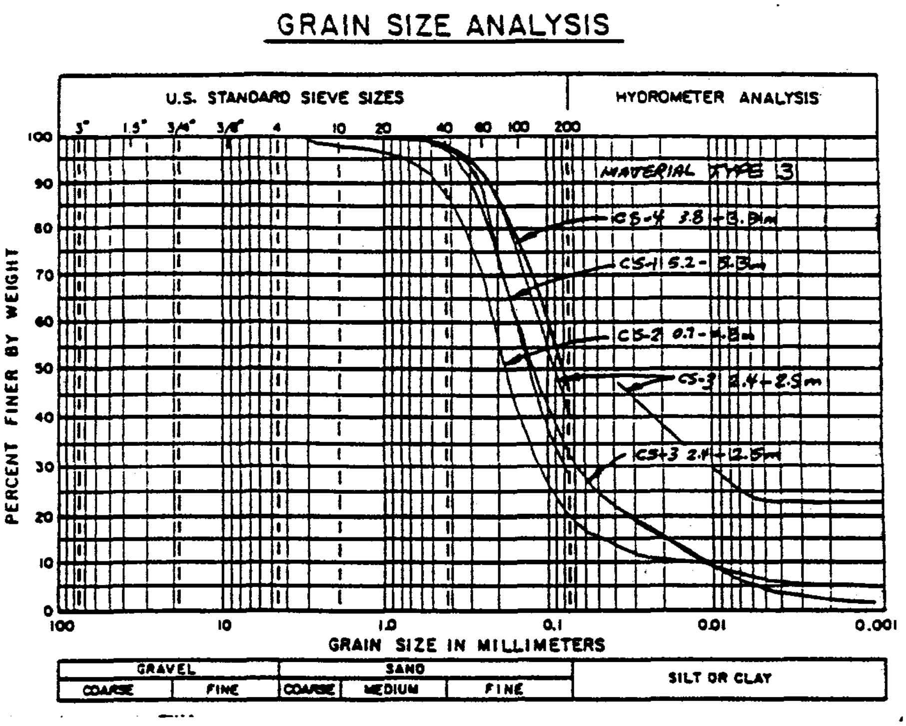


FIGURE D5. - Grain size analyses; material type 3

APPENDIX E

ESTIMATING THE HYDRAULIC CONDUCTIVITY FROM PIEZOPROBE PORE PRESSURE DISSIPATION CURVES

The pore pressure dissipation curves (e.g. figure 8) obtained from piezocone testing are similar to the deformation-time curves obtained from the standard laboratory consolidation test. The latter curves are used to calculate the coefficient of consolidation, c*. The coefficient of consolidation and the hydraulic conductivity are related, based on the Terzaghi consolidation theory (11, 20, 30), as follows:

$$k = m_v \gamma_w c = \frac{a_v \gamma_w c}{1 + e_o}$$

where:

k - hydraulic conductivity (LT^{-1})

c - coefficient of consolidation (L^2T^{-1})

m_v - coefficient of volume change ($M^{-1}LT^2$)

a_v - coefficient of compressibility ($M^{-1}LT^2$)

γ_w - unit weight of water ($ML^{-2}T^{-2}$)

e_a - initial void ratio

Various empirical procedures have been proposed for the calculation of the coefficient of consolidation from the piezoprobe pore pressure dissipation results. Based on the results from laboratory consolidation tests, Jones and van Zyl (25) proposed the following relationship:

$$c = \frac{50}{t_{50}}$$

where:

c is in m^2/yr

and t_{50} is in minutes.

---

*the symbol c is used here instead of c_v so as not to confuse the horizontal and vertical componentof coefficient of cosoidation,c_h and c_v.

Substituting equation 2 into equation 1:

$$k = \frac{3.11 \times 10^{-7}}{q_c \, t_{50}} \quad \text{cm/sec}$$

where $\gamma_w = 9.81$ kN/m^3, c in m^2/yr and q_c in MPa (see Table E.1 for details on selection of m_v.)

A substantial number of other correlations have been proposed based on cavity expansion theories. Summaries of some of these solutions are presented by Gillespie and Campanella (21) and Battaghlio, et al (19). The investigation by Gillespie and Campanella concluded that the approaches proposed by Baligh and Levadoux (18) and the spherical and cylindrical cavity expansion approaches of Torstensson (24), give the most reasonable results. For the latter it is necessary to compute the stiffness ratio for the soil. Stiffness ratio is defined as the ratio of the shear modulus to the undrained shear strength. The following calculation shows that for tailings, this ratio is between 21.5 and 100.

$$G = \frac{E}{2\,(1 + \mu)}$$

$$E = \frac{D(1 + \mu)(1 - 2\mu)}{(1 - \mu)} \quad = \quad 3.7\ q_c \text{ when } \mu = 0.3 \text{ (see Table E.1)}$$

From Figures B1-B4 in Appendix B, on the average q_c = 3 to 7 MPa, so G = 4.3 to 10 MPa. Now, τ_u (undrained shear strength) = 100 to 200 kPa (gold tailings (16). Thus, $21.5 < G/\tau_u < 100$.

It was further suggested by Gillespie and Campanella (21) that the validity of the solution method should be checked by comparing the predicted coefficient of consolidation at different levels of dissipation. For this purpose it is useful to compare the various solutions on the basis of a plot of time factor, T, versus degree of consolidation u.

$$T = \frac{ct}{r^2}$$

where:

t = time (T)

r = length of drainage path, taken as radius of cone (L)

$u = \dfrac{u_i}{\Delta u}$ (%)

Δu = total dissipation

u_i = specific value of dissipation

Note that taking the length of the drainage path to be the radius of the cone is obviously a simplified assumption as the true drainage path length is not known. However, data presented by Roy, et al (23) tend to confirm the reasonableness of this simplification.

Battaglio, et al (19) present time factor curves based on the stiffness ratio and the Skempton pore pressure parameters at failure. They also discuss the oversimplifications involved in using this approach for the calculation of the coefficient of consolidation. It is pointed out that for cylindrical cavity expansion $c = c_h$, the horizontal component of coefficient of consolidation, and for spherical cavity expansion $c = c_h$, the average coefficient of consolidation expansion, where $c_v < c_{av} < c_h$.

Figure E1 presents a plot of time factor versus degree of consolidation for the solutions above as well as a few others. A summary of the time factor values for u = 60, 50 and 40 percent is given in Table E1.

The procedure for calculating the hydraulic conductivity from the coefficient of consolidation is described in Table E2.

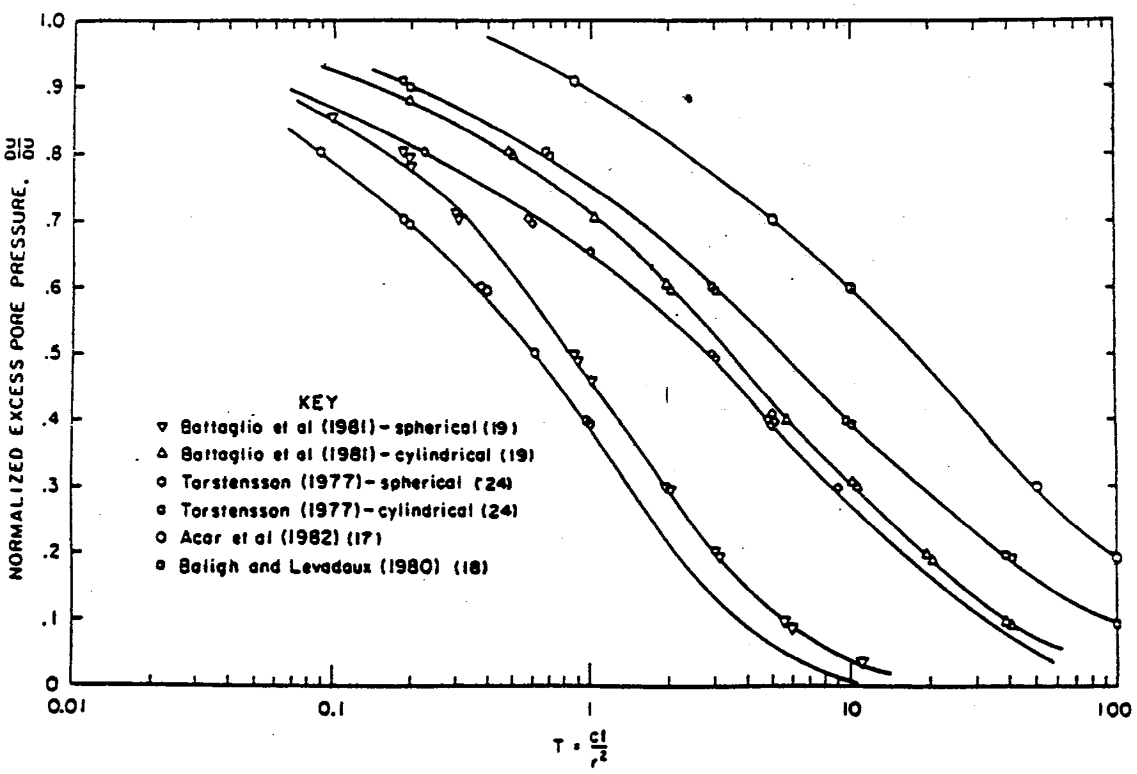


FIGURE E1. - Time factor versus degree of consolidation for various theoretical solutions

TABLE E1. - Time factor values for various theoretical solutions

Solution	Normalized excess pressure 60 pct (t_{60})	50 pct (t_{50})	40 pct (t_{40})
Baligh and Levadoux (18)	2.8	5.4	9.5
Acar, et al (17)	10.0	20.0	40.0
Battaglio, et al* (19)			
spherical	0.52	0.88	1.2
cylindrical	2.0	3.6	5.8
Torstensson** (24)			
spherical	0.37	0.6	0.98
cylindricla cavity	1.4	3.0	5.2

*$G/S_u = 100$, $A_f = 0.33$

**$G/S_u = 100$

TABLE E2. - Procedure for calculating hydraulic conductivity from coefficient of consolidation.

1. Calculate coefficient of consolidation from:

$$T = \frac{ct}{r^2} \text{ by using } r = 1.784 \text{ cm}$$

2. The constrained modulus D is defined as:

$$D = \frac{1}{m_v}$$

Correlations have been made between constrained modulus and cone resistance. A summary of these was published by Lunne and Kleven (26). It was found that $D = \alpha q_c$ ($\alpha = 3\text{-}11$ for normally consolidated sand and $\alpha = 5\text{-}30$ for overconsolidated sands. Due to dessication, tailings are usually slightly overconsolidated so that it will be assumed that $D = 5q_c$ for tailings. This value is close to that obtained by Baldi, et al (27) for normally and overconsolidated medium dense to dense sand. Thus,

$$m_v = \frac{1}{5q_c}$$

3. From equation (E1):

$$k = m_v \gamma_w \ c$$

$$= \frac{\gamma_w \ c}{5q_c} \qquad (\gamma_w = 9.81 \text{ kN/m}^3)$$

$$= \frac{9.81 \ c}{5q_c}$$

$$= \frac{1.96 \ c}{q_c}$$

Note that with r in cm, t in min, γ_w in kN/m^3, q_c in MPa,

$$k = \frac{1.96 \ T \ r}{tq_c \ (6 \times 10^6)} \quad \text{cm/sec}$$

$$= \frac{1.0397 \times 10^{-6} \ T}{t \ q_c} \quad \text{cm/sec}$$

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

ENVIRONMENT CANADA - MR. KEITH FERGUSON

Mr. Ferguson presented the perspective of the regulatory agency with regard to tailings models. Please refer to hand out:

- Regulatory Agency Needs For Tailing Models, by K. Ferguson, presented at the end of these minutes.

Mr. Ferguson indicated at the start of his presentation that regulators may not be interested in the details of the calculations and may not be knowledgeable about acid mine drainage modelling. Regulators may only be interested in the results of abatement technologies, not how they work. Regulators are sceptical about models and will believe the modelling results if the results indicate that the envisaged technology will not work, but will not believe the model if it indicates that the technology will work.

Mr. Ferguson continued by summarizing the needs of the regulator. The model must be accurate, but may be not as accurate as Dr. Morin indicated because it depends on the concentration. Sometimes accuracy is not important; however, the accuracy of the model must be given one way or the other. The model must be flexible and this is key as it must be applicable to as many sites as possible. The program must be capable of running on a PC 286; the input must be minimum and user friendly, the output must be produced in a fast way and must be easy to interpret, and include graphics or transfer capabilities to a graphics package.

The model must be easy to calibrate for individual sites. The output must include information on all the key parameters, and must give the concentrations and loadings at the end of the pipe.

Welcome Screen Search Report List

Regulators are interested in the long term projections. They like to connect the model to down stream migration models. Some regulators are interested in the metal species, others are more interested in the total concentration. Regulators require clear documentation including key references and assumptions.

The model must be applicable to both actual and future tailings impoundments. Mr. Ferguson commented that this is key and that RATAP.BMT may not be as well suited to those two cases. In British Columbia, he looks at a lot of new cases and needs a model that is able to help him.

Mr. Ferguson further indicated the questions that regulatory agencies like to ask and get answers to and added his understanding of RATAP's capabilities to address each of the questions:

- Will the actual or planned tailings impoundment generate acid mine drainage? Mr. Ferguson was of the opinion that RATAP can answer this question.
- In the positive case, how long will it take before the supernatant or seepage becomes contaminated? Mr. Ferguson seemed to understand that RATAP can answer this question.
- What parameters are likely to be of environmental concern? Mr. Ferguson indicated that RATAP seems to be able to answer most of the questions.

Dr. Nicholson clarified that RATAP will not give any answers as far as the down stream environment is concerned . Other models are needed for this. Dr. Ritchie added that RATAP is a source term model, the model will not tell how long it will take for contamination to reach the receiving environment.

- Where should we monitor to detect early signs of acid generation or stream contamination? Mr. Ferguson expressed his opinion that RATAP can help answer this question but that there might be simpler ways to answer this question.
- What parameters would be best to test and when and how frequently do we need to monitor? Mr. Ferguson indicated that it is difficult for a model like RATAP to answer this question.

- When is it too late to implement reclamation?
- Will the proposed abatement plan protect the downstream environment?
- How much confidence can we place in the results?

Mr. Ferguson indicated that it appears that RATAP can address the last questions. Mr. Ferguson asked his other regulatory friends if he missed anything. Mr. J. Barr indicated that a model will give one answer to many concerns.

Mr. Ferguson continued his presentation with some technical considerations related to the case of Westmin's tailings which could be a case for the application of RATAP. Some characteristics of this tailings pond might be different from other tailings ponds and the data involved sophisticated and not so sophisticated techniques. There were some useful relationships and it gives some idea of a technical application of RATAP. He showed slides, indicating the lack of uniformity of pH due to the heterogeneity and crack formation. The silt layer stops the oxygen from getting underneath; except when there are cracks, the oxidization is extensive. (pH 2.2 versus 5.8).

He showed a slide indicating the relationship between pH and the diffusion coefficient; as the diffusion coefficient increased, the pH decreased. The model he used seemed to fit reasonably well. A question resulted (Dr. Ritchie) with respect to the method used to determine the diffusion coefficient. The answer given was that measurements were done of the porosity and the water content and the coefficient was calculated the same way as with RATAP.

Mr. Ferguson indicated that with this type of work there are two major concerns for the use of RATAP.BMT:

- lack of homogeneity
- cracking.

A question resulted (Dr. Ritchie) with regard to the thickness of the surface where the measurements were taken place. The answer was 10 to 20 cm, which is very shallow.

Mr. Ferguson indicated that is was difficult to measure the unsaturated flow and he needs better ways to measure how fast water will flow in such a situation. He further indicated that the model is not working very well with diffusion coefficients at high moisture contents.

Dr. Nicholson indicated that this has been a problem with other models. The RATAP.BMT module for oxygen concentration at high moisture levels near saturation is now being revised.

Mr. Ferguson concluded by saying that the regulatory agencies have a range of needs for acid mine drainage modelling. RATAP.BMT seems to fulfil some of those needs if it is used 'very very carefully and with knowledge'. The main problem appears to be for new mining operations because the input information is lacking and guessing is necessary. He estimated that because of the significant input data requirements, RATAP will require a significant amount of effort to be run. It might be that we will have to be satisfied with a simpler approach, especially for the new mining operations. He concluded further by expressing the opinion that 'the bottom line is that RATAP is useful, that it will be used, and that it will provide some valuable data for the regulatory agencies'.

QUESTION AND ANSWER PERIOD:

Dr. Ritchie:	This is a philosophical question, what do you in fact mean by calibrating? It is worth while discussing?
Mr. Ferguson:	When I think about calibration, I think about changing or adjusting the input data that might be used for one site and adapting it to another site, like changing the sulphur content, moisture content, the layering and then to run some simple tests to see if the model is running properly for that site. In the case of RATAP, one could calibrate the oxygen profiles and then validate RATAP against the measurement of acid flux.

Dr. Scharer: He liked the idea of calibrating using oxygen profiles because it is easy to measure and lots of data is available.

Dr. Snodgrass: He explained that there is more than one site and testing needs to be done.

Dr. Ritchie: He suggested that the oxygen diffusion coefficient could be estimated or measured directly and then be eliminated as a parameter.

Dr. Nicholson: This will help cut down the degrees of freedom. He added that originally RATAP was not calibrated, grain size estimates were used and this produced a diffusion coefficient. The oxygen profiles came out very well that way.

A discussion resulted related to the sulphur content and the depth of reaction and its dependency on concentration. The oxygen profile is dependent on the reaction rate.

Mr. Davé: How many holes one must drill to obtain confidence in the results? A discussion resulted.

Mr. Garisto: He made an analogy with radon coming up in cracks on the thick clay beds of Winnipeg and the oxygen seeping down in cracks at the tailings dam.

Mr. St. Arnaud: How were the cracks produced at Westmin?

Mr. Ferguson: Mr. Ferguson explained that this was due to drying. Once the cracks are made, they do not reseal with time due to flooding or moisture.

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REGULATORY AGENCY NEEDS FOR TAILINGS MODELS

Assumptions

- regulators may not be interested in the details of the source calculations
- may not be that knowledgeable about AMD or modelling
- may not be interested in how abatement technologies work, but, only in the results
- are skeptical about the accuracy of models
- will believe a model if it says a technology will not work

Needs

- accurate
- flexible
- limited easily obtainable input requirements
- easily run on PC (286)
- simple to interpret output
- user friendly input
- output for all key parameters (metals - Al, Cu, Zn, Pb, Cd, As, Ni and pH, acidity, SO4)
- easy to calibrate and verify
- fast
- calculates concentration and loadings on source wide basis
- provides for long term projections
- includes or connects to downstream migration models
- provides the metal species
- gives some assessment of accuracy (error bars)
- has clear documentation including list of key assumptions and references
- applicable to both actual and proposed tailings impoundments
- graphics output or transfer to graphics package

Regulatory questions to be asked

- Will this actual or planned tailings impoundment generate acid mine drainage?
- If it will generate AMD, how long before the supernatant or seepage becomes contaminated? Fronts established? Reclamation needed?
- What parameters are likely to be of environmental concern?
- Where should we monitor to detect early signs of acid generation or stream contamination? What parameters would be the best to test? When and how frequently do we need to monitor?
- When is it too late to implement reclamation (ie. when is the build-up of salts too great?
- Will the proposed abatement plan protect downstream water values?
- How much confidence can we place in the results?

Technical considerations

- heterogeneity of deposit (horizontally and vertically)
- cracking
- unsaturated flow
- diffusion coeficients at high moisture contents

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

INDUSTRY PERSPECTIVE BY DR. ERNEST YANFUL
NORANDA TECHNOLOGY CENTRE

The mining industry will be asking the same questions of a model as the regulatory agencies. Additionly, the model will be required to verify that a particular reclamation effort or technology will work. In this, industry will differ from the regulatory body. Dr. Yanful prefaced his remarks with the qualifier that his remarks may not be acceptable to all mining firms; however, he does offer a perspective on modelling generally. A copy of his text slides appears at the end of this summary.

The mining industry is faced with two differing requirements:

- stringent regulations for environmental compliance
- disposal of mine wastes in an environmentally acceptable manner.

Disposal during operations and at the end of mine life must be acceptable to both the regulatory agencies and society. Mining firms are confronted with the problem of mine waste disposal that is environmentally acceptable, yet at the same time, is affordable. Firms must be able to stay in business. This has led industry to ask the question: "What are we doing right now? Do we know how to do it very well; if not, what can we take advantage of in order to improve what we are doing right now?" Then industry must agree on a treatment method: effluent treatment, revegetation, flooding, or engineered covers.

Industry feels that an Acid Mine Drainage model should be focussed on end user needs. The end user will dictate if a very sophisticated or simple tool is required. The degree of sophistication will determine the amount of user effort and is dependent on the type of industry user, i.e. mill superintendent, environmental coordinator or research scientist. Should RATAP be developed any further as it presently is a very sophisticated model?

In the ideal case, the end user won't matter. Industry feels that it is more important to have a model where:

1. the data collection process is presented in a simple manner
2. data input process is simple and interactive with on screen messages
3. prompting messages are easily understandable
4. numerical input should be readily understandable
5. dataset must be available for large data input.

Education will be required prior to any model release so that misuse ending in inappropriate answers can be avoided. Education must emphasize that:

1. models will not relieve us of the burden of difficult decisions. One can not stop thinking.
2. models must be thought of as providing additional information to consider.
3. the model can not substitute for understanding the system and processes involved.

End users must understand how the model works in order to make decisions on which model will be appropriate for their needs. Understanding the model will provide meaning to the numbers generated by the model.

The end user must ask himself several practical questions on what needs to be modelled, why a model is needed and how is the modelling going to be done. How the modelling will be done will determine the type of model to be used.

Industry's main objective with modelling is to properly manage the acid mine drainage (AMD). This requires prediction of the total amount of acid water to be produced from whatever source and the prediction of water quality. Prediction is a very complex problem that must firstly assess the oxidation rate and hence the amount of acid generation.

The quality of mine drainage has serious implications on operations water management. Can it be reused as makeup water in the process, can it be discharged, does it require treatment? Its source is seepage and run-off from mining faces, waste rock, and tailings.

Dr. Yanful then reviewed the areas where industry required models: open-pits, waste rock dumps and tailings. Open-pit problems associated with flooding and acid generation from surface exposure require predictive models. The mining industry favours open-pit disposal of mine wastes as AMD is relatively low due to smaller exposed surface. Pits can also be effectively flooded to prevent the generation of acid. The model must predict the rate/amount/quality of acid generation and the monitoring scheme required.

Waste rock is a complex problem with the differing minerals oxidizing at different rates. The model must predict the reaction rates and rates of flushing of oxidation production. Industry's strategy is to control/reduce the amount of oxidation which then reduces the amount and length of AMD treatment and the costs involved.

Industry requires a model to determine the effectiveness of control measures. Dr. Yanful posed the question: "Do we have one model right now that can do this or do we require more models?" The question is made more complex because of the heterogeneity of the subject to be modelled. A tailings model requires answers to the same questions as waste rock and mine drainage adding in the buffering factor present in tails.

Work done at Waite Amulet suggests that a combined model that predicts flow and containment transport is required. The model must evaluate the effect of reclamation measures: flooding incorporating hydraulics and the role of hardpan; type of covers; and the processes occurring in wetlands.

Once a model is developed that answers these questions, Dr. Yanful suggests that the following documentation should be provided with the model:

1. a description of the underlying problem being solved
2. clear identification of site specific data to be collected for use in the application of the model
3. a list of assumptions used in the model with their rationale so the user can understand what he is doing
4. Validation given where the model was applied to problems of known solutions

5. a description of the acceptable level of precision, accuracy, and uncertainty
6. results of quality assurance.

In conclusion, industry needs are many, requiring prediction and measurement of parameters. Education of the end user is required for the use of the right model in the correct application. This will require determination of who is the end user, how simple is the model, and what is the total cost of the model in relation to the reclamation costs.

QUESTION AND ANSWER PERIOD:

Mr. Davé:	Does industry see RATAP as suitable for its needs? Is there any deficiencies requiring changes?
Dr. Yanful:	RATAP is seen as a very useful model. It should be used. However, RATAP has not been sufficiently validated. Someone needs to be charged with the responsibility to see that it is rigorously tested and adjusted.
Dr. Ritchie:	You have stated that the disposal of waste rock in open-pits is acceptable. The cost of this you are prepared to bear?
Dr. Yanful:	For our property in New Brunswick, we are considering moving the waste rock back into the pit or covering it with soil. We are faced with the question of do we have enough soil materials in the area to design an effective cover? The cost of this is compared with the cost of waste rock haulage back to the pit and flooding it. Flooding the pit poses questions like what are the fluctuations in the water level going to be. It sounds attractive because acid generation under water is very low. It is not done on a routine basis. We need more studies and a model to help us with the predictions.

Dr. Ritchie: What is the scale of the costs?

Mr. Davé: Most likely $1.00 a ton per mile.

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COMPUTER MODELS FOR PREDICTING AND MANAGING ACID MINE DRAINAGE:

THE PERSPECTIVE OF THE MINING INDUSTRY

as presented by Ernest Yanful

MINING INDUSTRY IS CONFRONTED WITH:

- stringent regulations for environmental compliance
- disposal of mine wastes in environmentally acceptable manner
- staying in business

PRIMARY FOCUS OF MODELLING.- THE END-USER

- sophisticated requiring intensive user effort
- reduced to simple tool requiring little user effort

KEY QUESTION (INDUSTRY PERSPECTIVE): WHO IS GOING TO USE IT?

- mill superintendent
- environmental coordinator
- engineer/research scientist

Answer to above question determines level of sophistication

IDEAL CASE

- data collection should be simple
- input data must be entered interactively. User responding to questions printed on screen (PC)
- prompting messages should be self-explanatory
- meaning of input variables should be clear
- if input data are large, use a dataset

EDUCATION

- models will not relieve us of the burden of making difficult decisions
- models simply provide additional information to consider
- not pick up a program, push some buttons and obtain solution to problem
- need to understand the system and the processes occurring
- decide which model is appropriate
- understand the meanings of numbers generated by model

INITIAL PRACTICAL QUESTIONS:

- what is it we wish to model?
- why do we wish to model?
- how do we model?

MANAGEMENT OF AMD MEANS MAKING DECISIONS AS TO:

- total quantity of acid water generated from pits, dumps and tailings impoundments
- quality of mine drainage

AN ASPECT OF AMD MANAGEMENT:

- time required for development of acid conditions can vary from 1 day to more than 50 years
- for example:
  - ore with more than 40% S, no AMD in 10 to 20 years
  - however, ore with less than 3% S, AMD formed immediately producing large fluxes of acid
- hence assessment of rate of oxidation and hence acid generation important

QUALITY OF MINE DRAINAGE

- has major impact on water management systems at operation
- determines whether or not water can be used as make-up water in process
- determines whether water can be discharged without treatment
- determines the type of treatment required

IN ACTUAL FACT, THE QUANTITY AND QUALITY PROBLEMS CANNOT BE SEPARATED.

MAJOR SOURCES OF AMD:

- drainage from exposed mining faces (underground operations and open pits)
- run-off and seepage from waste rock dumps
- seepage from tailings

EXAMPLES OF MODELLING NEEDS PERTINENT TO:

- open pit
- waste rock piles/dumps
- tailings impoundments

OPEN PITS:

- stability of walls (geotechnical engineering adequate)
- flooding
- acid generation from surfaces due to exposure

MINE WASTE DISPOSAL IN PITS ATTRACTIVE BECAUSE:

- AMD production is relatively low due to smaller exposed surface
- pits generally fill with water after production, hence only small portion of wall surface exposed to air for most of time. Only exposed rim generate acid in the long term.
- acid generation under water is low

OPEN PITS PREDICTIONS INCLUDE:

- rate of acid generation from pit walls = f (mineralogy and morphology of exposed rock)
- monitoring scheme for decommissioning depends on rate of outflow of pit water as well as its quality
- loading = f (balance of inflows and outflows)

WASTE ROCK PILES:

- oxidation and AMD generation complex
- strategy is to control oxidized leaching to reduce reaction rates and minimize removal of oxidized products
- ability to predict reaction rates and rates of flushing of oxidation production

WASTE ROCK PILES: EFFECT OF RECLAMATION MEASURES:

- How do we assess effectiveness
  - test plots in field trials?
  - one or several models?

Very difficult because of heterogeneity

TAILINGS IMPOUNDMENT:

- need to predict:
  - rate of oxidation
  - acid fluxes and rate of production
  - rate of movement of oxidation front
  - rate of oxidation after buffering is exhausted
  - water quality in seepage ditches to make decisions or treatment
  - long term pore water evolution
- combined flow and containment transport
- assessment of effect of reclamation measures
  - raise water table (hydraulic properties, role of hardpan)
  - engineered covers (single and multiple layers)?
  - wetlands?

DOCUMENTATION SHOULD INCLUDE:

- a description of the underlying problem being solved
- clear identification of site specific data to be used in the application of model(s)
- list of assumptions used in the model - should also provide rationale for their use
- calibrations - applications of the models to problems of known solutions
- a description of the acceptable level of precision, accuracy, and uncertainty
- results of quality assurance

CONCLUSIONS:

- needs of industry are many, no easy answers
- need to predict but also to observe
- understand the meaning of models
- learning the modelling process
- who should be modelling
- how often
- how simple should the model be
- what is the cost of modelling compared to total cost of operating or reclamation?

to measure the oxidation of the salt. We haven't done this yet to verify that it will work.

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WORKSHOP ON MODELLING OF REACTIVE TAILINGS
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SWEDISH PERSPECTIVE BY MR. BJÖRN SODERMARK AND MS MARIE COLLIN

Presentations were made by both Mr. Björn Sodermark and Ms Marie Collin on the Swedish Perspective.

Björn Sodermark Presentation:

Mr. Sodermark viewed his remarks as an introduction to the work being carried out by Ms Collin.

Swedish work in the area of acid mine drainage began 10 years ago with a simple survey of base metal mines in Sweden. Samples were taken from 15 tailings sites by drilling or digging down to a few centimetres below the water table. Analysis of the extracted samples found that most of the tailings, with few exceptions, had a very low pH in the upper half metre (of the drill sample). Most samples were taken from abandoned sites, only four sites were in operation.

These results caused alarm within Swedish circles and instigated an investigation into what could be done to prevent further acid generation and what would happen if nothing was done with the tailings.

To determine a solution, the Swedish first decided to classify each tailings site according to a priority level for treatment. Those sites with a sulphur to calcite ratio greater than 1 were assigned top priority or "high ambition" while those sites with a sulphur to calcite ratio less than .1 received very low priority status. Some sites were in between the two.

Secondly, the Swedish looked at possible abatement measures applying the criteria that the solution must stand for the long term and must require no supervision and maintenance with the exception that periodic checks would be made on the tailings to verify that the abatement measures were working. The long term is

1,000 years. Collection and treatment was ruled out because it was not feasible over the long term. Flooding was ruled out because of weather and the instability of dams in the long term without maintenance.

Swedish researchers determined that somehow they had to cover the tailings to restrict the flow of oxygen and minimize the water flow reaching the tailings as their work had determined that the major factor in acid generation was the amount of oxygen reaching the tails. It is a philosophy of controlled dispersion they are using. Covers fulfilled their criteria of no supervision and maintenance and long term viability.

The next step involved determination of how they were to construct the cover. The amount of acid flux received into downstream waterbodies could not be the primary indicator on how to build a cover; one had to go closer to the source. Hence the request to Marie Collin and Anders Rasmusson to develop a cover model that would determine how to build an efficient cover. The determining factor for cover efficiency would be the level of oxidation in the upper tailings level.

Sodermark feels that there will never be a comprehensive model that can be fully trusted to calculate the final acid flux for all systems operating within acid generating tailings. Also, it is not necessary as each problem is site specific with a million different causal factors; however, there are not that many abatement measures from which to select.

Sodermark then showed how they used the model in a case study done at Saxberry tailings site in Sweden. Emphasis was placed on the types of till covers, especially the sealing layer, to determine what the technically best and cheapest cover would be. They looked at:

- cefil which is coal fly ash mixed with cement
- till mixed with bentonite
- till - compacted fibre from pulp and paper mills
- till - compacted peat

The cover model calculated the reduction of sulphur oxidation and water percolation through the cover. They made rough estimations of the associated costs and long term stability for each solution. In high priority cases, they required a 97 - 99% reduction in sulphur oxidation to be successful. Costs are high for top priority solutions although the case study had relatively low associated costs.

Sodermark noted that the Swedish Environmental Protection Act requires a balance between what is technically feasible, the need environmentally for corrective measures, the risks of negative ecological effects, and the costs to come up with a reasonable protective measure. Sweden faces a major problem with the high costs of mitigating existing tailings problems, especially if they have been assigned a top priority or "high ambition". Even if they can find the responsible company, the costs are too high to require that company to fix the problem with high ambition covers. The government must provide the extra funding for these top priority costly actions to provide the best solution. This is a costly policy so Sweden is now developing better knowledge, better modelling, better modelling calculations, and putting more chemistry in the model to hopefully reduce costs. It will be a couple of years before they get a better model; but in the meantime, they will continue to fund what they think is the best solution.

QUESTION AND ANSWER PERIOD:

Dr. Robertson: You say your objective is to design for a 1,000 years. What work was done on the acid attack, on the sulphate attack on the cefil to establish its resistance over a 1,000 years?

Sodermark: A lot of work has been done on similar mixtures, but not cefil. Should be asking Vanloongen. Cefil is extremely resistant to sulphate and acid.

Dr. Robertson: Does it have something special other than portland cement and fly ash, that changes its characteristics from normal cement?

Sodermark: It has a very high hunkland???? content. In many cases in Sweden, we use cefil instead of concrete because it is more resistant to all types of water with high salt content.

Marie Collin Presentation:

Ms Collin provided a short summary of her work with cover models. The presentation was divided into two parts:

- a description of her model, and
- a description of the calculations made.

Copies of the overheads used by Ms Collin appear in this section following the meeting notes.

A. Model

(Exhibit 1) In principal, the model consists of three different parts: water transport calculation, diffusivity calculation, and oxygen transport reaction model.

Water Transport Model

The water transport model is the usual one for acid drainage in porous media, see Exhibit 2. The input data used geometry which is how the soil cover is configured. Exhibit 3 is the most ambitious configuration they have developed to date with sealing, protection, vegetation layer on top, precipitation and evapotranspiration.

The climate data uses simplified Swedish climate data. See Exhibit 4. Sweden has snow melt in March, drying in summer and autumn rains. Hydraulic data was unavailable at the Workshop.

Output of the water transport model are calculations of the percolation through the cover and water content profiles especially how these profiles vary in time during the year. The water content profiles are then entered into the diffusivity calculation. Diffusivity in all parts of the cover is calculated with the results used as input for the oxygen transport and reaction model.

Diffusivity

See Exhibit 5 which uses a log scale. Diffusivity is highly dependent on water content especially at high water content levels. Involved is experimental data from Dr. Yohanns Fluhler in Zurich of two different materials: the small circles are loamy sand material, pluses are loam. Very distinct differences between the two sets of data are evident.

See Exhibit 6. Ms Collin has determined that the best way to predict gas diffusivity at high moisture contents is the estimation method developed by Millington and Shearer. They have one method for non-aggregated media which fits quite well to the loamy sand data from Fluhler; and a method for estimating the structure of soils. The squares in Exhibit 6 represent the loam data from Exhibit 5. Solid lines are the calculated diffusivities for aggregated media. Two extremes are evident dependent upon where water is put within the system.

Oxygen Transport Reaction Model

The oxygen transport reaction model involves two calculations: coupled diffusion and reaction as well as the reaction rate constant. These are provided in Exhibit 7.

Transport Equation: accumulation is in soil and air with oxygen through to the water coupled with the diffusion term reaction. Ms Collin modelled the oxygen consumption rate constant as constant first order reaction giving full effect to available pyrite surface and also first order with respect to oxygen concentration.

Exhibit 8 A, B, C. Ms Collin then demonstrated some calculated results on water permeability. First was depth of root penetration which affects the moisture content profiles in the cover greatly. It is critical to understand how far the roots penetrate in your cover. Example A is a simple calculation of a homogeneous moraine with no doubt about the water. Consumption of water occurs just at the top of the moraine layer. At the top, moisture content is quite low; at the bottom it is quite high.

Example B is an example of a moraine cover with grass roots going down some thirty centimetres. Example C is an example of a moraine cover with small trees and bushes roots going down to one metre. Vastly different moisture content profiles are predicted.

Please see Exhibit 3 and 9. Exhibit 3 demonstrates the best cover they could come up with. It is an expensive one. They have tried to take away the coarse layers and have left the moraine layer and fine-grained layer. Exhibit 9 reflects the cover principle they have adopted: sealing layer, moraine protective layer and a layer in which to encourage vegetation. This simple cover is almost as effective as the more complex cover in Exhibit 3 when a low permeability material is chosen as the sealing layer. The low permeability material will maintain a high moisture content although there will be some transport of water upwards and downwards.

Exhibit 10 is an example of how the moisture content profiles vary during the year when you have a sealing layer of silt with a hydraulic conductivity of ten to the minus 8. In the autumn there is an increase in the moisture content of the moraine layer. During the summer, there is evapotranspiration with roots consuming the water. In the silt layer, there is a small water transport upwards; however, the moisture content is still high in the silt layer at the end of the summer.

Exhibit 11 is an example of a sealing layer with less permeability. Only the top part of the clay area is affected by upward water transport.

Exhibit 12 shows the calculations done for the Bersbo tailings site by a colleague of Ms Collin. The exhibit simulates the second year. Slope of the cover is one to five. The site is now covered and Ms Collin is measuring ground water levels above the low permeability sealing layer. Saturated conditions are expected above the sealing layer because of its low permeability. The cover is a till layer above a clay layer. The moisture content has continued to increase every year from a low level starting point with saturation of the till layer at the bottom at year three. This has led to concerns about erosion in the till layer. If the entire till layer is saturated, surface runoff may cause erosion problems.

See Exhibit 13. In a cover using a similar sealing technique, there is a large variation in moisture content. In some cases there may be almost total saturation in part of the year.

Ms Collin then went on to show some results of oxygen transport and reaction calculations. Exhibit 14 with a no flow boundary condition shows diffusion into an uncovered homogenous tailings and reaction for different sets of diffusion coefficients and reaction rate constants. For reaction rate divided by diffusion, the maximum to be obtained, one gets a very steep oxygen profile. The solid curve is the more likely type of curve to be obtained. With a very low reaction rate constant and high diffusion coefficient, one obtains the dotted line curve. These oxygen profiles are bent the other way from the oxygen profile curves obtained by the RATAP model.

Exhibit 15 A and B demonstrate the possibility of using steady state approximation for oxygen concentration profiles. Exhibit 15A is for a very poor cover, a sandy moraine, with a reading taken in mid summer when it is almost dried up. The calculation starts at a high oxygen concentration level but very quickly goes down to the steady state.

Dr. Nicholson made a comment about the far right curve of this graph. This is the situation that the RATAP model is experiencing where the pyrite has been depleted and it makes its own cover. One has the oxygen profile through the cover where there is no pyrite, giving a series of linear gradients and then consumption occurs down below.

Dr. Scharer: Some of the pyrite was also where diffusion coefficient changes were made.

Dr. Nicholson: Yes, it isn't homogenous in terms of the diffusion coefficient.

Ms Collin: This exhibit is just to demonstrate that this is a fairly quick process and that the steady state approximation may be used for this type of calculation.

Dr. Nicholson: Except when? I always make the assumption that steady state for diffusion can be used except when it gets to be saturated.

The next Exhibit 15B shows the same calculations made for a very efficient cover. It starts with a very high oxygen concentration and makes steady state within six months. However, the transport rate of oxygen from the sealing layer to the tailings has reached 1.5 times the steady state value in two weeks.

Ms Collin went on to discuss the key question of the long term stability of the cover. See Exhibit 16 where Kemakta Konsult has identified four mechanisms which may destroy the cover:

- erosion
- freeze/thaw
- fractures
- root penetration.

Freeze/thaw every year may give an aggregation structure to the sealing layer which leads to high permeability and higher diffusion coefficients.

See Exhibit 17 A and B. Many fractures through the sealing layer may be a serious problem. Seventeen B demonstrates calculations of the oxidation rate down in the tailings depending on the width of the fracture and the properties of the tailings. After awhile the pyrite around the fracture will be oxidized and the rate will slow down. General consensus of the audience was that the curves were very similar but not parallel. Ms Collin has done no checking on this.

Dr. Scharer: How did you calculate these curves?

Ms Collin: She solved it with a very simplified model, complete typed soil cover, no diffusion through it but radial. I assumed that would have the ------??? concentration down at the bottom of the fracture and then it is just diffusion and reaction. Variable used is the fracture width and the oxidation rate is per metre of fracture width.

Completing the discussion on mechanisms destroying cover is root penetration. Holes are created by the roots going down and eventually dying within the sealing layer. The roots also consume water which causes a dramatic rise in the diffusion coefficients. How roots grow in a salt cover is an important question that needs an answer.

Ms Collin asked a few questions about the RATAP model particularly page 27 and 28, the temperature module. Is this a misprint or how did you get this; do you use this in your model?

Dr. Scharer: No. The temperature model has been changed completely. This was our first attempt at it. The problem we had was in determining the temperature of the oxidation. We were looking at the global thermal properties, which you can't do. Now, we were looking at temperature in two cases. We have a baseline temperature model to calculate the change in temperature due to oxidative processes.

Dr. Nicholson: It should be noted that the original RATAP model was made for a low sulphide tailings where there was no temperature variations except ambient seasonal temperature fluctuations. When it got to including the high sulphide content, we have seen from the work of Ian Ritchie that there is an energy production and it was thought that the process occurring in the waste rock piles should be included in RATAP. However, I haven't seen any definite data on Canadian tailings, not waste rock, that shows the temperature kicks in fairly moist tailings and I'm are not quite sure why this is. I think it has to do with the large heat capacities involved and the moisture balance. So it seems that the heat balance, temperature, is much more important in waste rock than in saturated tailings.

At this point, Dr. Steger interrupted the discussion on the RATAP model to suggest that it be carried on after the presentation by Mr. Bruce Halbert of Beak Consultants Ltd.

Mr. St. Arnaud: The model for the fracture, was it a two dimensional model of oxygen diffusion into the tailings?

Ms Collin: It is a one dimensional cylindrical model.

Dr. Snodgrass: What data did you use for setting for rate of oxidation? the K?

Collin/Sodermark: Literature study gave a few reaction rate constants which were followed up by a lot of laboratory investigations of all the tailings in Sweden. It seems that the reaction rate constant was much lower in the tailings than was found in the literature. Measurements of tailings into water gave better chan???? higher than the column experiments.

Dr. Scharer: My comment is about the assumption of first order reactions with respect to oxidation concentration. My review of the literature indicates some evidence for first order in terms of normal oxygen processes, but it certainly isn't first order for oxygen biological processes.

Mr. Sodermark: No, we checked that and if you have a cover on then its diffusion controlled and the rate doesn't matter as much. Ms Collin has a model with a zero order reaction as well.

Dr. Scharer: The good news is that it doesn't make much difference. The RATAP model uses the next order.

Dr. Ritchie: In a good news/bad news scenario, there is worst news. Bacteria tends to have a different rate constant which if you are going to put that in, you must determine what the microbial ecology is. It really is a waste of time.

Dr. Snodgrass: Every organism has it own saturation point but it ends up averaging out in the wash.

Mr. Sodermark then made a few comments on the results of the work done at the Bersbo tailings, a full scale cover project with clay at one deposit and cefil at the other with two meters of glacial till above that. After one year we have in all our pipes less than .2 percent oxygen. It is probably much lower than that as this is the lower limit of the measuring instrument.

Dr. Nicholson: A point to be brought up here is measuring oxygen is one thing; but measuring the oxygen concentration doesn't give an indication of the oxygen rate. So are you collecting seepage data or in situ data in any profile to monitor the effectiveness of this decrease in oxidation? How are you collecting this data?

Mr. Sodermark: We have a controlled monitoring program of the streams from the deposits. Nothing inside. We have piezometers measuring the water going through. Water going through the sealing layers, the clay layer is one millimetre a year, through the cefil is nothing.

Some boxes are directly under the sealing layer where we can flush with nitrogen and then measure the oxygen content to calculate the diffusivity. This gives a field diffusivity. Other boxes have a sodium salt which we can crack at some time

PRINCIPAL MODEL

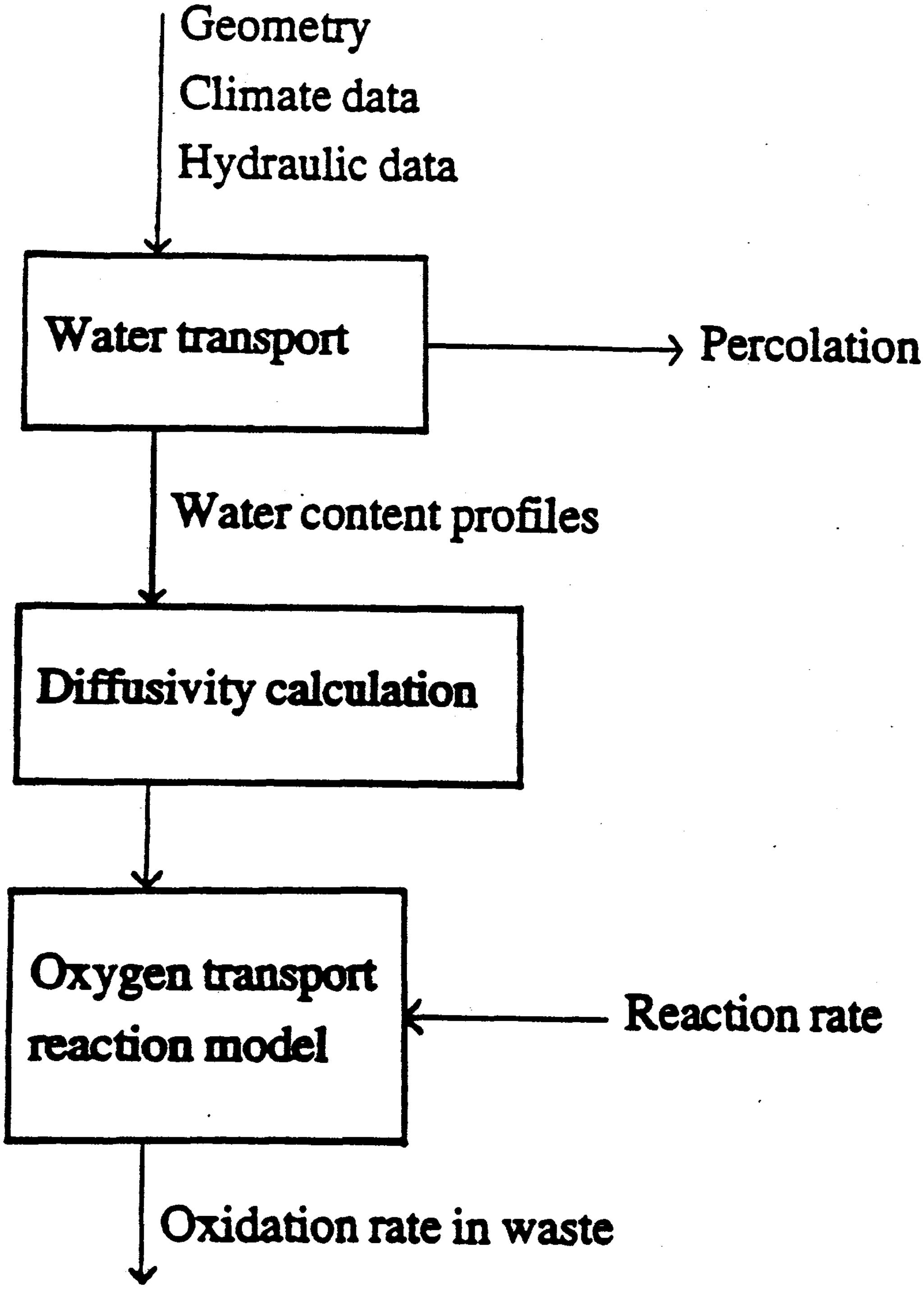


EXHIBIT 1

WATER TRANSPORT

flow: $\bar{q} = -K(\theta)\,\nabla(\psi + z)$

conservation of mass:

$$\frac{d\theta}{d\psi}\frac{\partial\psi}{\partial t} = \nabla\cdot\left[K(\psi)\,\nabla\psi\right] + \frac{dK}{d\psi}\frac{\partial\psi}{\partial z}$$

acc. capillary grav.

TRUST (Narasimhan, 1975)

Integrated Finite Difference Scheme
3 dimensions

EXHIBIT 2

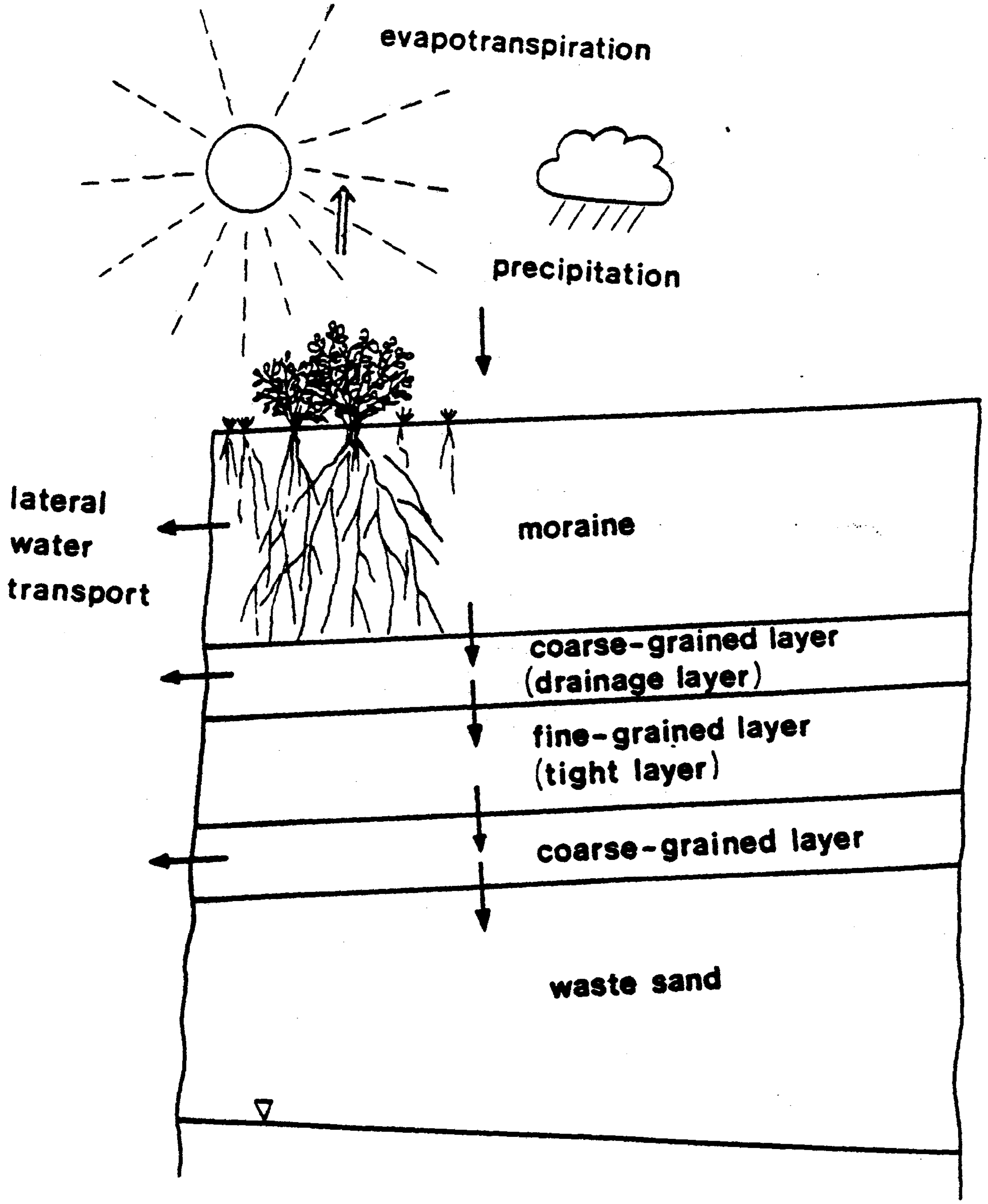

evapotranspiration
precipitation
lateral
water
transport
moraine
coarse-grained layer
(drainage layer)
fine-grained layer
(tight layer)
coarse-grained layer
waste sand

EXHIBIT 3

CLIMATE DATA

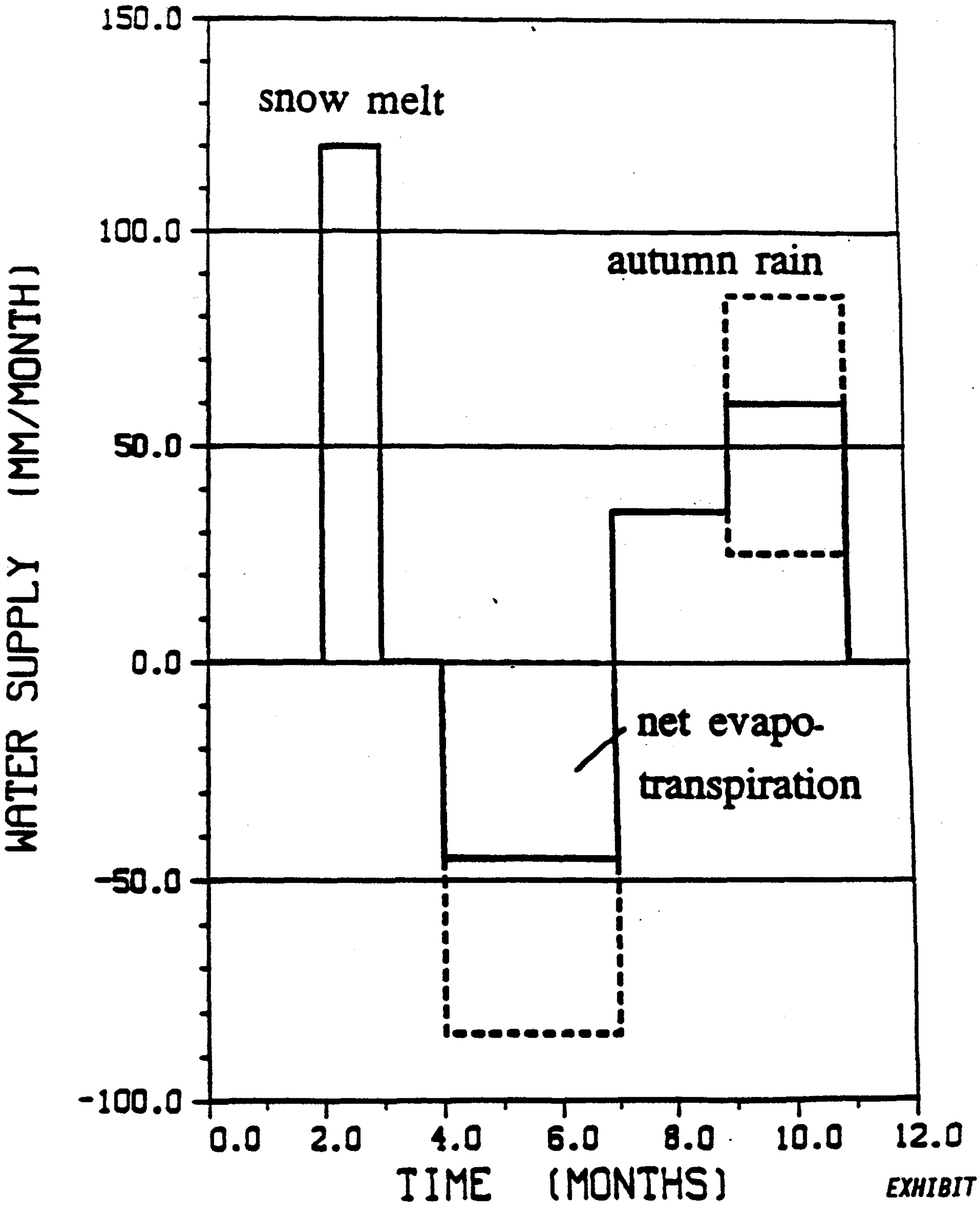


EXHIBIT 4

Experimental diffusivity data from Flühler (1973).

Relative diffusivity $\frac{D}{D_a^0}$ as a function of moisture content α.

+ Schmidwald 25-35 cm, loam

o Winzelerboden 70-80 cm, loamy sand

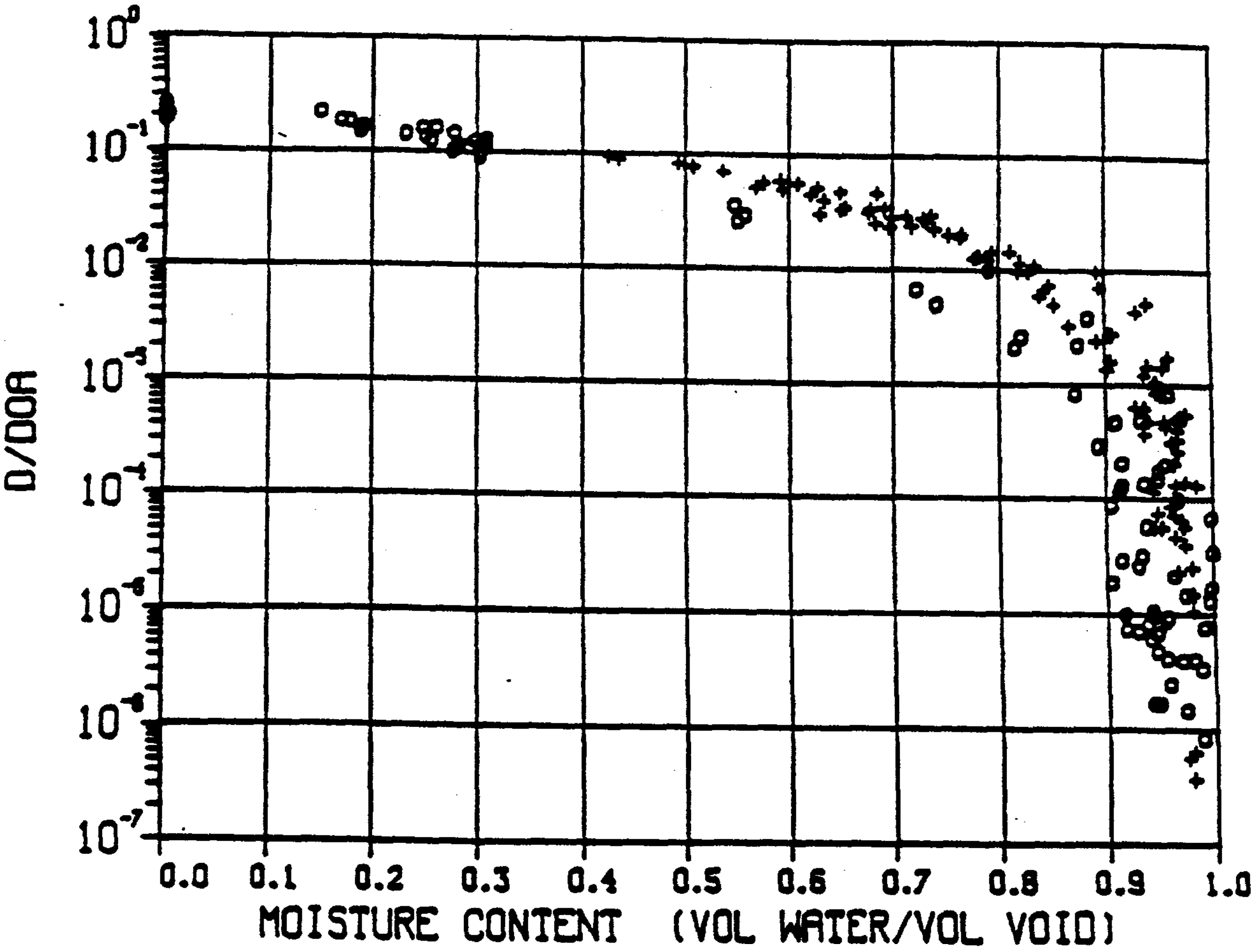


EXHIBIT 5

GAS DIFFUSIVITY

Estimation method from
Millington and Shearer (1971)

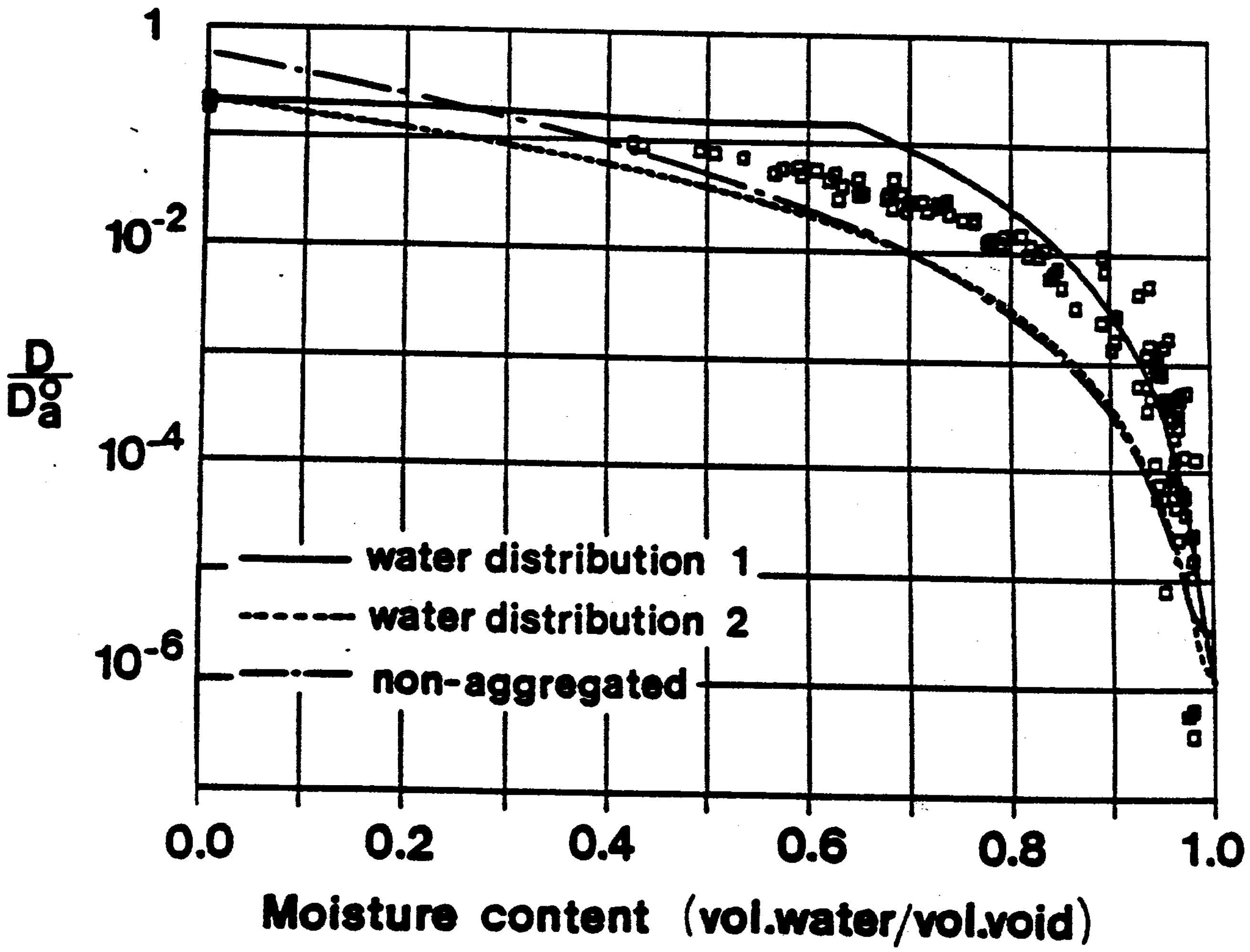


EXHIBIT 6

Coupled diffusion and reaction

1 dimension

$$\varepsilon(1-S+HS)\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} - k_r c$$

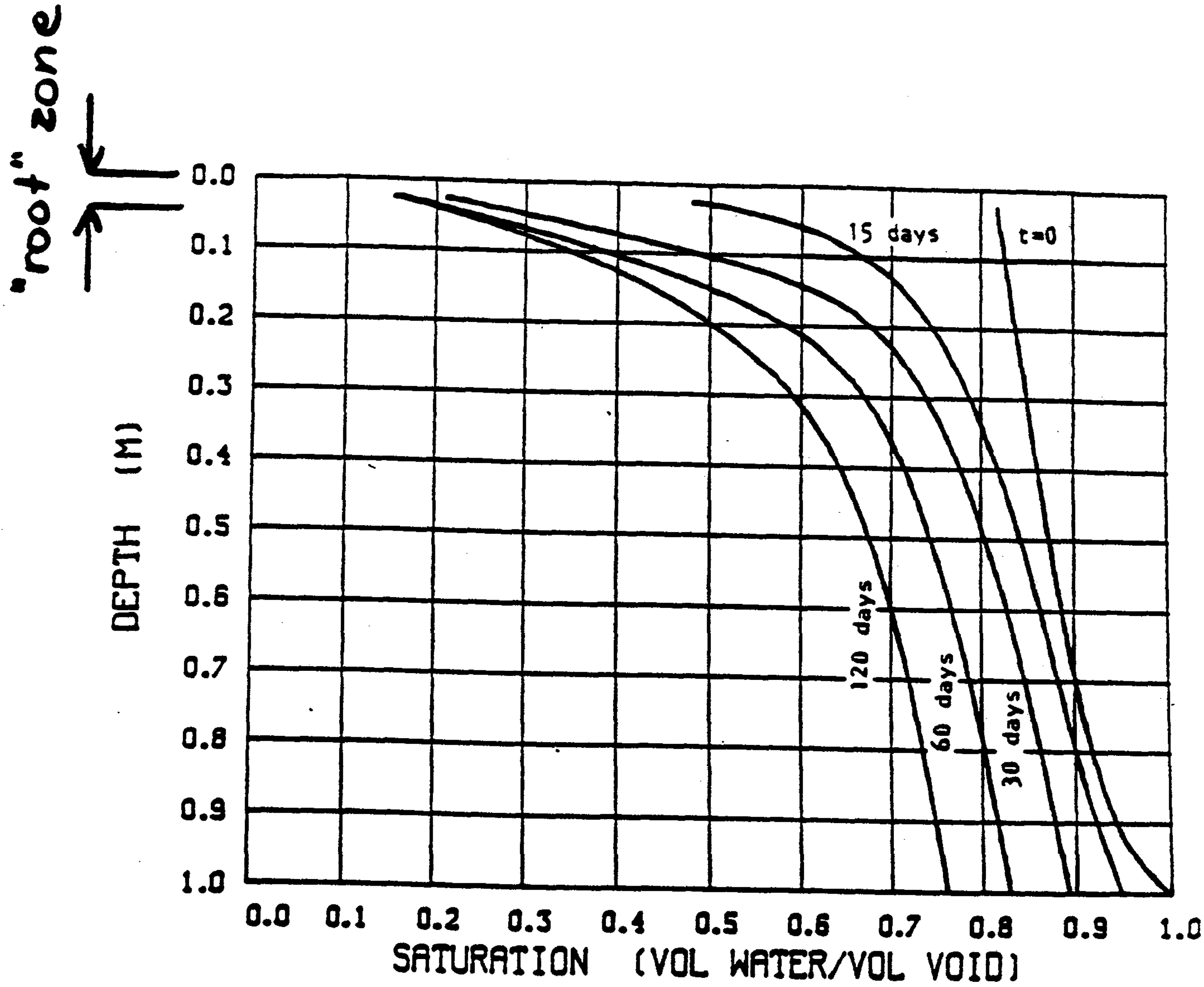
accumulation diffusion reaction

Reaction rate constant

Oxygen consumption rate =

$$= k_r \cdot c = k' \cdot a_{pyrite} \cdot c$$

EXHIBIT 7



"root" zone
DEPTH (M)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
15 days
t=0
120 days
60 days
30 days
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SATURATION (VOL WATER/VOL VOID)

EXHIBIT 8

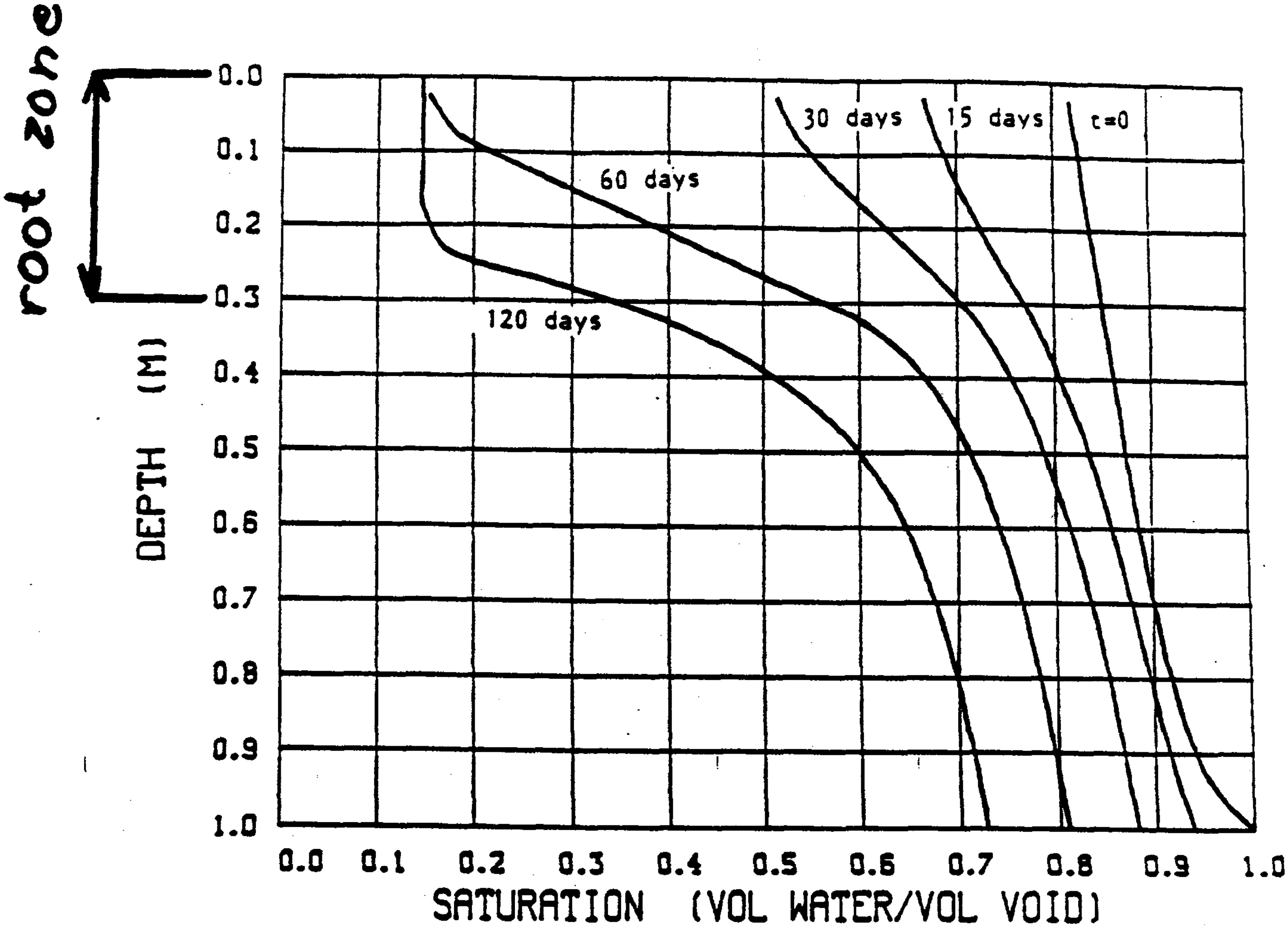

root zone
DEPTH (M)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
30 days
15 days
t=0
60 days
120 days
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SATURATION (VOL WATER/VOL VOID)

EXHIBIT 8b

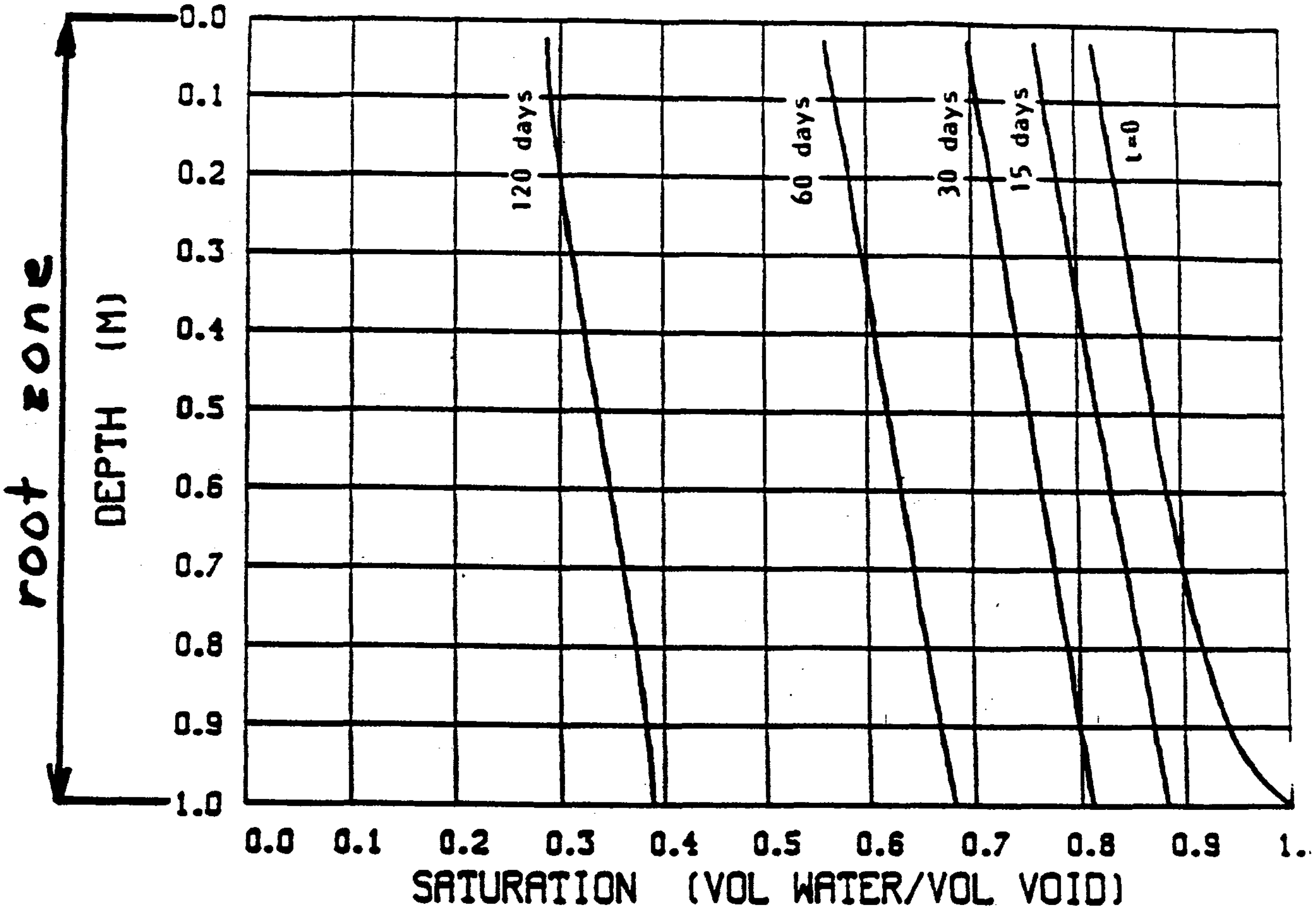

root zone
DEPTH (M)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
120 days
60 days
30 days
15 days
t=0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.
SATURATION (VOL WATER/VOL VOID)

EXHIBIT 8c

SWEDISH ENVIRONMENTAL PROTECTION AGENCY

Principle for Cover Design

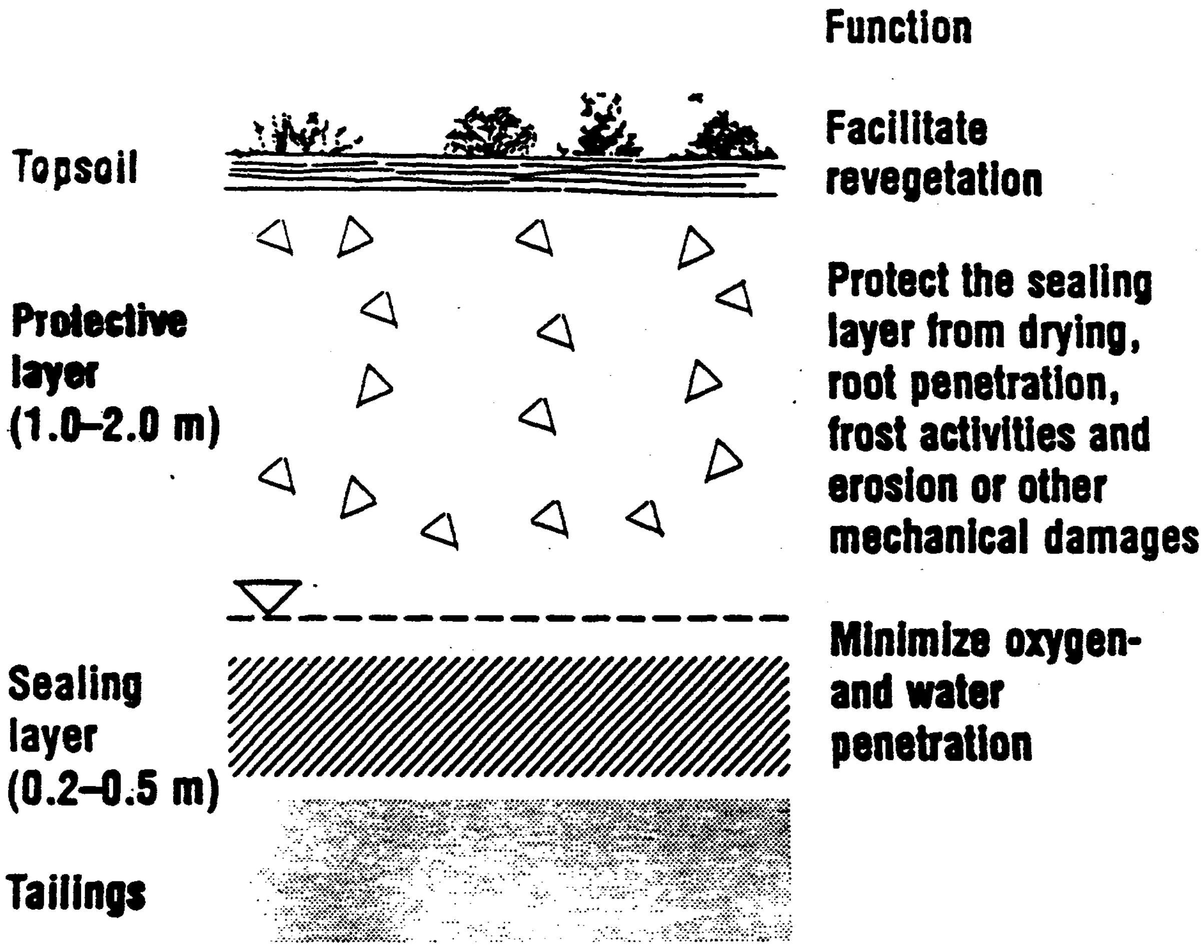


EXHIBIT 9

Welcome Screen | Search | Report List

DRYING AND REWETTING

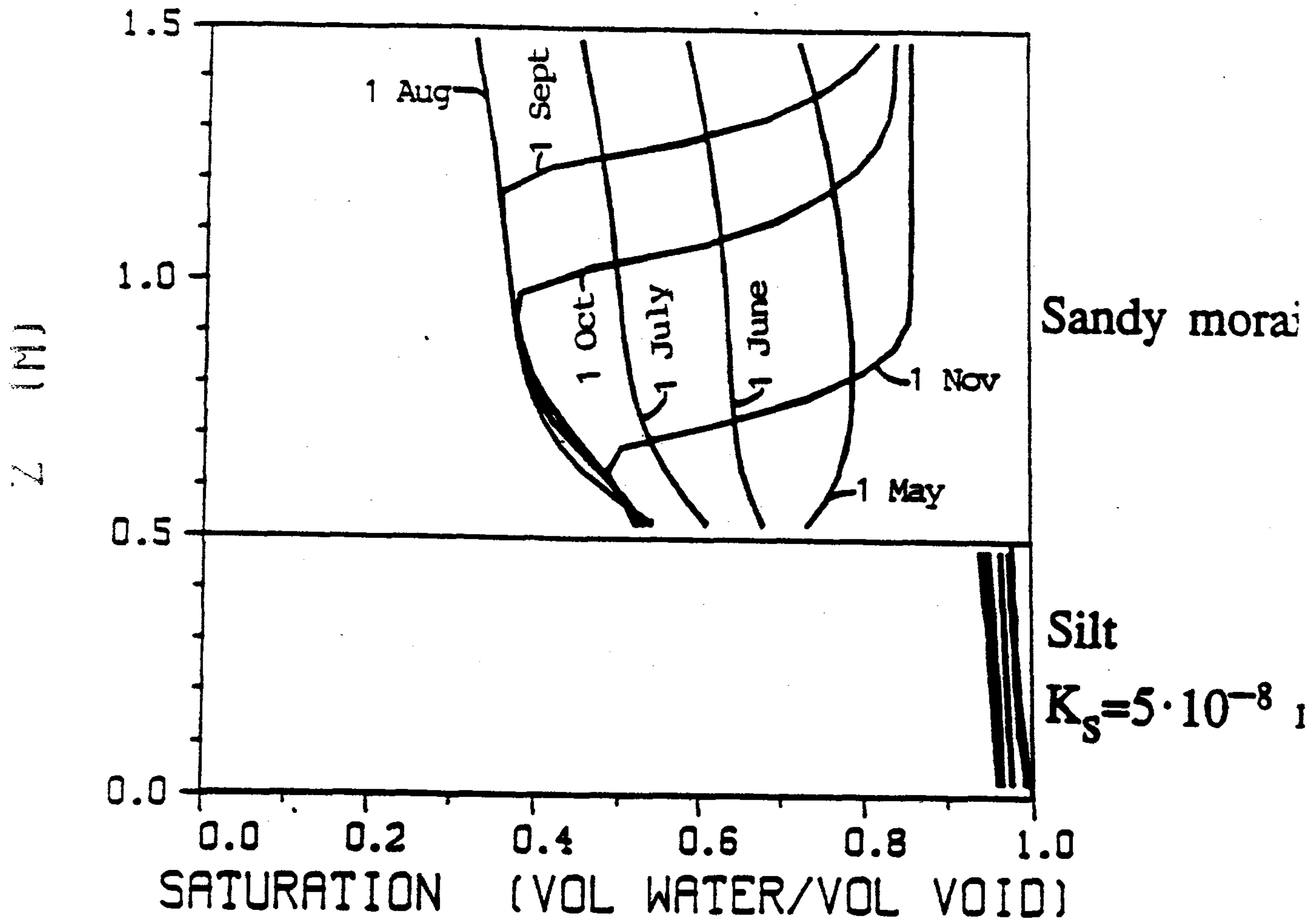


EXHIBIT 10

DRYING DURING THE SUMMER

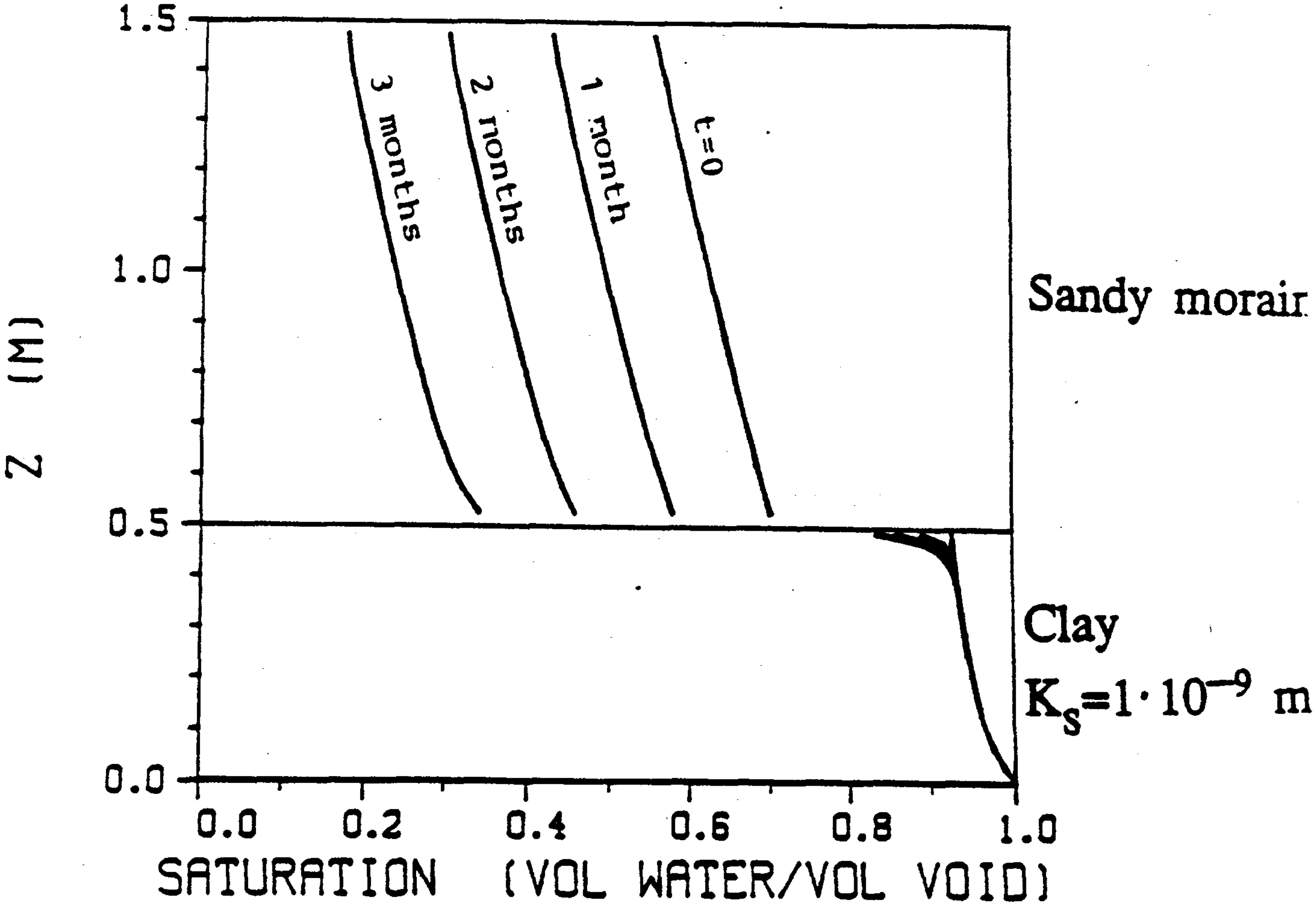


EXHIBIT 11

BERSBO

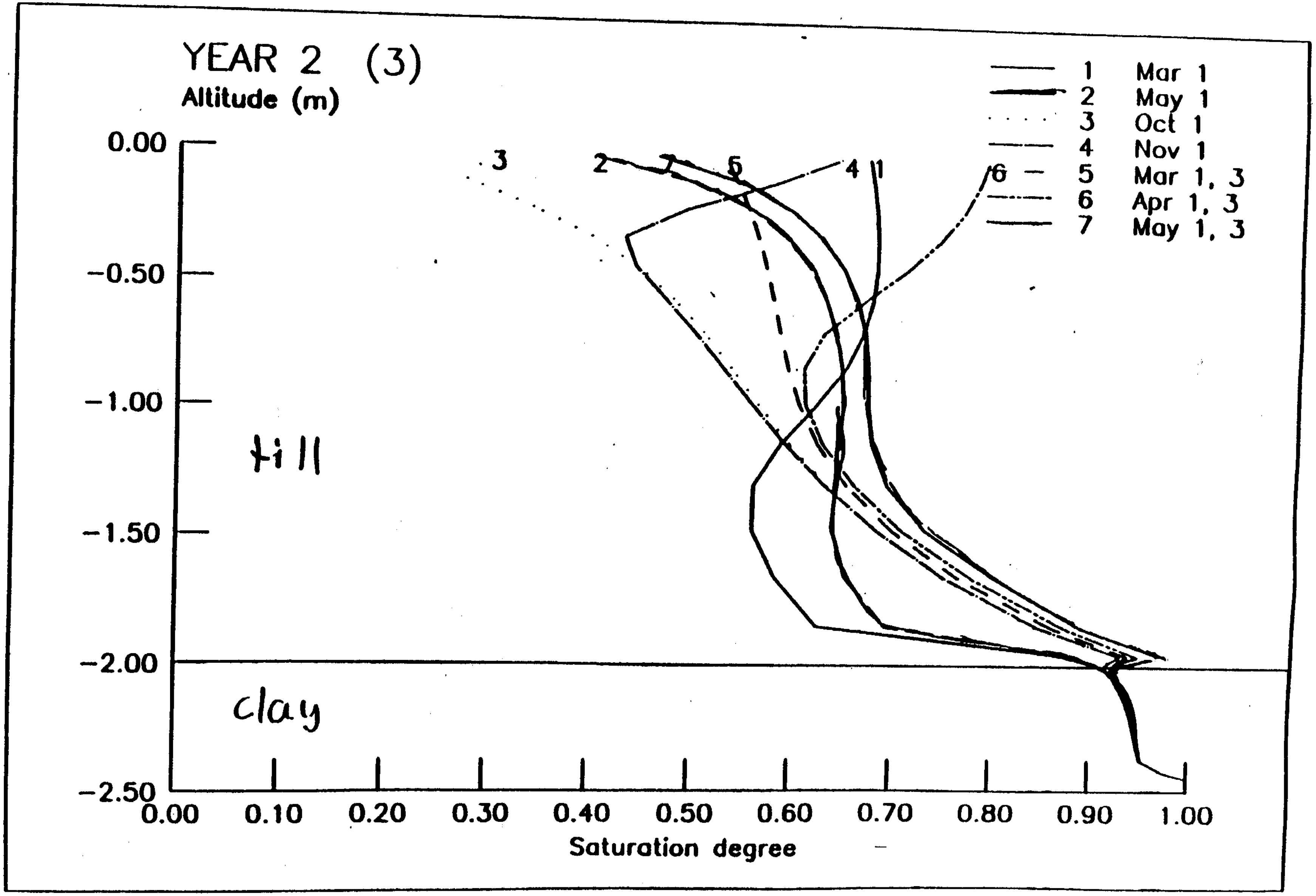
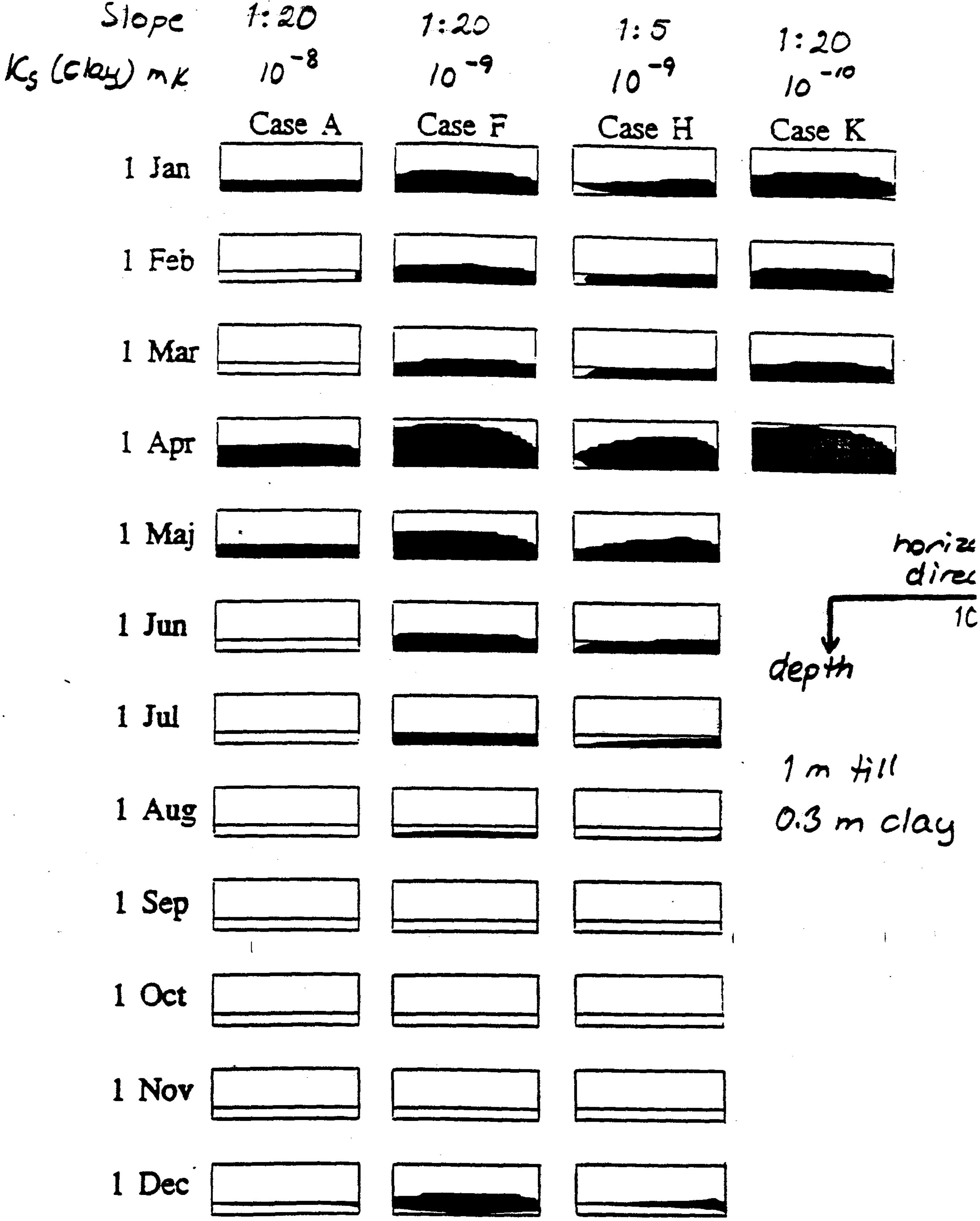


EXHIBIT 12



Variation of saturated part of soil cover during one year.

VATTENFALL

EXHIBIT 13

OXYGEN CONCENTRATIONS IN UNCOVERED TAILINGS

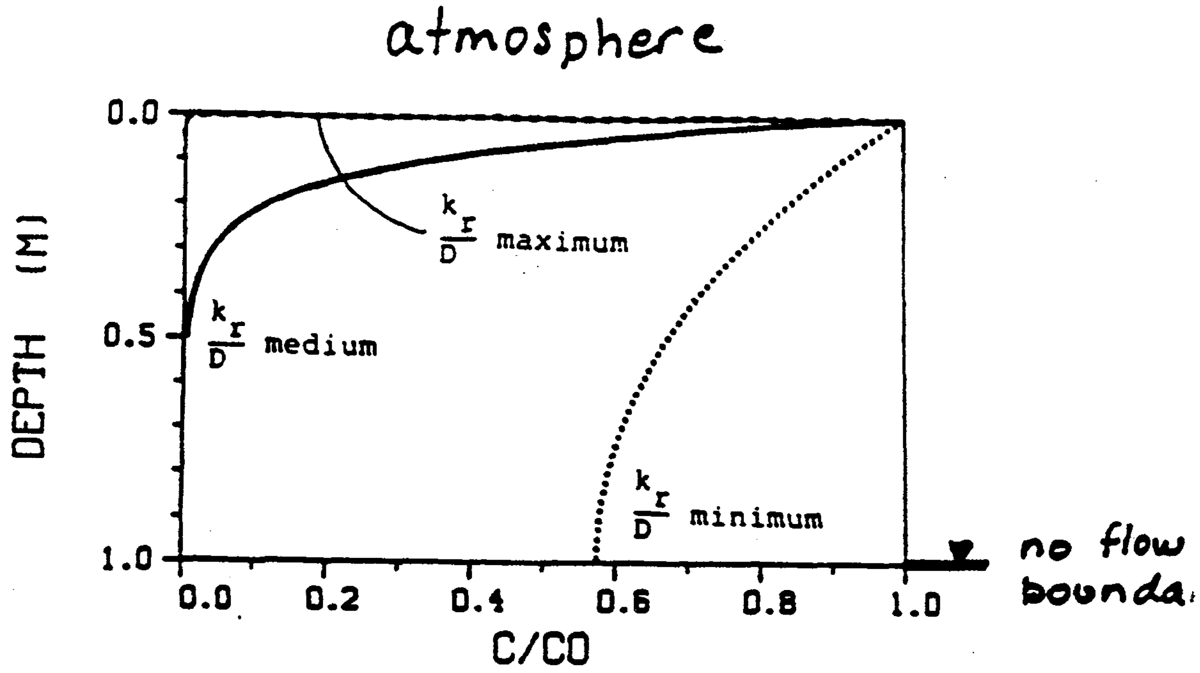


EXHIBIT 14

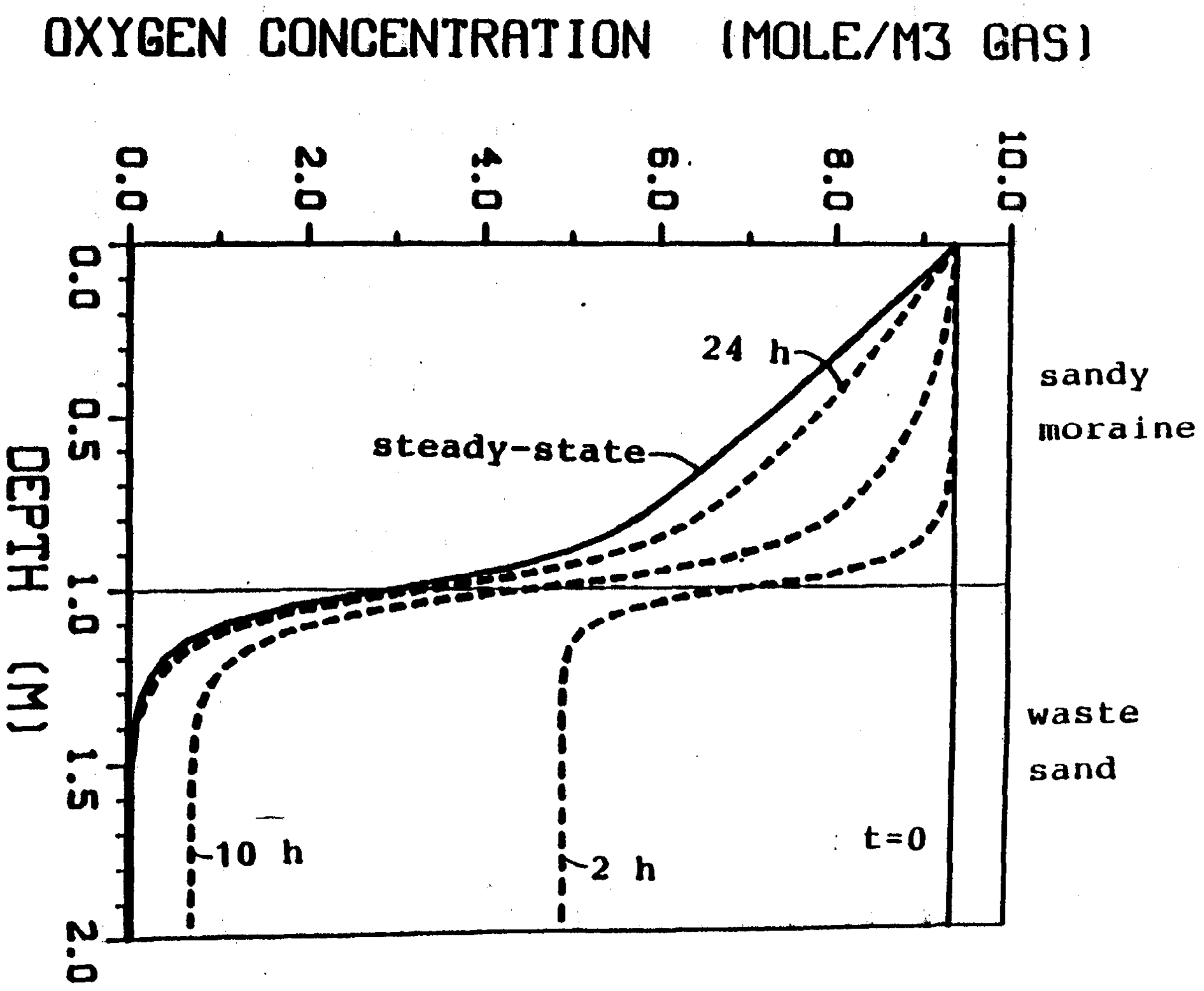

OXYGEN CONCENTRATION (MOLE/M3 GAS)
0.0
2.0
4.0
6.0
8.0
10.0
DEPTH (M)
0.0
0.5
1.0
1.5
2.0
24 h
steady-state
sandy
moraine
waste
sand
10 h
2 h
t=0

EXHIBIT 15a

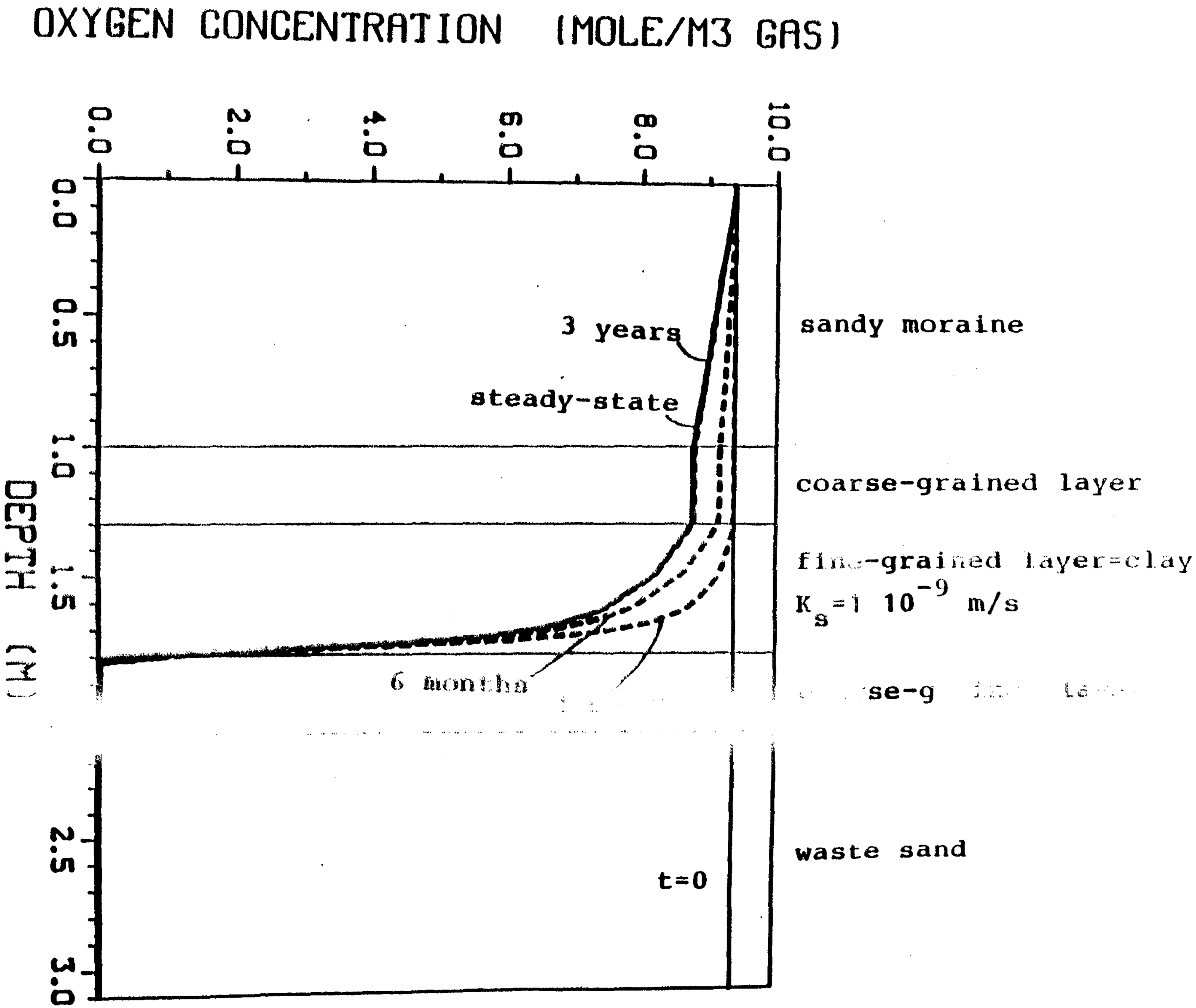

OXYGEN CONCENTRATION (MOLE/M3 GAS)
0.0
2.0
4.0
6.0
8.0
10.0
DEPTH (M)
0.0
0.5
1.0
1.5
2.5
3.0
3 years
steady-state
6 months
t=0
sandy moraine
coarse-grained layer
fine-grained layer=clay
$K_s = 1\ 10^{-9}$ m/s
se-g
waste sand

EXHIBIT 15b

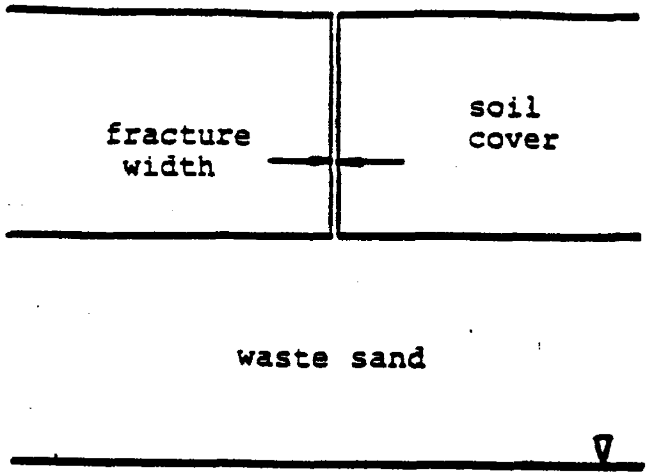
Long term stability of the seeling layer.

- freesing/melting ⇒ aggregation structure
- fractures
- root penetration
  - holes
  - drying

EXHIBIT 16

Oxygen diffusion through a fracture through the soil cover.

a: The fracture through the soil cover.



b: The simplified case. Radial diffusion with cylindrical symmetry.

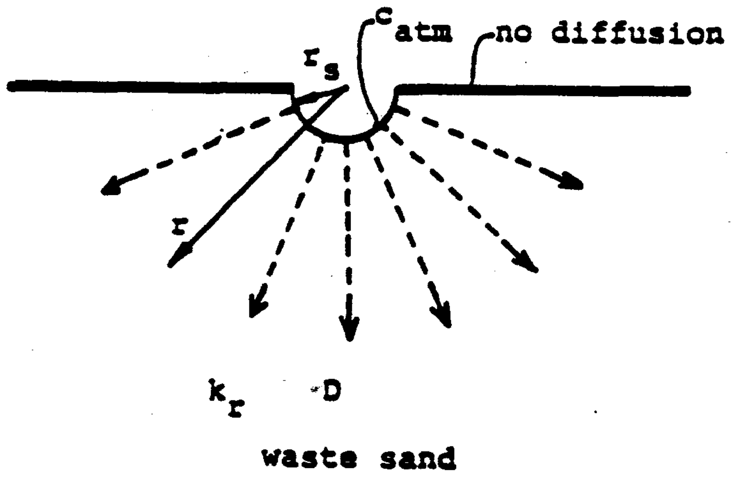


EXHIBIT 17a

DIFFUSION THROUGH A FRACTURE IN THE COVER

SPRICKA

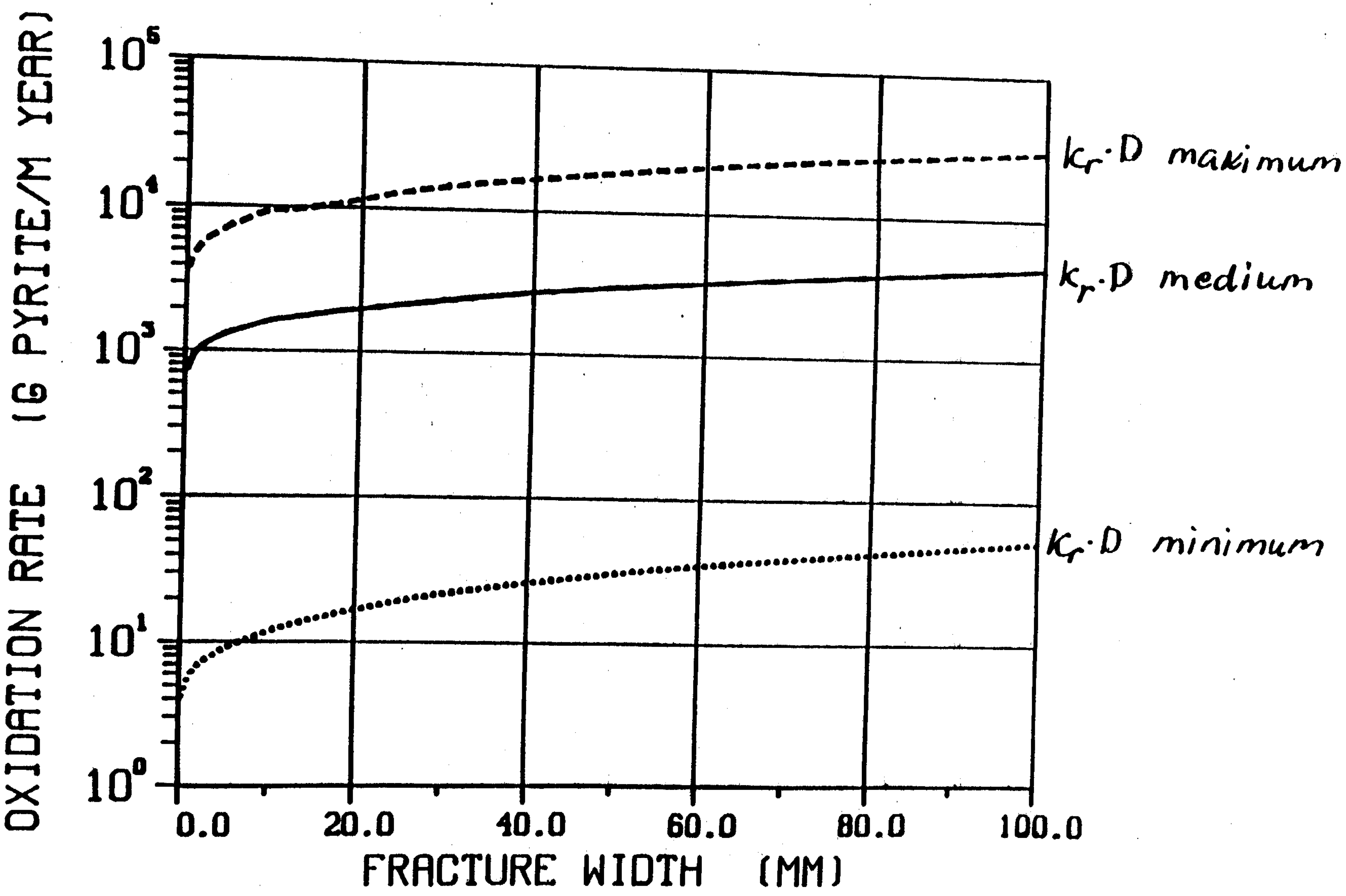


EXHIBIT 17b

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

PERSPECTIVE IN THE UNITED STATES
PRESENTATION BY DR. KIRK NORDSTROM OF THE US GEOLOGICAL SURVEY

Dr. Nordstrom attributes the differences in his perspective to two things:

1. Present conditions in the United States differ from those in Canada
2. He is a research scientist interested in understanding the complex and interesting processes that produce acid mine drainage (AMD) and what happens to that AMD when it enters the environment.

His personnel philosophical approach views nature as a laboratory where accurate field measurements determine the processes operating i.e. what processes are coming to equilibrium, what processes are rate controlled and what are the rates?

As he is involved in the use of several geochemical models, his presentation will provide an overview of some of investigations done in the United States where geochemical models were used to interpret the processes involved. A couple of examples will show where flow has been combined with geochemical models to look at the dynamics of a moving acid plume.

American Situation

It is estimated that there is 55 billion tonnes of mining waste, eighty-five percent of which is from copper, iron, uranium and phosphate mining. Copper and uranium together are the largest component. In some contrast to Canada, the U.S. is primarily looking at old, rather new sites.

Exhibit 1 prompted the questions brought up by Keith Ferguson and others in the Workshop--How much generation? how fast? and can it be predicted? These apply primarily to new sites. In the United States, they are almost always dealing with old sites, inactive or abandoned, where the acid is moving. The United States Geological Survey (USGS) wants to know how will the acid be dispersed, polluted, neutralized to any extent where is it not a problem and is some action required? Many investigations, most Superfund investigations under the Cercla Act, have been undertaken to determine the extent of the problem. The two remedial measures considered are source control or effluent control.

Investigations and Treatment Overview in the United States

In the 60's and 70's, considerable money was spent by the EPA on experimental sites and experimental laboratory efforts to determine alternate clean-up measures. Many wild and fantastic things which seemed quite viable were considered; things like reverse osmosis, chemical treatment; the sawdust pile treatment where the sawdust acted as a reducing agent to reduce AMD in streams by instigating reducing conditions and precipitating sulphides. In the end, most were not cost effective.

There were several experimental plots set up with covers and revegetation efforts. Dr. Nordstrom was involved with one in Virginia that wasn't too successful. In this case, three sulphide tailings piles from copper/zinc mines were contributing AMD to an adjacent stream. Treatment consisting of applying lime limestone as a neutralizing agent after grading. On top of that was sewage sludge with a top coat of soil. All was revegetated. Within a short period of time, AMD was still produced that would come to the surface and kill the vegetation. Bald spots would appear with the pile going back to its original state. They failed because there was a large lateral flow of oxygen and water entering the tailings maintaining the AMD process. If there had been some sort of barrier to that flow, the experiment might have been more successful.

Mine sealing was also tried as a treatment method for AMD.

Over the years, there has been a shift in emphasis of funding after all these treatments were tried. For example, it has been determined that lime limestone is the most cost effective in the short term; but as we know, it is not in the long term, so the United States is still facing some of the same problems. In a few cases, mine sealing has been quite successful in the short term; however there is no long term data to verify its effectiveness over the long term. There is some data available for some coal mine treatment sites and those seem to be not as successful as the United States would like to think they are. Some weren't successful at all because it wasn't possible to flood the mine to the point where oxygen was cut off from the system.

Only in the last ten years has serious consideration been given to precious metals mines mostly hard rock in the Western United States. Previously, most emphasis was placed on coal mine sites. It was thought that these sites would not pose any AMD problems because of the lack of water. This is true for some areas, but not for all. Precious metal/hard rock mining in the Western United States is the area of Dr. Nordstrom's experience.

Work in the United States has emphasized the development of hydrogeological models to look at mine sites with minimal emphasis on the geochemistry and little effort on investigating the wastes and the heterogeneity of those wastes.

In comparing the work done in the 60's and 70's with that in the 80's and 90's, there has been a major shift in sourcing. In the 60's, AMD work was carried out by universities, research institutes and federal agencies where considerable training and expertise exists. In the 80's the trend has been to fund consultants to investigate AMD sites. This is successful when the consultant has considerable training; but many times the expertise does not exist. Dr. Nordstrom wished to stress that there must be closer cooperation between researchers and government/industry who are dealing with this problem. Secondly, more use must be made of geochemistry to benefit the industry and the taxpayer. Geochemistry has many deterministic tools that are currently not being used or being used ineffectively by people who do not have a proper understanding of them. Geochemistry can illustrate processes, rates of processes that are retarding the movement of contaminants in the environment.

Geochemical Models Used For AMD Reactions

Dr. Nordstrom provided an overview of geochemical models in use within the United States, at which sites and the sources of literature for each. Please see Exhibit 2.

PHREEQE:

The PHREEQE program was developed by the U.S. Geological Service and is a thermodynamic mass transfer program somewhat similar to MINEQL and MENTEQ. It does not include transport; but has been combined with a flow model as in the Riverton, Wyoming site.

MINTEQ is a program that comes out of the Ridicule/Minicule series that was combined with the database from the Watec program. It has been applied to the Anaconda site and the Canon City site.

The MINEQL program has been used at Whitewood Creek, an active gold mining site.

WATEQ4F/BALANCE/PHREEQE is a strategic combination of programs by the U.S. Geological Service to evaluate geochemical processes in groundwater systems generally. The Iron Mountain Project is the first use of this program with a mine waste site. Charlie Albers and Dr. Nordstrom presented a paper on their Iron Mountain Project work at the GAC-MAC Conference in Vancouver, May, 1990.

Riverton, Wyoming

Two pieces of literature on this site exists. Art White, a geochemist, emphasizes the chemical modelling while Narasimhan, the ground water modeller, looks at flow modelling.

Please see Exhibit 3A through 3F. The study compared field measurements with both chemical and flow modelling results.

Exhibit 3A is a general site map locating wells, the piezometer sites, elevation of the groundwater, and the area of the uranium mill tailings. Area water flow is going down to the Little Wind River.

Please see Exhibit 3B. Full chemical analysis was done on the samples collected. Chemical analysis provided data on the major constituents and trace elements required for the chemical modelling. Exhibit 3B are the plots produced by the chemical modelling for distribution of sulphate, uranium, molybdenum and pH. The plots show the distribution in the shallow groundwater aquifer around the mill tailings.

Sulphate Plot:

The plot represents isosulphate concentrations. Hot spot of over 3000 at lower end of plume near Little Wind River.

Uranium Plot:

A similar picture is provided for the uranium. Very high concentration of 2 - 3 mg/litre are found at the lower end of the plume.

Molybdenum Plot:

Molybdenum behaves differently than the uranium which could be expected considering the geochemical properties. The highest concentration up to almost 1 mg/l are directly under the mill tailings. The molybdenum is getting hung up in comparison to the uranium and sulphate.

Question: What is the major factor affecting the molybdenum and uranium?

Dr. Nordstrom: This is an oxidizing environment so the uranium is going to mobilize at a very high source from here. The moly should do the same thing; however, the report is not clear on what is happening with the moly as it has not been studied that much. One would expect that the more alkaline the water, the more mobile the moly would be. One would expect in the studied environment that it wouldn't be that much different from the sulphate and uranium. All that can be suggested is that there is some type of strange absorption happening. Precipitation is possible if there is enough iron around which could be absorbing the moly or trying to make ferromolybdenite.

A comment was made by Mr. St. Arnaud on waste rock leaching sites in uranium deposits. Molybdenum has been observed to be much more mobile than the uranium.

Dr. Nordstrom: It is known from observance that moly will be absorbed because it is an oxi-ion. In oxidizing environments it should absorb as the pH decreases until extremely low pH's are reached. It should be more mobile in alkaline environments. This holds true for arsenic and selenium.

pH Plot:

pH distribution shows there is some change from the normal background of 7.5 to 8. Eventhough there is considerable sulphate being produced, the small variance in pH suggests that there is considerable neutralization occurring.

Dr. Steger: How are the sulphate and uranium results explained?

Dr. Nordstrom: Please refer to Exhibit 3C, the depth profiles of pore water in the tailings, to shed some light on that question. The water table is at 6.6 m.

pH Profile:

pH are running between 1 and 3 until a big increase in pH occurs at the 3 m depth. The groundwater which is neutralized and fluctuating moves upward during certain periods in the year to neutralize the portion below the 3 m mark. This is further illustrated when you look at the Cu, Se, Zn Profile, where these elements are more concentrated in the upper 3 m and decreasing drastically in the mixing zone.

Uranium Profile:

The same thing is occurring with the uranium profile. Molybdenum is totally different.

Na, Ca, Mg Profile:

It could be interpreted that a lot of Ca and Na have already been leached out of the system to normal background concentrations in the groundwater at the 6.6 level. There is still Mg around being leached out moving back to groundwater concentrations at the groundwater level.

Mn, Al, Fe Profile:

The same thing is occurring with these elements except during mixing there is some precipitation occurring at the 3.0 m level.

HCO_3, SO_4,Cl Profile:

This profile reflects the same processes as the Mn, Al, Fe profile.

The emphasis on White's paper was to put together a mixing model that could explain this groundwater mixing combined with a geochemical model looking at the precipitation of the solution in the mixing. The PHREEQE program was built to look at mixing of two different kinds of waters and to illustrate what kinds of mineral solubility reactions take place under those conditions.

Mr. Davé: What are the values in the saturated zones? Are they the same as at the lower end of the profile or the high peaks?

Dr. Nordstrom: There are low values at the water table level illustrated. The farther down one goes in the saturated zone, the more the values move to the background concentrations normally found. The peaks are an anomalies.

Dr. Steger: Why would you get the concentration of the uranium and sulphate away from the source of the plume?

Dr. Nordstrom There was residual sulphate in the tailings used in the refining of the uranium which was dumped with the uranium in the tailings for a certain period. Now that has moved down. We have an estimate of the travel time as we know when it was stopped.

Dr. Scharer: Was there gypsum in the tailings?

Dr. Nordstrom: Yes, gypsum is normally found there and shows up very nicely in the calculations. Referring back to Exhibit 3B, the shaded area in the sulphate diagram is the water supersaturated with gypsum. Since the sulphate came from the combination of initial sulphuric acid and pyrite oxidation, it is keeping the Ca concentrations lower than expected because of the saturation of gypsum.

The researchers of this site took an average pore water concentration of elements from the tailings data and a background groundwater chemistry composition mixing them in the portions using sulphate as a conservative mixing parameter to determine what happen with the precipitation of the solution. Their results in the mixing zone showed that, on the average, 1.7% of the tailings water would mix with the groundwater and also that calcite and gypsum saturations would be reached. With those constraints, they calculated what the results of pH would be. Calculated results were compared with actual field measurements. This simple model was quite successful. The pH range is very close to 6.5 in the mixing zone which they could achieve with the constraints mentioned.

Chemical modelling on uranium distribution was also done with some estimates of species produced and solubility controls by White.

See Exhibit 3D. Narasimhan's paper looks at the flow modelling and how it was combined with the geochemical model. The problem was looked at like any other flow model. Three stages were used. The infiltration problem looked at the amount of infiltration doing a water balance flow through the unsaturated zone to the water table. The second stage was the interaction of the aquifer with the tailings in the mixing zone. The third stage was the plume migration moving away from the tailings site. The DYNAMIX program used for this modelling was a combination of the earlier programs called Trust and Trump. They carried through the flow modelling to a stage where they had the initial constituents concentrations whereby they introduced the geochemical model to look at the mass transfer of the constituents and the interpretation of different solution processes. They continued to the next stage of flow modelling and again looked at the geochemical distribution of species, carrying that all the way through.

Please see Exhibit 3E for some of the results of their modelling which demonstrates in a time series the manner of the sulphate plume moving out at 2, 4, 5 and 20 years after the active period of dumping. Twenty years was the approximate time to which they were doing the study. At five years, one can see the plume moving out and the concentrations of sulphate increasing from the sulphate moving from the tailings to the shallow groundwater system.

Exhibit 3F compares the modelled plume with field measurements of the plume. For this complex problem, the calculations were somewhat approximate. Dashed line is the field data. The model gives the right general features and fairly reasonable estimates of the flow characteristics and travel time. If this was done on a conservative basis without the inclusion of gypsum saturation, the results would look remarkably different. I would like to have seen the difference done for the paper.

It is standard procedure to measure the isotopes of water in hydrogeochemistry, the O 18 deuterium and tritium, to obtain a better idea if evaporation is a major process. At the Riverton Site, it was shown that it was and that it concentrated the sulphuric acid to enrich the water than otherwise would be. An isoevaporation line was shown for this data, Exhibit 3G. Tritium would give some resident times for barelium??? water.

Anaconda Smelter Site

Investigations were done by Tetratec under contract to Anaconda Minerals. It is in an RIFS. The Anaconda Smelter Site is near Butte, Montana and is an area of historically large copper reserves. There are three possibly four Superfund sites all in some sort of disarray.

Historically at the Berkley Pit, the company pumping water from the abandoned copper pit ceased operations in light of possible EPA action. The pit is slowly filling up with a considerable amount of acid water at 3/3.5. This acid water is now reaching the aquifer for the town of Butte and getting into the mine workings under the town of Butte. It could be a major disaster. So much has been produced, that one wonders even if it were treated if it would make any difference. The ministry hasn't been doing anything to correct the problem.

Please see Exhibit 4A. Down gradient from the pit is Silver Bow Creek, a tributary of the Clark Fork River at some 200 kilometres long. The Superfund site which is the worst site is known as the Anaconda Smelter Site and contains tailings piles, waste piles and settling lagoons. The largest tailings piles and ponds are known as the Opportunity Ponds. These have been divided up into different domains, samples have been taken and wells introduced. The groundwater movement of the contaminants has been going roughly north towards the top right corner. The questions were how fast were the contaminants moving, do we need to worry about it and what should be done?

Exhibit 4B shows a schematic cross section of the Opportunity Ponds. The tailings sit on an alluvial aquifer. The groundwater table goes into the tailings a little bit coming down to the surface at the lower end of the cross section. This is a complex area with numerous changes in the distribution of grain sizes and types of material that were installed. Good records were not kept by the operating company. The area is difficult to sample.

Exhibit 4C shows the results from the water sampling, the well locations, and the concentrations of sulphate in mg/l. The sampling shows certain hot spots and the suggestion that a plume is moving. Two hot spots are shown; one near the arbiter plant and one just past the lower edge of the Opportunity Ponds. Sulphate more or less moves with the groundwater flow; so these measurements indicate that there is a plume moving out. Sulphates in this environment are fairly conservative in that they may be reacting and the measurements are a small portion of what is actually there.

Most everything else has not moved with the sulphate. There are zinc and arsenic anomalies in the data which would suggest that these elements are moving out as well.

A problem with the site is that oxygen profiles were not measured which you would like to see. There was a program to calculate the oxygen in the tailings as an stimating step for the production of acid water and molybdenum contaminants. Exhibit 4D is one example of these calculations looking at the movement of oxygen in different time periods. This work was part of an overall model done by Steve

Greedy. Mr. Greedy built the ILWAS model, a watershed type model. They applied it when looking at the contaminants in the tailings pile. It is a fairly good approach; but its weakness is that there wasn't sufficient site data to really confirm how things were moving and how they were being attenuated.

Please see Exhibit 4E. From the geochemistry of the solids at the site, they found some reduced layers, some very dark carboneous material. A conceptual picture was put together of the processes occurring from reduced layers and the site data. There is a 6-9 foot oxidized zone with the lowest pH's and oxygen profiles. Contaminants are moving down into the lower 10-70 zone of the tailings. A lot of the metals are coming out here because of the reduction occurring. There is no oxygen with a pH of 6.0 - 6.5. Not many of the contaminants are moving into the groundwater layer because of this barrier. Elements that are not affected by this reducing environment, Ca, SO_4, are moving into the groundwater and are evident in the plume moving out. One of the problems with this is that there is only one good cross section of this reduced zone in the tailings. There is no understanding of how extensive it is or where it is. Most likely it is fairly erratic and scarce. This leads to some doubt as to how effective this model theory really is.

One conclusion of the study was that it would take in the order of 20,000 years for significant contaminants to move down into the groundwater. Dr. Nordstrom feels that this is a dangerous conclusion. All that would be needed would be a few leaks in the right places to skew the conclusion.

Whitewood Creek, South Dakota

This is a Colorado School of Mines publication by Dr. Cherry, Morel and others. It looks at the source of the arsenic and selenium bleeding into the creek and what happens to it. The site was a combined study by consultants and the Geological Survey. Please see Exhibit 5A. The area has historical and current mining operations and is subject to flash floods with rapid movement of sediment down through the system. Whitewood Creek goes into the extensive Belle Fourche River System. One problem is that the sulphide tailings are deposited in the slow moving sections of the river. They start oxidizing as the water goes down.

Exhibit 5B shows a typical cross section of Whitewood Creek with shale underlining all, an alluvial aquifer, tailings on that, some slime material and yet more tailings. The problem when they looked at the solid phases and the water chemistry of the tailings material was that they found arsenic and selenium were bleeding out. They found that the mobile arsenic had already been oxidized from arsenopyrite and other arsenic-bearing sulphides and that it was in an exchange site. It was undergoing mobilization through desorption.

The selenium was not found in source material or exchanged source material but was bleeding from the shale. It is common in the Western United States to find selenium in shale which is a considerable water quality problem. Thus, there are two different sources in this study: one relating to mining and one not. This is often not obvious to investigators working on a site.

Exhibit 5C shows some profiles from the Martin Site. The interesting thing is that there are two monitoring locations at the one site. The oxygen profiles vary from concave to convex.

The modelling done at this site used MINTEQ. Exhibit 5D shows examples of their modelling results with input concentrations of Mg, Ca, SO_4, AsO_4. Their calculations closely resembled actual measured concentrations. Mg is doing nothing, the Ca is involved with gypsum saturation to give changes. These values are minus the log of the molar concentrations so the higher the number the lower the actual concentration. Arsenic using the adsorption model of MINTEQ got very good agreement between predicted and actual. This is one of few cases where it has been successful.

Pinal Creek

Please see Exhibit 6A. Pinal Creek is a copper mine near Guelph, Arizona. A reservoir of acid water in the lake is seeping under the tailings into the local alluvial aquifer. This plume of acid is slowing heading down gradient to the reservoir of the City of Phoenix. Considerable investigation is currently underway on the site by both mining industry and the Survey.

It was felt that Webster Lake was the recharge source for the acid plume that is now in the alluvial aquifer. All the leach liquors with pH of 2.5 to 3.0 were dumped here. There is a nose cone of acid water moving down the rather narrow valley. The nose cone has varying pH from 2.5 to 3.0 in the central area as the worst case up to background levels elsewhere. Under study is the rate of movement and the rate of attenuation. The Lake has since been drained to eliminate the recharge source. The mining company has put three wells in the center of the acid plume and are pumping the contaminated water out to the top of the tailings piles. The tailings stretches over a one mile area and are about two hundred feet high. Being an arid climate, the pumped solution dries out and sits on the top of the piles except for the question of air pollution. The area is subject to high winds with the dried solution blowing around. Nordstrom finds it hard to believe that there are not some contaminants being blown around. This factor has not been investigated. It is hoped by pumping the central core, the worst stuff, that the remainder will be dispersed and will not pose a threat to the Phoenix aquifer.

It has been an example of the mining industry and the EPA working closely and well together. One reason for this has been attributed to the fact that this is not a Superfund site. The EPA simply came up with the Clean Water Act and asked what could be worked out with the problem. The mining industry complied.

QUESTION AND ANSWER PERIOD:

Dr. Nicholson: The issue was brought up yesterday that it would be very relevant in the modelling of tailings to get down to less than one ppm concentration coming out of the end of the pipe through geologic material into the receiving environment. With our present tool box of geochemical modelling, how effective would that tool box be in getting us those predictions with any precision for metals?

Dr. Nordstrom: It will depend on partly how well we know the hydrogeology. With surface or groundwater systems, the larger uncertainties are with the hydraulic properties. We can measure things and do geochemical calculations for some things that have a much lower uncertainty than a discharge measurement or a hydraulic properties of a tailings pile or a groundwater aquifer. The kind of models we use are deterministic and do not need calibration. The only problems involving uncertainties are involved with two major sources: thermodynamic data and I can give good information on things we do and do not know, things like gypsum, calcite, fluorite. A lot of these common minerals turn out very good data; maybe better than we realize for modelling purposes. In terms of cadmium, copper, zinc it is more difficult.

I would like to see a convergence of good field data with application to chemical models extracting rate data, rates of attenuation. Therefore we don't have to understand the process in effect entirely, but we do know the rate which would be quite good for modelling the overall picture.

Dr. Nicholson: That field data link does not exist yet.

Dr. Nordstrom: I cannot emphasize enough that there is not enough good field site data. There is a lot of water quality and mineral data, but often it wasn't collected with those objectives in mind and has many incomplete parts.

Dr. Scharer: There are two problems here. One is lack of field data and the other is marrying the rate modelling with equilibrium modelling. It is not always easy.

Dr. Nordstrom: The way I see this is we task nature to see what is in equilibrium. This becomes a reference point and from there, we see what things are clearly not in equilibrium and what are the rates of those?

Dr. Snodgrass: This relates to geochemical modelling. In your view for trace substances not dominated by the sulphites, is it mineralogical pure phase minerals or is it coprecipitation in solution a more probable area of uncertainty in chemical modelling?

Dr. Nordstrom: Yes. There are some things that precipitate as if not pure, near pure minerals. We are getting a better idea of what other phases there are. Others are clearly salt-substitution minerals or minerals that have high concentrations of trace elements. There are other minerals which we don't have any data on to provide comment.

Dr. Snodgrass: Can you provide such an example of minerals?

Dr. Nordstrom: A lot is known about calcite including on salt-substitution solubilities and what trace elements are going to change that. Gypsum tends to be fairly pure for modelling. An example of a salt-substitution mineral is jaercite. Although jaercite can be treated with a stoichiometary saturation approach so that the composition of the thing in low temperature environments that we are looking at doesn't change that much. What variations that occur are within the errors that occur elsewhere.

Dr. Snodgrass: What happens in aluminium hydroxide regimes?

Dr. Nordstrom: I think aluminium is in good shape. The problem is the rate of transformation between metastable phase like base alumni that we know precipitates readily and what happens during the transformation of that to aluminite which is really the most stable phase. This is where we need better field data.

* * * * * *

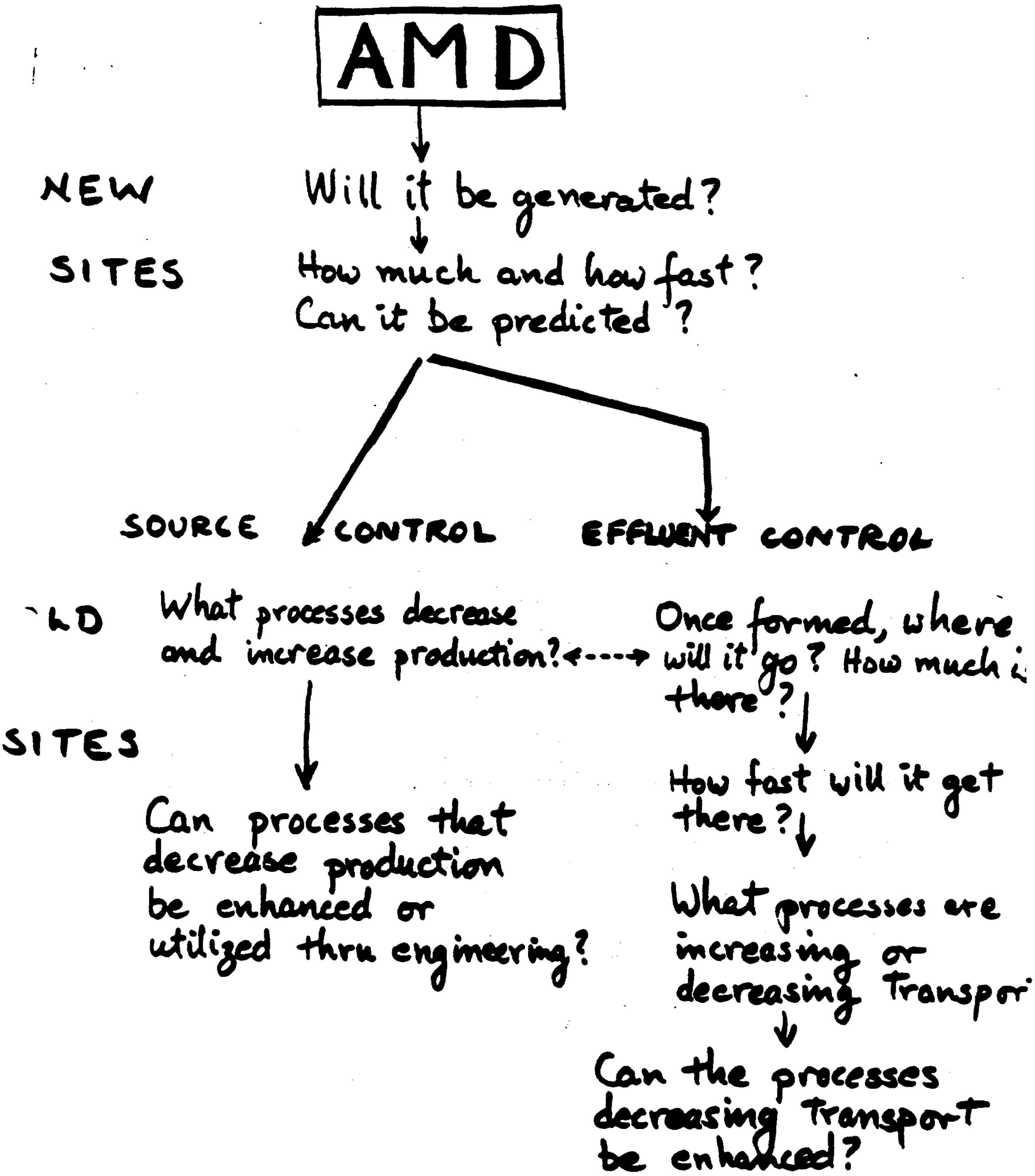

AMD
NEW
SITES
Will it be generated?
How much and how fast?
Can it be predicted?
SOURCE CONTROL
EFFLUENT CONTROL
LD
SITES
What processes decrease and increase production?
Once formed, where will it go? How much i there?
How fast will it get there?
What processes are increasing or decreasing Transpor
Can processes that decrease production be enhanced or utilized thru engineering?
Can the processes decreasing Transport be enhanced?

EXHIBIT 1

GEOCHEMICAL MODELS USED FOR AMD REACTION

PHREEQE -

Riverton, Wyoming (+ DYNAMIX)

MINTEQ -

Anaconda smelter site
Canon City, uranium mill tailings

MINEQL -

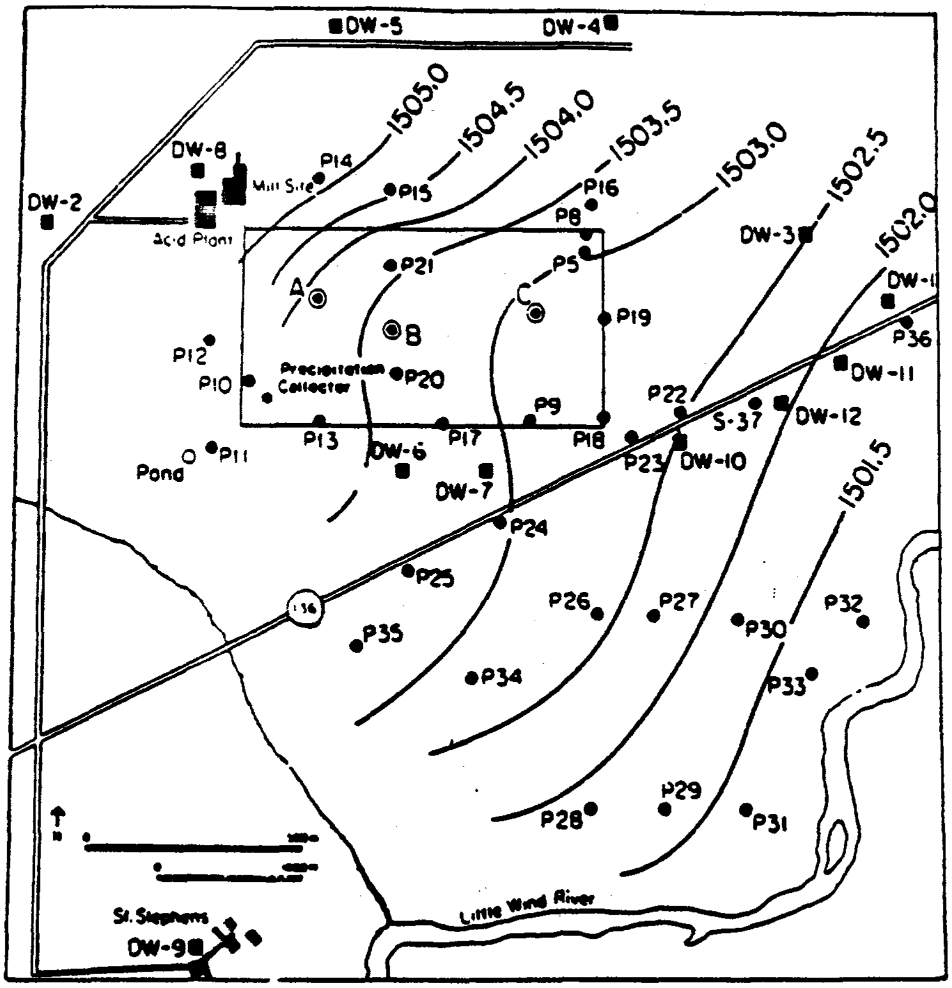
Whitewood Creek, South Dakota

WATEQ4F/BALANCE/PHREEQE -

Iron Mountain, California

EXHIBIT 2

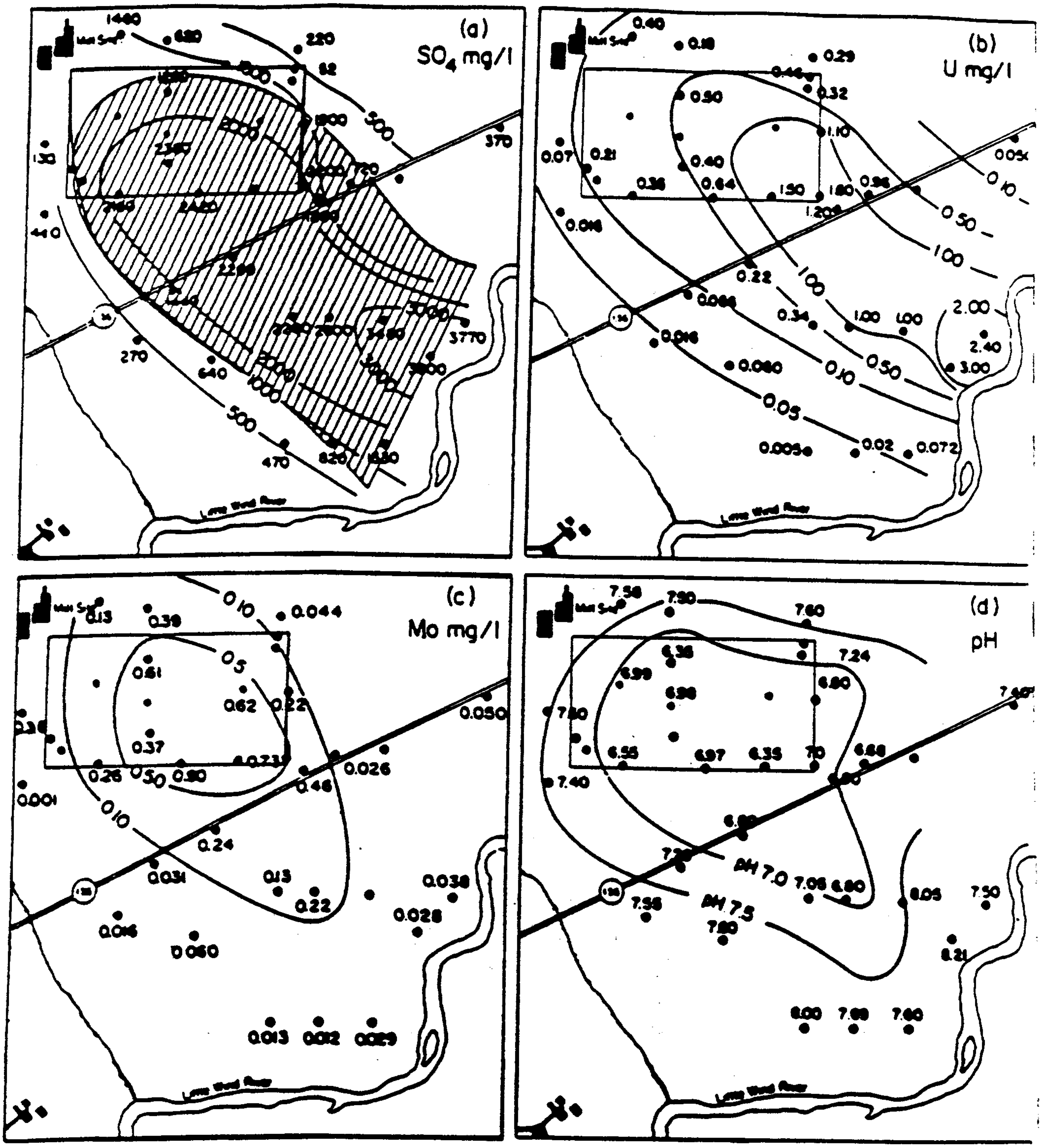
Welcome Screen | Search | Report List



Location map of the Riverton mill tailings. Designated sites beginning with DW are domestic wells in the Wind River aquifer, P sites are piezometers completed in the alluvium, and A, B, and C sites are nested suction water samplers completed in the tailings pile. Rectangle enclosing sites A, B, and C shows approximate dimensions of the tailings pile. Elevations are for the groundwater surface in the alluvial aquifer.

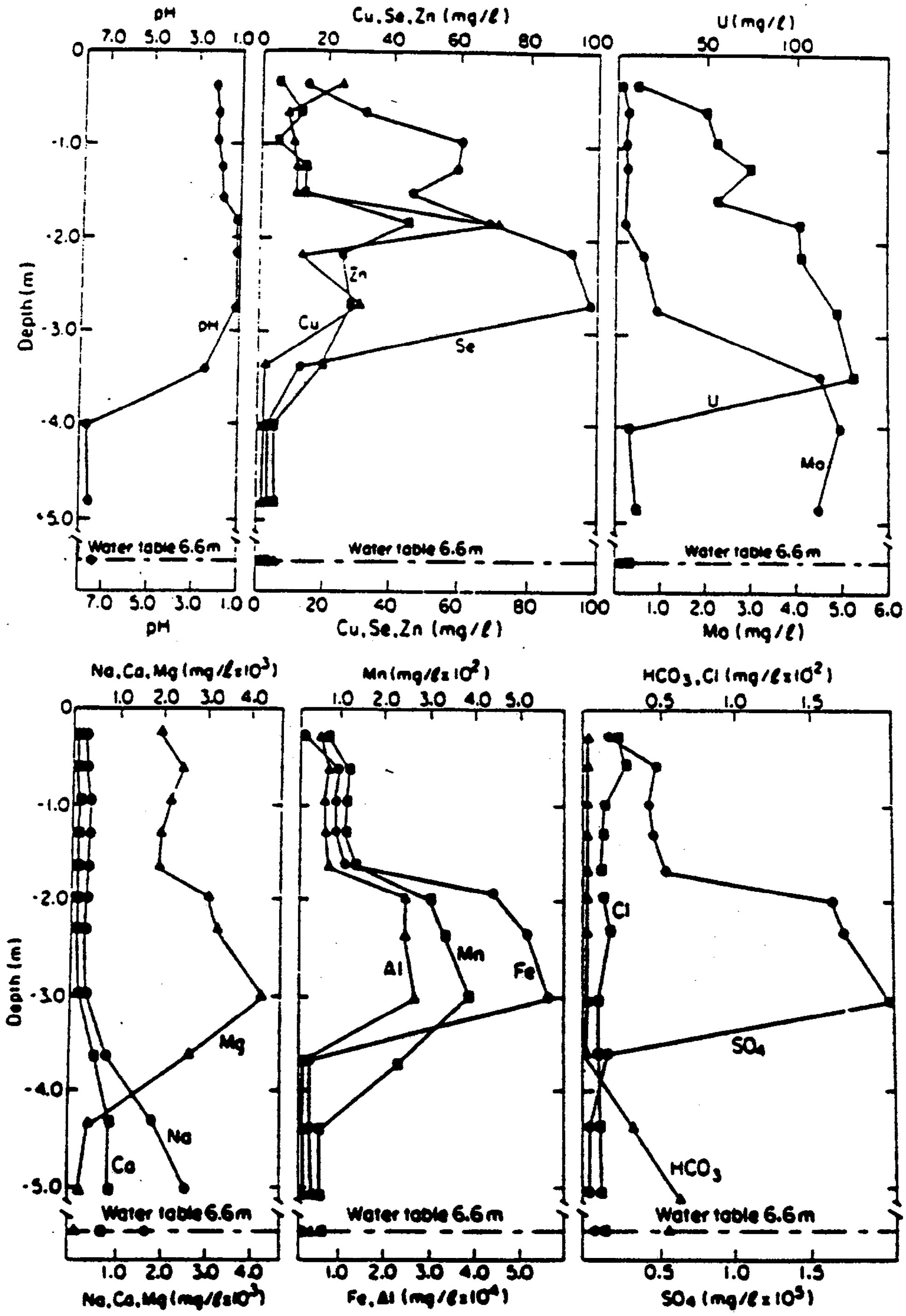
EXHIBIT 3a

Welcome Screen | Search | Report List



Contaminant distributions for groundwater in the shallow alluvial aquifer. Extent of gypsum saturation is shown by shaded area in Figure a.

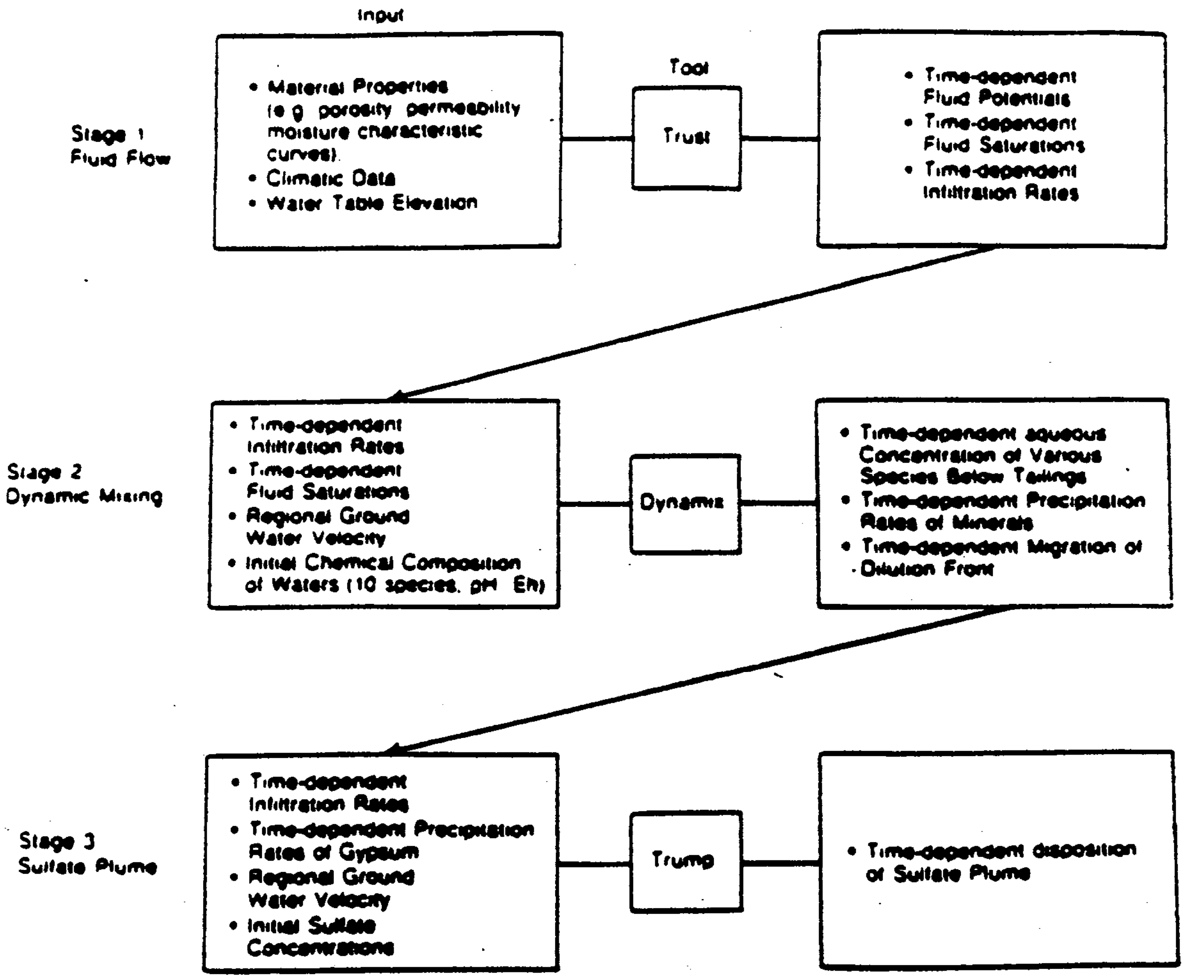
EXHIBIT 3b



Vertical chemical distribution of pore waters in the tailings pile.

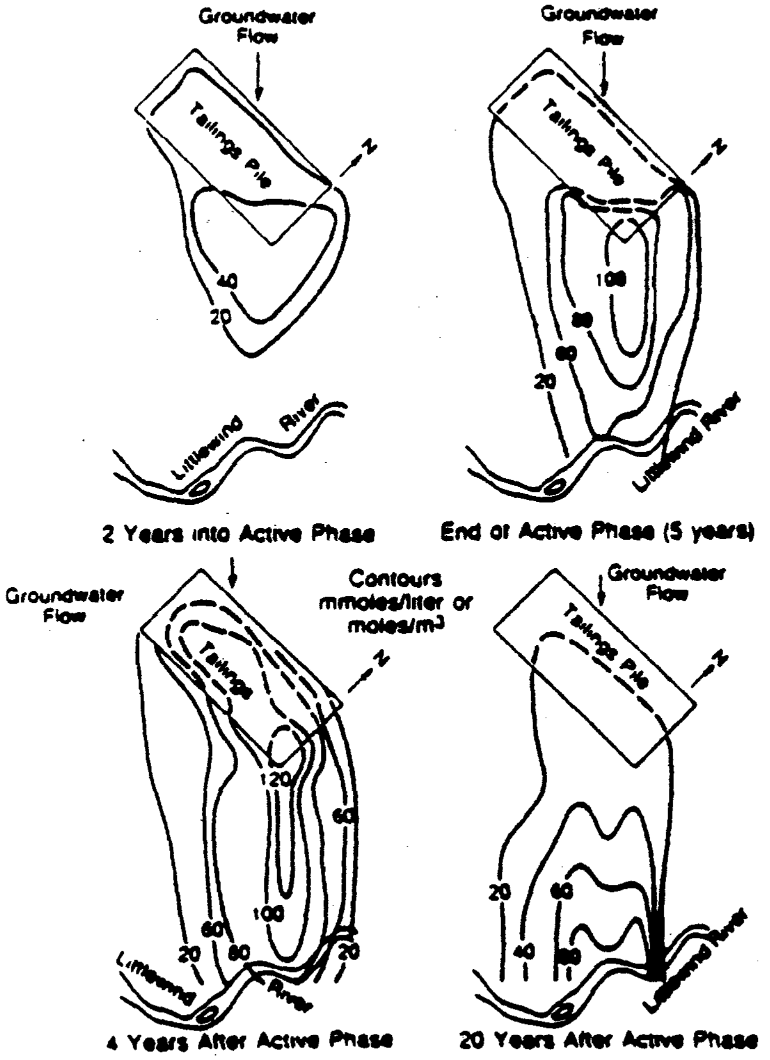
EXHIBIT 3c

3-Stage Sequential Approach for Modeling
Hydrology and Geochemistry
at Riverton, Wyoming



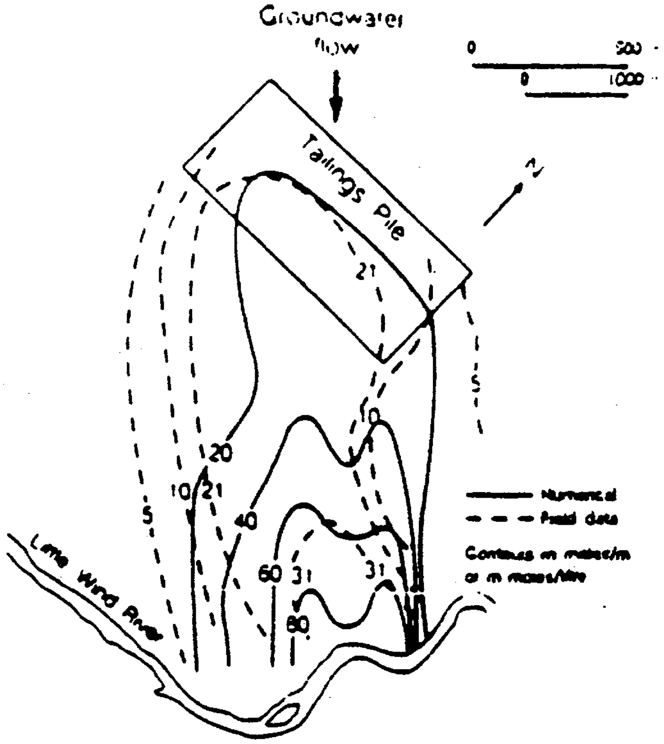
Three-stage sequential approach to history matching.

EXHIBIT 3d



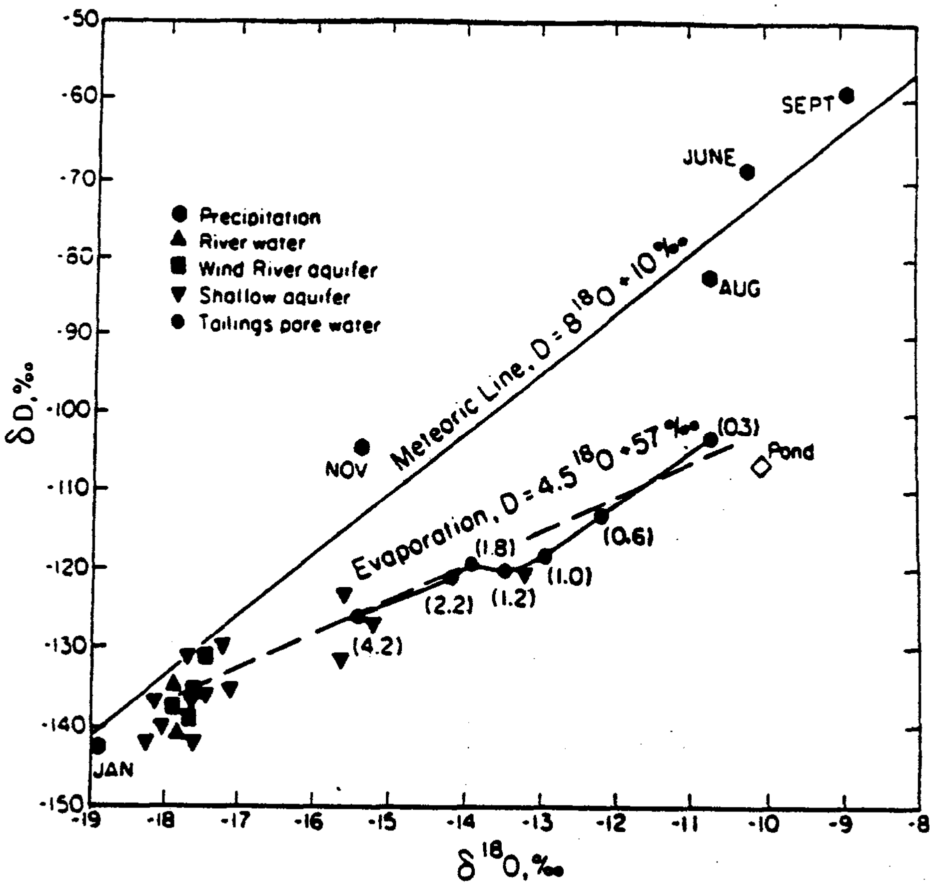
Results of simulation: sulfate plume as a function of time (Riverton).

EXHIBIT 3e



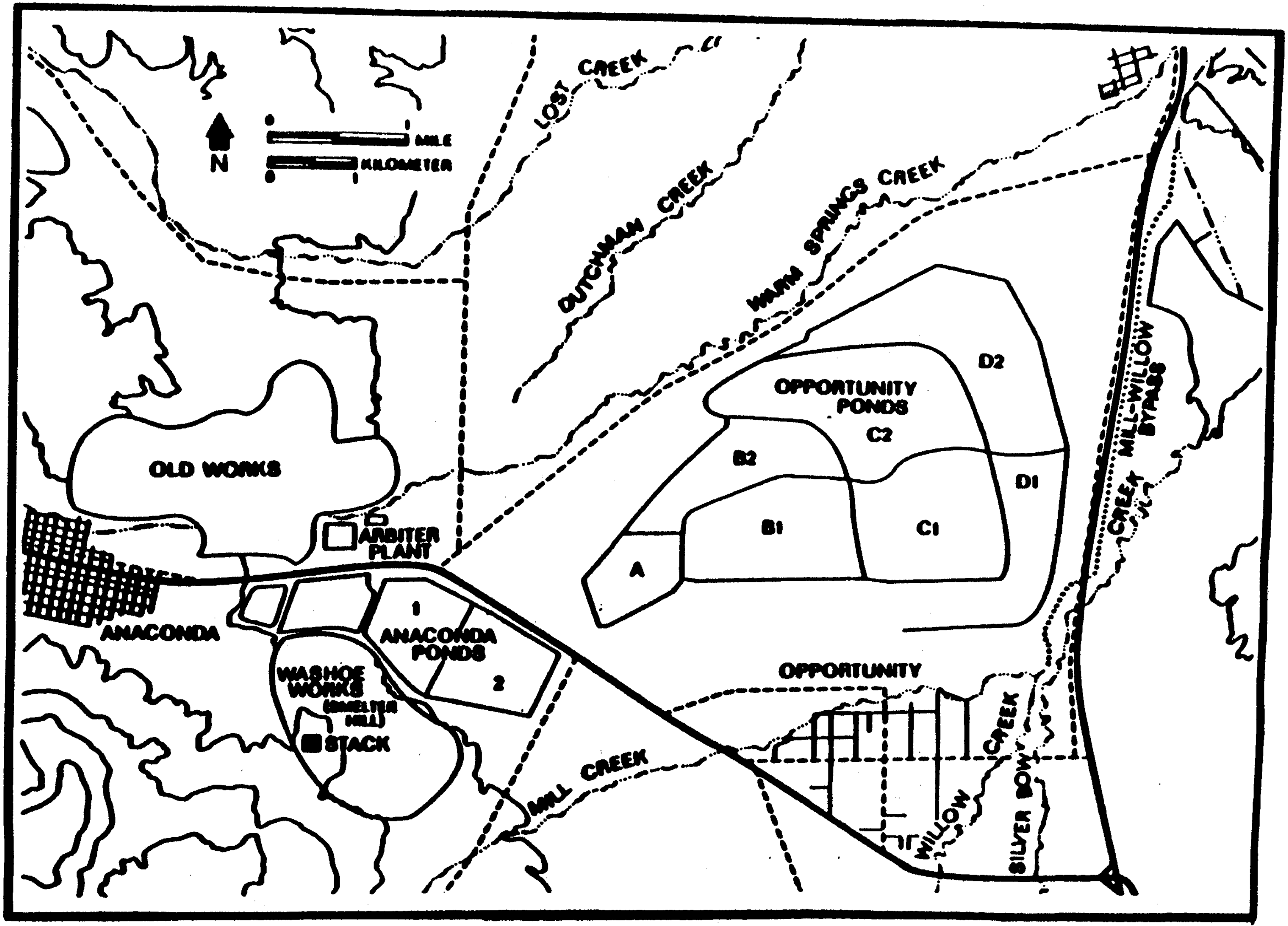
Results of simulation: comparison of simulated and observed sulfate plumes. Twenty years after abandonment

EXHIBIT 3f



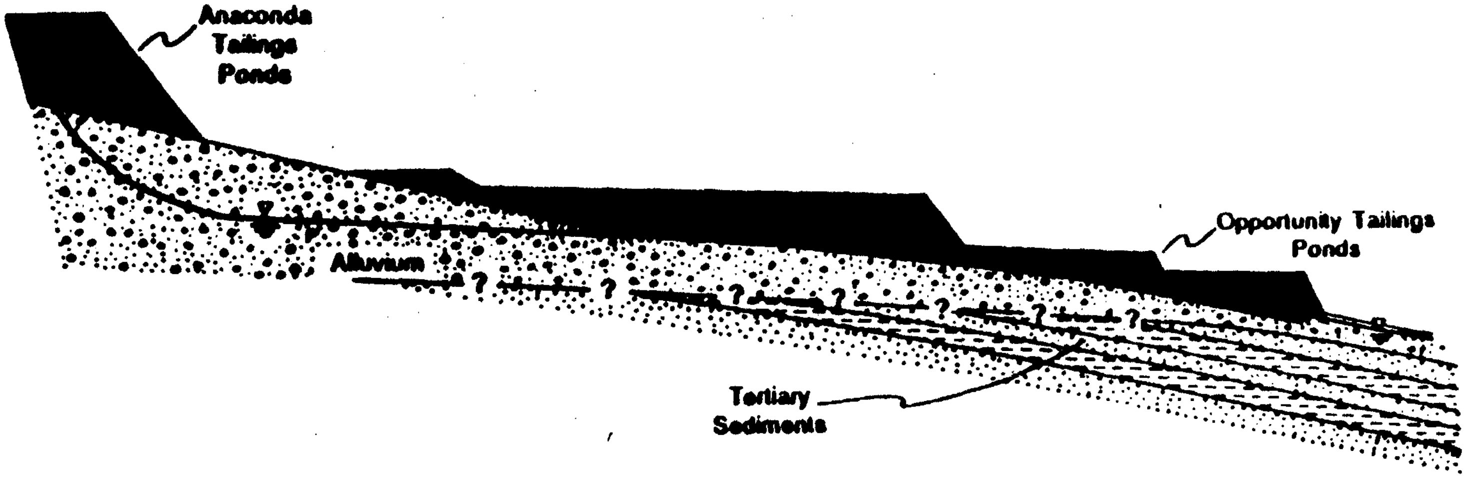
Deuterium-oxygen 18 values for waters contained in and surrounding the Riverton tailings. Numbers in paren theses are depths in meters of tailings pore water below tailings surface.

EXHIBIT 3g



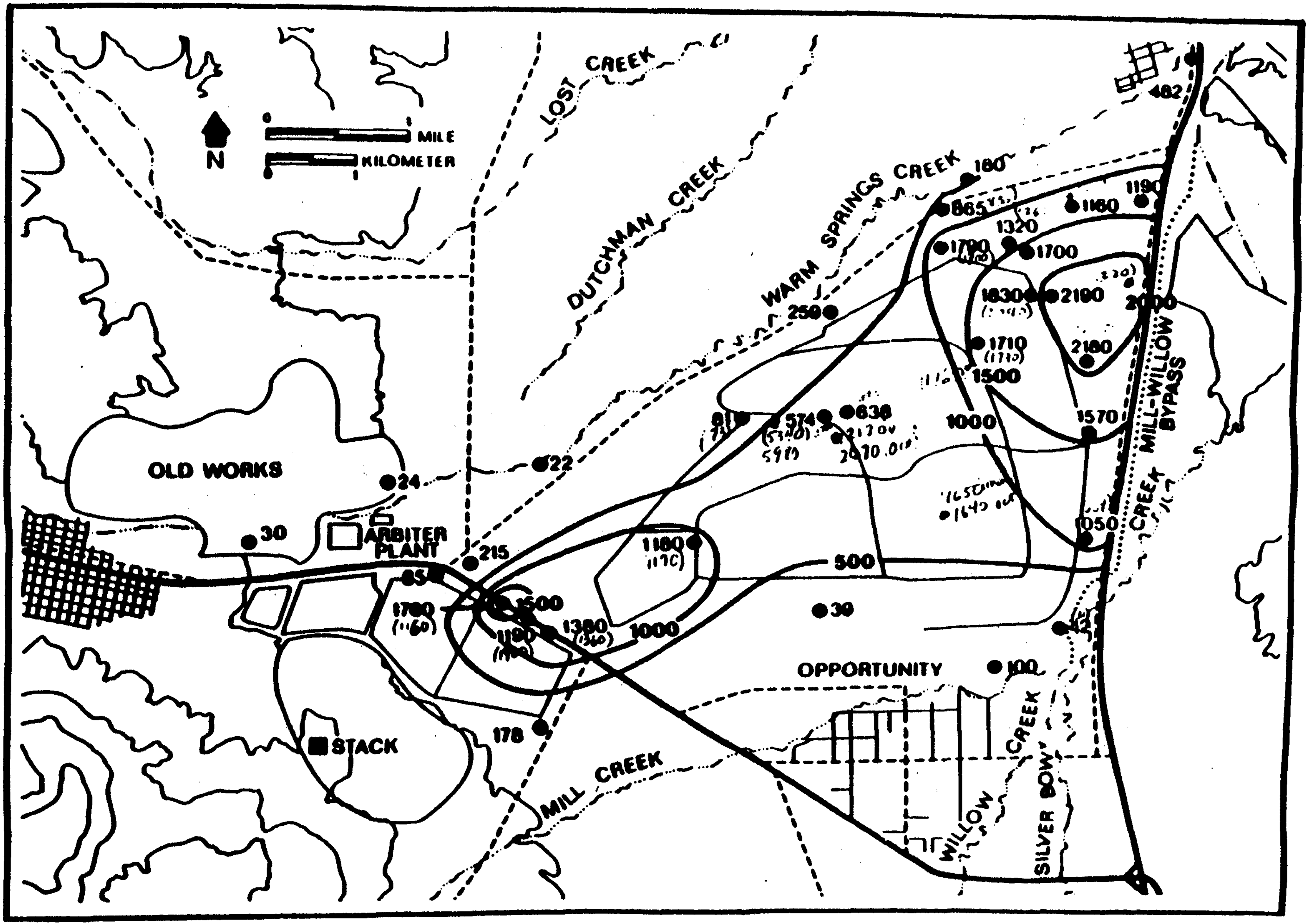
Map of the Anaconda Smelter site and associated tailings ponds.

EXHIBIT 4a



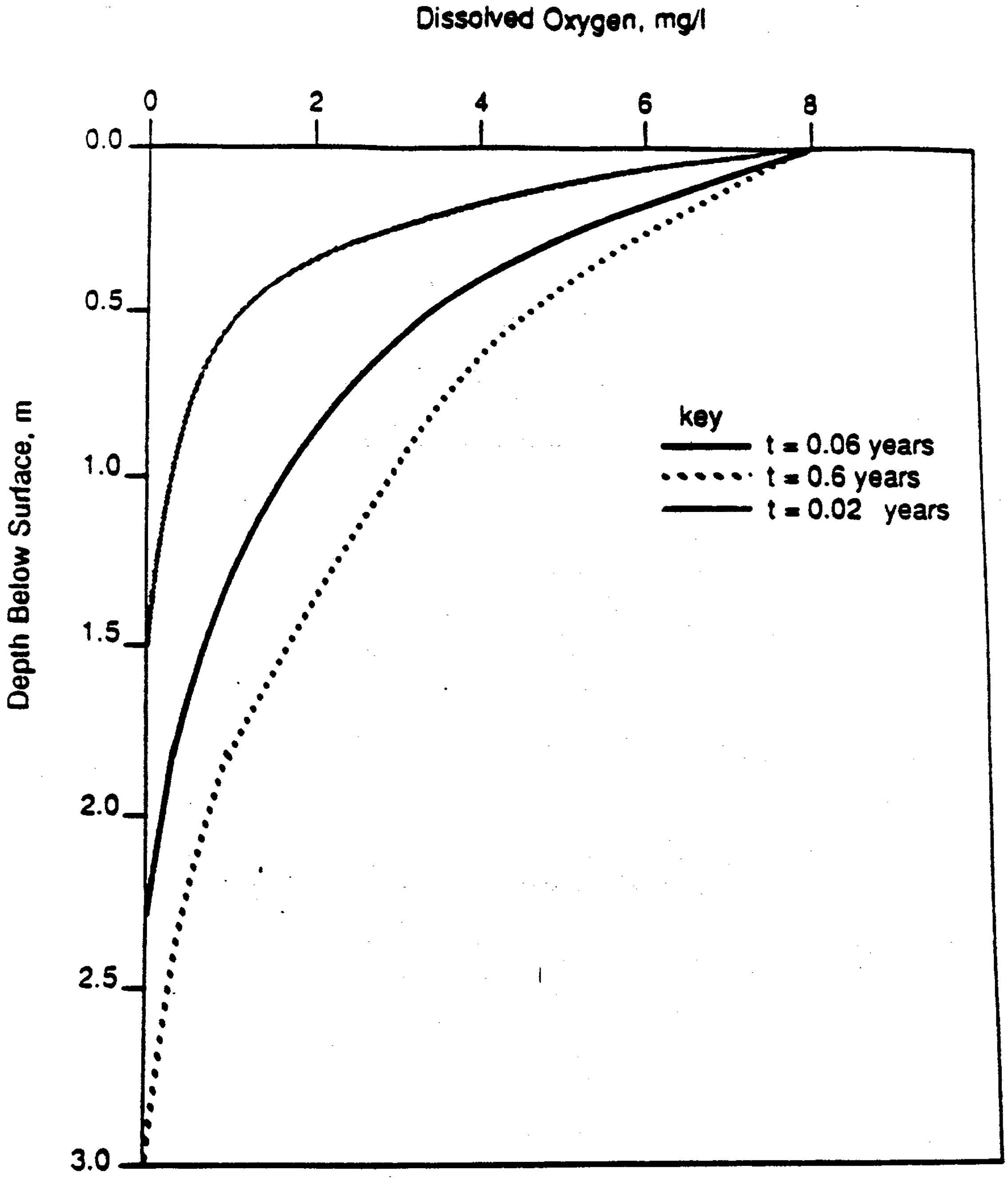
Schematic northeast-southwest stratigraphic cross section along long axis of Opportunity Ponds.

EXHIBIT 4b



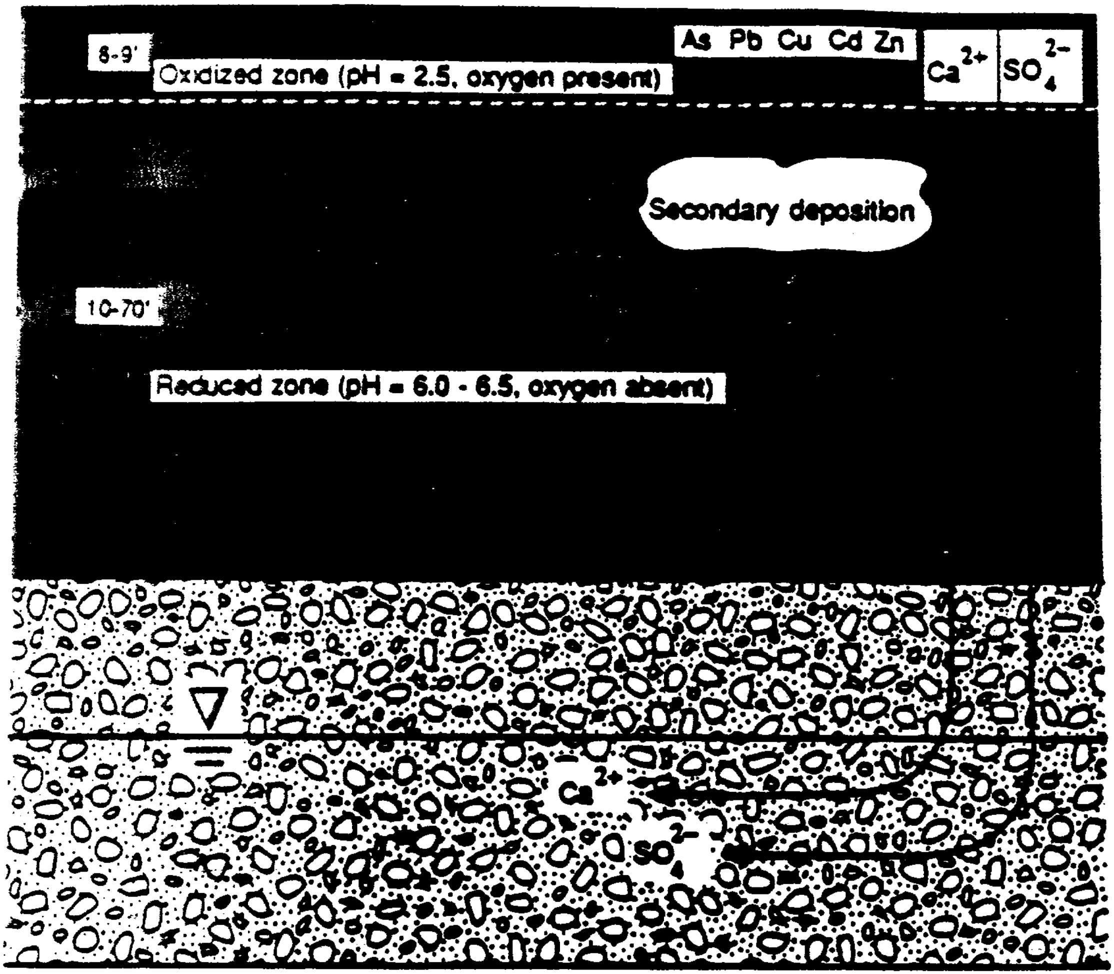
SO_4 concentrations (mg/L) in October, 1985 in alluvium in vicinity of tailings ponds.

EXHIBIT 4c



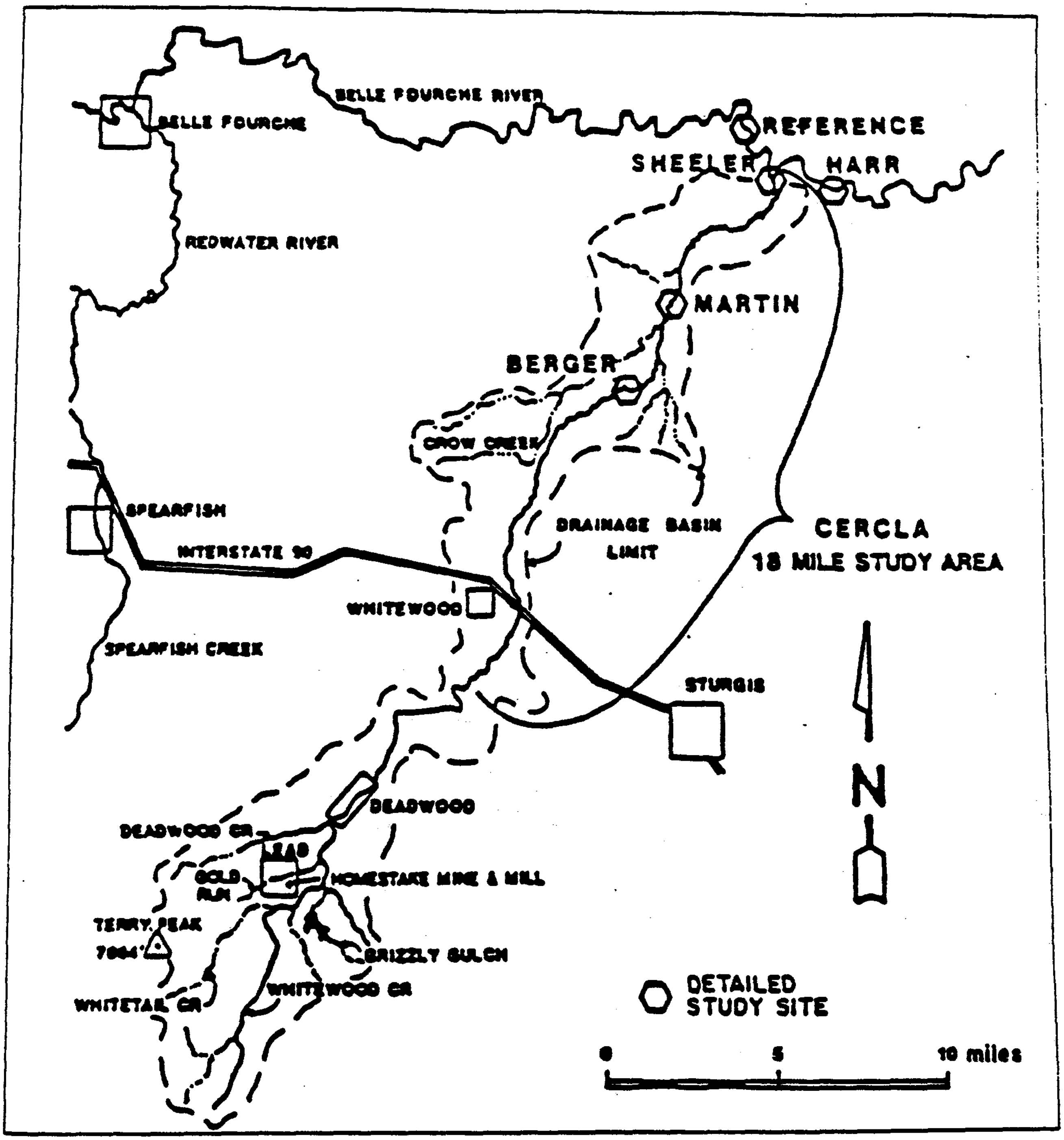
Predicted dissolved oxygen profiles in tailings ponds for t=0.02, 0.06, and 0.6 years, assuming no dissolved oxygen present at t=0.

EXHIBIT 4d



Conceptualization of secondary deposition of solutes in reduced zone of tailings deposits.

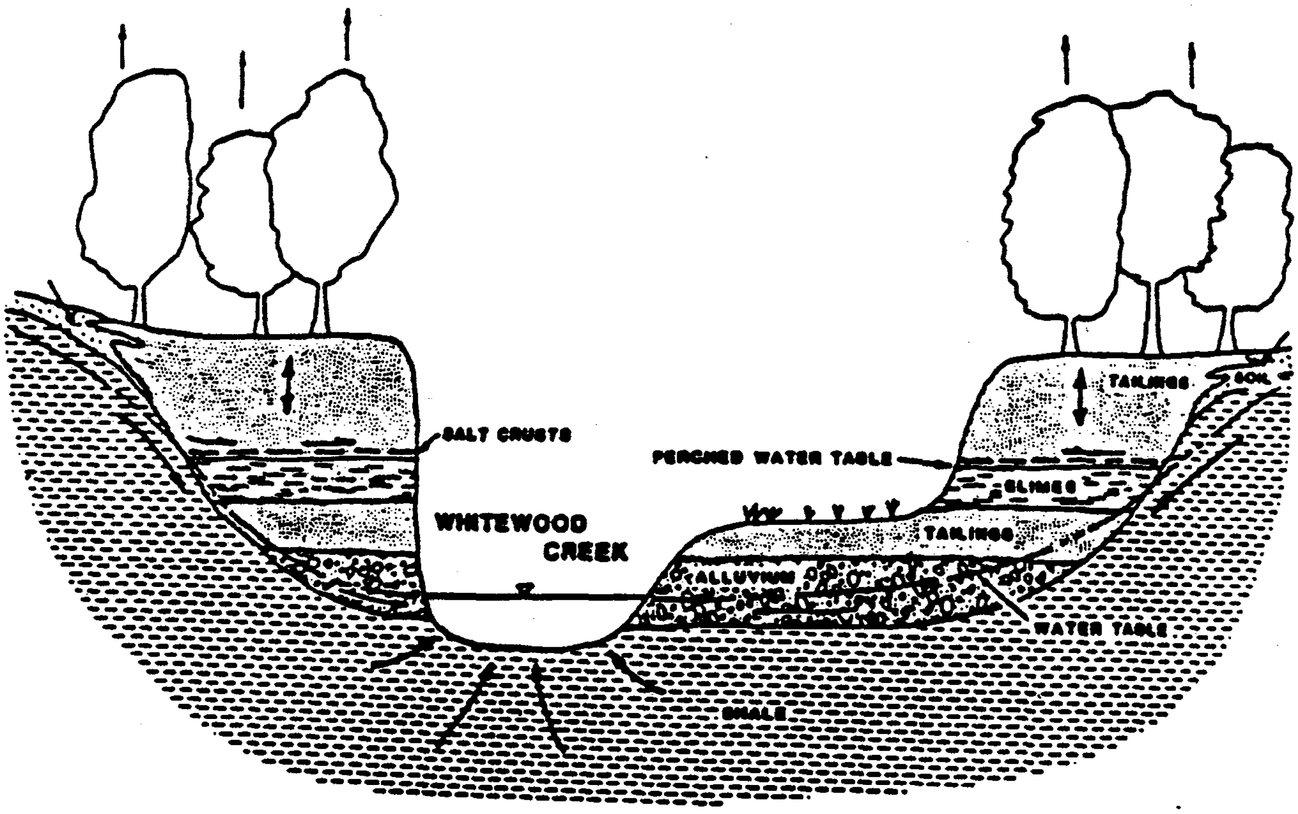
EXHIBIT 4e



The Whitewood Creek drainage basin and the local study sites within the CERCLA study reach.

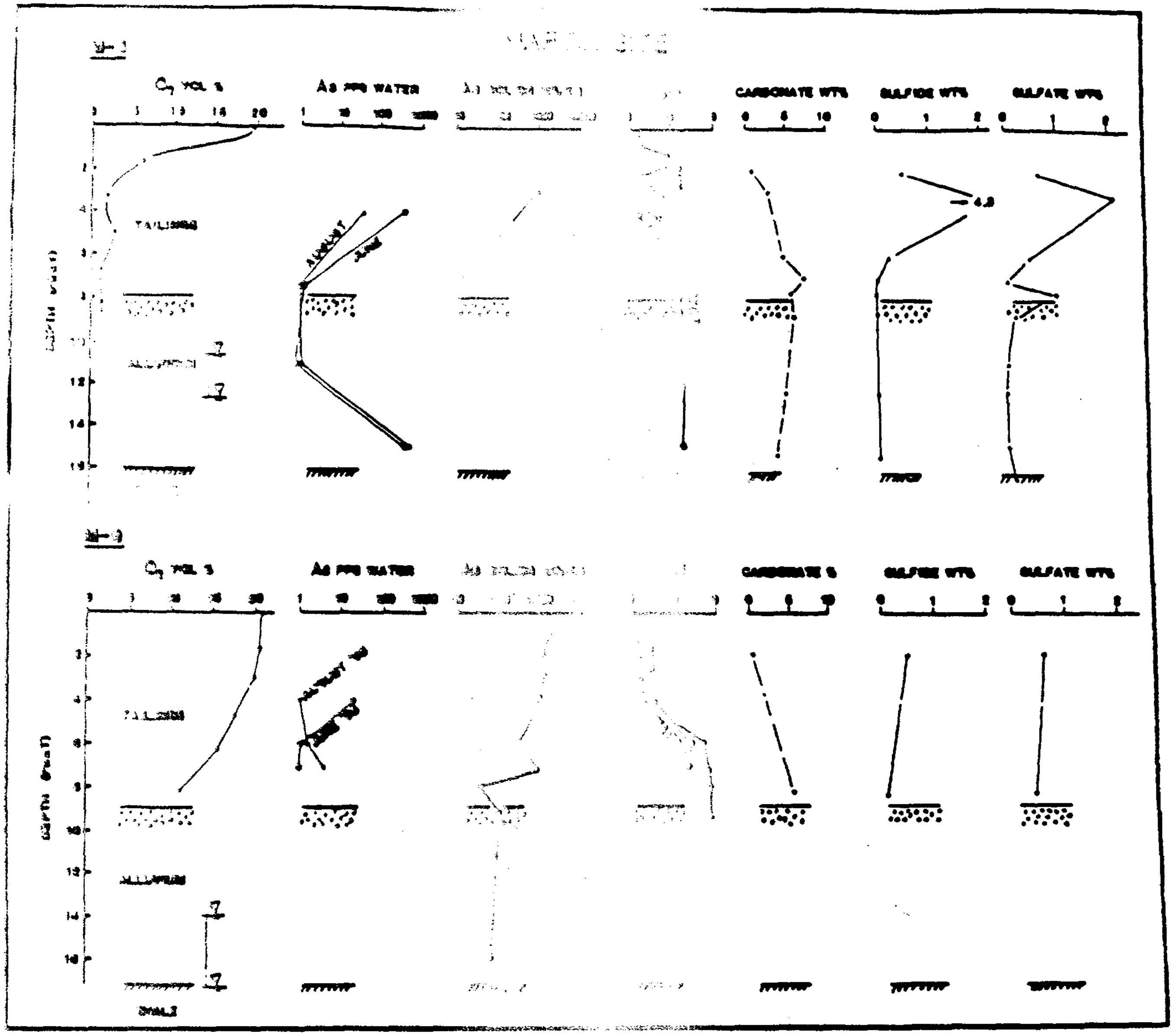
EXHIBIT 5a

Welcome Screen | Search | Report List



Schematic representation of the geology and water-circulation pathways in the Whitewood Creek valley.

EXHIBIT 5b



Vertical profiles of chemical parameters at two monitoring locations at the Martin site.

EXHIBIT 5c

Example of model calculations for groundwater.

	Mg^{2+}	Ca^{2+}	SO_4^{2-}	AsO_4^{3-}
I. Model**				
Input ccn	1.95	1.70	1.52	2.7***
Major Species	Mg^{2+} 37% $MgSO_4$ 63%	Ca^{2+} 19% $CaSO_4$ 29% $CaSO_4(s)$ 56%	SO_4^{2-} 22% $MgSO_4$ 23% $CaSO_4$ 17% $CaSO_4(s)$ 38%	$XOH_3AsO_3^+$ 6% XOH_2AsO_3 92% $XOHAsO_3^-$ 2%
Calculated Soluble ccn.	1.95	2.06	1.72	5.84
II. Measured average ccn	1.96	2.01	1.70	5.77

*Concentrations given as -log of molar values.
Other principal inputs: pH = 7.5, pTOTX = 1.7; adsorption constants from Farley and others 1984, sulfate ion pairs and solubility constants for low ionic strength from Smith and Martell 1976. TOTX represents density of adsorbing sites provided by the oxide.

**TOT As = 31 mg/kg x 5 kg/L x 1.33 10^{-5} mol/mg = 2 10^{-3} M.

EXHIBIT 5d

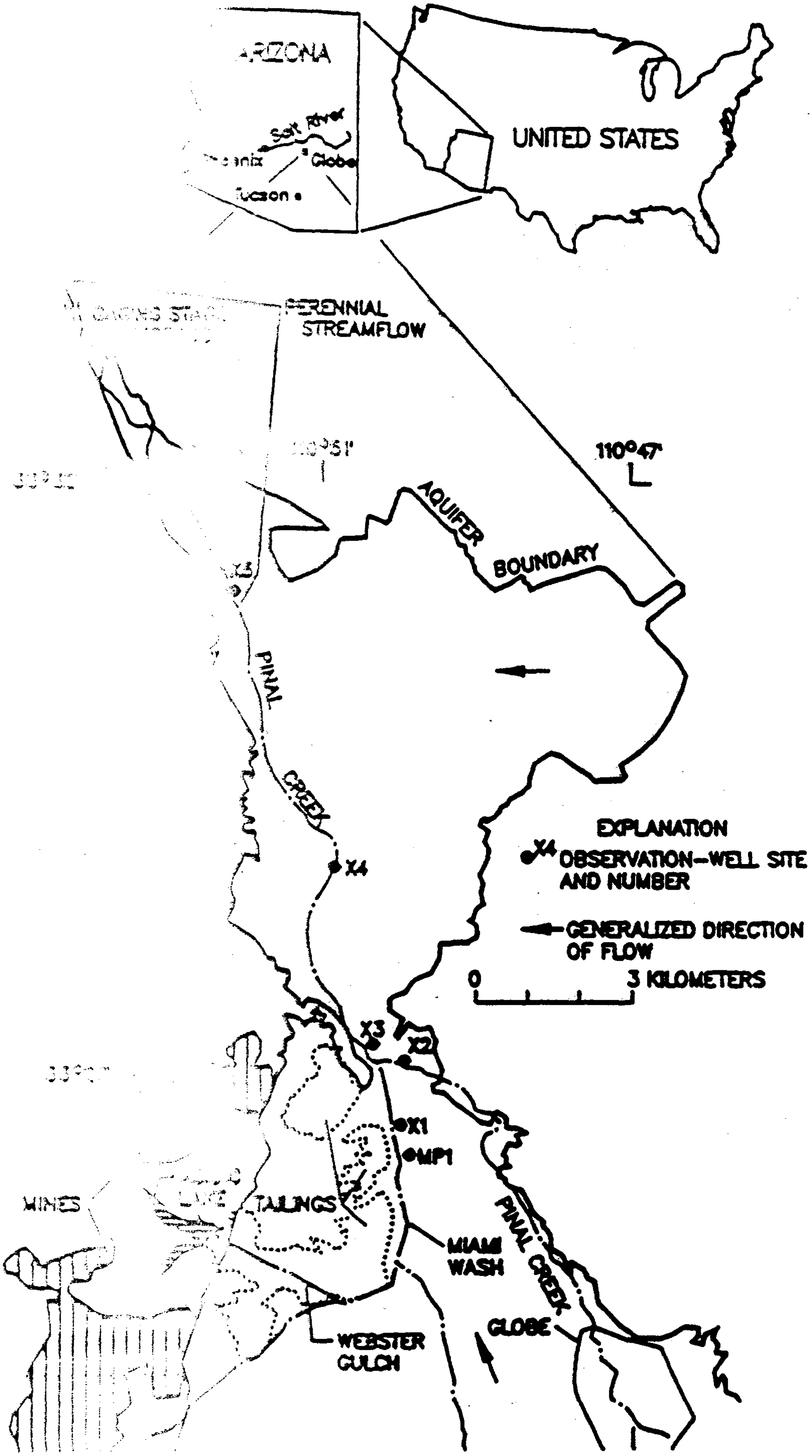


EXHIBIT 6a

Area of study

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

THE AUSTRALIAN PERSPECTIVE BY DR. IAN RITCHIE, ANSTO

Dr. Ritchie's presentation has been divided into two specific areas:

1. Comments on RATAP
2. A chronological history of the modelling work at the Australian Nuclear Science & Technology Organization (ANSTO).

As his comments follow very closely his written presentation done after the MEND Workshop, the notations here will be necessarily brief to avoid repetition and will only present material and questions not included in the written presentation found after these minutes.

<u>Comments on RATAP</u>

In summary, Dr. Ritchie believes that RATAP is a good modelling tool which appears to encompass most important physical and chemical phenomena used to estimate pollutant transport from tailings. Comparison with Waite Amulet data suggests that the model is predicting in the right ball park; however, he was surprised that comparison with other tailings data was not made. He recommended that well thought out laboratory experiments may provide the data required to validate the model especially in light of the uncertainty expressed in comparing the original field data, particularly the original pyrite concentrations, and present measurements.

He also suggested that sensitivity studies would be beneficial in determining how critical temperature affects and reaction rates are in the model. This is in light of comments made earlier in the Workshop that the temperature model had been included but had not been evaluated properly as to its importance in raw modelling. Temperature is extremely complicated and if it isn't important in the modelling, it should be removed. In light of the RATAP objective to estimate the time to oxidize all the pyrite and to detail how long acid generation will be a problem, temperature and oxidation rates play a significant role and should be included.

The present report on RATAP was difficult to read. Clarification is required on the formalism, the assumptions made and the solution technique prior to public issuance.

Dr. Ritchie believes that RATAP will be a useful tool for regulators and operators in evaluating differing strategies in limiting acid mine drainage (AMD). It shouldn't be a requisite of the model to predict water quality, which is very difficult to do. It should look at generic problems.

Work in Australia

Primarily two organizations are active in modelling in Australia: ANSTO and Stuart Millar's group. ANSTO is looking at physical processes while Stuart Millar is looking at the chemistry; however, both are concentrating on waste rock rather than tailings.

ANSTO philosophy differs from RATAP in that a model generates the kind of field data required. The field data is collected to verify the model assumptions and if the data does not, then the model is changed for the cycle to begin again.

Simple Homogenous Model

Please see Table 1. The first model produced by ANSTO was the simple homogenous model based on the specific question: Can diffusion through the pore space for oxidation at the rate which we got from field measurements be predicted? The answer is yes. One thing the model predicted was high temperatures in the waste rock dumps (400 m across, 20 m high) being modelled, based on the oxidation rates present. Temperatures were in the 60 °C range. This led to discussions with their microbiology associates on the types of bacteria operating in these temperatures. It was first argued that the bacteria were t4 oxidans that died out at 45°C. In the interim, large numbers of high temperature bacteria have been identified. It appears that there is a whole microbial ecology going from

10°C up to 100 °C. The fact that one has high temperatures working in the waste rock system does not matter.

Please see Figure 1A for the temperature, oxidation, oxygen concentration predictions of the simple model. The temperature distributions in the field did not match the predicted. This lead ANSTO to believe that their approach was to simple. They believed that the reaction process was quite fast, the rate was limited by the diffusion through the pore space. ANSTO had considered the dump to be a homogenous fine grain material so they had got the predicted reaction front running as it did.

Dr. Ritchie then gave a short discussion of the time mathematical model used in the simple model and as presented in Figure 1A. ANSTO has found this equation to be very helpful in determining how long it will take to oxidize the material.

The Two Component Diffusion Model

ANSTO was unhappy with the simple homogenous model as it didn't seem to take any account how the particle was reacting. Their next model, then, would look at diffusion through the pore space and diffusion into the particle. Please see Figure 2 for their vision of the moving reaction rate within the spherical particle which was incorporated into the two component diffusion model. In this model, they were asking "What is the impact of including oxidation at the particle level?"

The result was modified oxygen and temperature distributions. Surprisingly the total predicted SO_4 production was the same in both models. Dr. Ritchie then reviewed the model predictions of oxygen, oxidation and temperature as found in Figure 1B. The mathematical formula underneath was used to predict the time to completely oxidize the waste dump material. T_c corresponds to the time taken for a particle immersed in air to oxidize.

Figure 3 shows the disappointing results of using the two component diffusion model. In fact the simple model predicts just as effectively. Meanwhile, Figure 4 shows the field measurements taken on waste rock dumps at Rum Jungle. These figures demonstrated that there was definitely over parts of the dump diffusion coming in from the surface; however in parts, there were concentrations of oxygenated air and heat generation. ANSTO concluded that this was most likely a convective process, possibly advective from wind blowing on the sides. This lead to the third model which combines both diffusion and convection processes.

Diffusion and Convection Model

The question here is how significant is convection? The answer is that convection certainly occurs in waste dumps. Its significance depends very much on the geometry and air permeability. Figure 2 shows the physical transport mechanisms which should be included in a model of this kind. One needs oxygen transport, diffusion, advective transport mechanisms. Advection is going to be assisted by temperature induced density changes.

As an aside, Dr. Ritchie spoke of Larry Cathles' convection model produced in the late 70's. His work left diffusion out which wasn't appropriate as the only way these systems kick off is from diffusion. It is unknown how he got his system started; however, he was limited in his computing power. Handling the diffusivity and convective term is very difficult without sufficient computing power.

Also needed in the model is the oxygen usage by the pyritic material. ANSTO used the same kind of model as in the two component model with its shrinking core. ANSTO was convinced they had to include water transport because it will measure the material porosity. The diffusion coefficient depends critically on porosity; the air current more so. Heat transport in their model uses both diffusion and advection systems.

Dr. Ritchie then reviewed a series of charts demonstrating both field and predicted results. Late last year they were looking at small gold dump leaches trying to estimate how fast these systems would go. Please see Figure 5 with a permeability of 10^{-10}. They quickly came to the conclusion that they required reasonably high permeability dumps. After two years the convection is just beginning to take off; oxygen concentration is decreasing from the surface as a result of diffusion. By year four convection has really pushed air into the system. In doing so, it has produced some corresponding hot spots reasonably far into the dump as time progresses. Their model also contains a cut-off for the reaction process at 100 °C. At this stage the water has boiled off and the bacteria have nothing to live in.

See Figure 6 of the same size dump with an increase in permeability by an order of magnitude. This has had a profound effect on the convection process which is firmly established by year one, the oxygen profile has moved half way through the dump, and a high temperature concentration covers an extensive area. In this instance, ANSTO was interested in optimizing the leach system. Figure 7 shows varying irrigation rates. By slowing irrigation by a factor of 10, they were able to get the leaching system working faster. This affect was attributed to a lessened cooling effect, greater air permeability, and a maximimized diffusion coefficient.

In an experiment on the same leach dump where they reduced the particle size from 5mm to 2mm, they increased the oxidation rate of the particle by a factor of 10. Does it have an effect on the whole dump? The answer was not much. It emphasized that these systems are limited by macroscopic processes rather than microscopic ones.

Figure 10 shows some field data of various bore holes into the dump. The data shows high permeability at the surface and at the bottom. Figure 11 shows the data for individual holes. This data shows that a reasonable permeability for a waste rock dump is 10^{-10}, a low permeability is 10^{-11}. Dr. Ritchie requested similar information on other dumps from the participants to eventually establish typical numbers for these type of systems.

Please see Figure 8 for recent work at ANSTO with larger dumps (400 m diameter and 15 m high). They posed several questions:

- Does convection occur? Yes and it gives rise to hot spots.
- What happens when you put a cover on the dump, all over, on the top, on the sides. The results were quite surprising. See Table 3 and Figure 9. Putting material on the sides gains very little in

decreasing reaction rates. Putting material on the top and not on the sides gains you as much as putting material all over. This tells us that although convection occurs and creates some spectacular effects, it is really diffusion through the large top surface that is the predominant process. Hence, if you are looking to limit oxidation rate in these systems, one must limit diffusion through the top surface. This reinforces the Swedish strategy of some sort of layered system to ensure the lowest possible diffusion coefficient as possible.

ANSTO's next step is to go back to the simple diffusion model and put in a layered cover factor. It comes back to the most appropriate tool thought. Dr. Ritchie recommends using the simplest tool that is effective for the purpose.

Another factor to consider in the diffusion convection model is how significant is wind driven convection. Evidence from Bersbo and the Heath Steele shows that it is a factor. ANSTO's next exercise is to check this out. Dr. Ritchie suspects that there will be some limit due to the air permeability. They have found with convection and permeabilities of less than 10^{-11} that convection never takes off. Something similar may be happening with wind driven convection.

QUESTION AND ANSWER PERIOD:

Mr. Bell: How were air permeabilities measured in Figure 10?

Dr. Ritchie: When we put in our standard stringer, we put two thin bore tubes down side by side instead of just one. We blew air down one and measured the pressure in the other. Mathematical computations would give the air permeability from the retrieved measurements. We employed 2D transport ports to do the air transport for us to make sure that what we were measuring was indeed sensitive. We felt that this was quite important to ensure that the results could be interpreted. Distance between tube ends was two centimetres.

The following discussion centered around the concern that this method could only be used in dumps with finer material than 2 cm since in many Canadian dumps the voids could be larger than two centimetres. Voids may occur and one would be unluckily to have a sampling point in a void; although they are relatively small in relation to the whole dump. Dr. Ritchie wished to emphasize that ANSTO measurements indicate that the dumps are remarkably homogeneous. Although it is a heterogeneous system with many processes happening on a macroscopic level, the system behaves in an homogeneous manner.

Further discussion occurred on various measurement procedures and their validity. Dr. Ritchie emphasized that one must be sure that what you desire to measure can indeed be measured and the results can be interpreted.

Mr. St. Arnaud: What produces the variations in permeability within the Whites Dump?

Dr. Ritchie: It was the way the dump was constructed, it was an end dump.

Dr. Robertson: In a discussion on hydraulic permeability, Dr. Robertson discussed their work at Island Copper dump which has overburden and various rock types. Permeabilities had at least five orders of magnitude differences in hydraulic permeability depending on rock type and location in dump. In further work in British Columbia, they are passing streams through waste rock dumps. Natural segregation causes the larger boulders to go to the bottom. Here the voids are much larger. When looking at ANSTO modelling with its uniformity, everything is happening on the sides; the results suggest that the chimney effect is where you connect this high permeability air space zone at the bottom with some sort of high permeability zone in the middle of the dump.

Welcome Screen Search Report List

Dr. Ritchie: Dr. Ritchie responded that ANSTO was just looking at the effects of the covers and determining if convection occurs. If the chimney effect is present within the system, a heterogeneity factor would have to be added to the model. He emphasized that ANSTO's philosophy is to get an idea of what sorts of processes are important rather than what is exactly happening.

Mr. Bell: Your conclusion that convection is a side effect, an edge effect and placing a cover on the side is a limited effect, whereas placing a cover on the top maximizes your benefit; is it not very dependent on the geometry and the construction of the dump by end dumping? End dumping causes a high permeability layer at the bottom and thus does not confine convection to the sides only. This bottom layer pulls air right into the middle of the dump. Heath Steele data supports this.

Dr. Ritchie: Dr. Ritchie put a scale on his edge effect of 70 meters which is larger than the dumps being studied at Heath Steele. Geometry plays a major factor.

Dr. Robertson: Dr. Robertson requested one last question on diffusivity in relation to his experience with Equity Silver's dump where it is warm all over with a very permeable base. There is venting happening all over; however, this has not been measured only observed. If you had a source of cold air at the bottom of the dump and you have these high temperatures, there must be a tremendous thermal effect going up through the dump. Isn't this going to effect the modelling of the top diffusivity down if you have air moving upwards? ANSTO is working on the edge effect, perhaps that is more uniform through the dump?

Dr. Ritchie: Sometimes diffusion and convection will have opposing effects referring back to Figure 5 and depending on the geometry could wipe out diffusion in some places.

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Welcome Screen | Search | Report List

THE AUSTRALIAN PERSPECTIVE

by Dr. A.I.M. Ritchie

Australian Nuclear Science & Technology Organization

This presentation will be in two parts.

- Some brief remarks on RATAP;
- A description of the modelling work done at Ansto.

BRIEF COMMENTS ON RATAP

1. RATAP appears to include the important processes which govern acid and pollutant generation in pyritic tails. I shall come back in a moment to the reason why I use the expression "appears."

2. On the basis of comparison with experimental data from Waite Amulet results predicted by RATAP are generally satisfactory.

3. Because of uncertainties in field data, particularly the initial conditions of the tails, well thought out laboratory experiments may provide better data for validating the model.

4. As Keith Phinney pointed out yesterday, the model contains a wealth of information on rates and their dependence on a variety of parameters. Of interest would be how important this detail is to answer:
   (a) time to oxidize all the pyrite;
   (b) how long will acid generation be a problem.

5. I used the phrase "appears to be" because I found the write-up very hard going. Before the model is released to users, I would expect a clearer exposition of:
   - the formalism;
   - the assumptions;
   - the solution technique.

6. Finally, I believe the model will be a very useful tool to allow regulators and operators to assess the relative merits of waste management options. I doubt if it will accurately predict the water quality at a particular seepage point in a tailings system; nor do I expect such a model to provide such detailed information.

▪ MODELLING AT ANSTO

Introduction

The description of modelling work at Ansto will in essence be a chronology of modelling work there. The philosophy has been one of producing models to answer questions, where the questions have frequently arisen from the results of field experiments. Table 1 summarizes the main steps in model progression, the questions which have been asked and some of the answers which have been given.

The Simple Homogeneous Model

This model assumes that the waste is homogeneous and that there is no need to model oxidation of the individual particles making up the waste. Further, it assumes that the oxidation rate is controlled by the rate of supply of oxygen to the oxidation sites and that the supply mechanism is diffused through the pore spaces of the waste. These assumptions mean that oxidation occurs at a front which moves through the waste. The main features predicted by the model are shown in Figure 1. The important result was that such a model predicts SO_4 production rates which were consistent with those measured in the field.

The model also predicted that at those SO_4 production rates we should expect to see temperatures of about 60°C in the waste. Such temperatures were incompatible with oxidation by thiobacillus ferrooxidans but further field measurements showed that temperatures of this order occurred in the dumps and that thermophilic pyrite oxidizing microorganisms were also to be found in the dumps.

The Two Component Diffusion Model

We felt that the simple model did not take adequate account of the oxidation process in the particles comprising the waste and could therefore underestimate the time to oxidize all the pyritic material and overestimate the SO_4 production rate. The moving front concept was therefore transferred to the particles and the model assumed diffusion through the pore space followed by diffusion into a reaction front in the particles comprising the dump (see Figure 2).

Figure 1B shows the main features predicted by this model. In essence it spread out the region where pyrite was being oxidized and as a result led to oxygen concentration and the temperature distributions slightly different from the simple model. The magnitude of the differences depended on the particle size distribution, the differences being small for small particles. The important result was that the total SO_4 production rate (pollution production rate) and the lifetime of oxidation predicted by this model was little different from that predicted by the simple model. This is shown in Figure 3.

Diffusion and Convection Model

Meanwhile, field measurements had produced results of the type shown in Figure 4. These indicate that convection as well as diffusion were transporting oxygen into the waste dumps. It therefore became apparent that if we were to predict

Welcome Screen Search Report List

oxygen and temperature distributions consistent with those met in the field we had to include convective transport in our modelling.

A diffusion/convection model must include the transport processes described in Table 2. It is essential to include water transport for two reasons. Firstly, water transfers heat as it moves through the waste. Secondly, the irrigation rate determines the moisture content which changes both the diffusion coefficient and the air permeability, particularly the latter. It is interesting to note that the model produced by Cathles in the late 70's and early 80's to describe bio-leaching in dumps of copper ore did not include diffusional transport of oxygen.

As in Cathles' model, we included a cut-off for bacterial oxidation as the temperature increased. In our model this cut-off is 100°C on the basis that water boils at this temperature and that bacteria require a water film in which to operate.

We have applied the diffusion/convection model to two rather different systems. Firstly, we have applied it to leach dumps where the objective is to oxidize the pyrite as rapidly as possible. Secondly, we have applied it to mine waste where the objective is quite the opposite.

Figure 5 shows gas trajectories, oxygen concentrations and temperature distributions to be expected in a dump with radius 20 metres and a height of 20 metres in the first four years of operation. The permeability is 10^{-10} m^2 and the particle size 5 mm. The results show that convection has become established by the first year and that it is an important transport process by the fourth year. Figure 6 shows that as the air permeability is increased to 10^{-9} m^2 the convection is well-established by the first year. Figure 7 shows that in such a dump the irrigation rate has a profound effect and that increasing the oxidation rate by about a factor of 10 at the particle level (by decreasing the particle size) has only a small effect on the overall performance. These results show the importance of dump size, dump gas permeability and the irrigation rate.

For larger systems, particularly mine waste dumps, the questions are:
- Does convection occur to a significant extent?
- How long does it take for convective transport to become established?
- What is the relative importance of diffusion and convection in the overall oxidation rate of pyrite in the dump?

Figure 8 shows the results of applying the diffusion convection model to dumps 50 metres high and 400 metres wide. It is assumed for convenience that the particles are all of the same size, and are spherical with a radius of 5 mm. The air permeability is taken to be 10^{-10} m^2 which is a reasonable value based on field measurements (see below). The results correspond to a time 30 years after the creation of the dump. It is clear that convection is occurring and is creating a hot spot about 30 metres in from the side of the dump.

To examine the relative importance of diffusion and convection we considered cases where 10 metres of material is placed on the sides or on the top of the dump. The material has the same physical properties as the material in the dump but is not reactive. In practice, a cover layer would be much thinner and would be tailored to have properties to reduce diffusive and/or convective air transport. Figure 9 shows a comparison of the four cases. It is apparent that the cover on the sides does not have a great effect and it follows that for these large dumps diffusive transport of air through the very large top surface dominates the pyrite oxidation rate within the dumps.

Figures 10 and 11 show some measurements of air permeability in a waste rock dump. It is apparent that the air permeability varies both laterally and vertically; but as can be seen from Figure 11, does not vary by more than two orders of magnitude. It is clearly of interest to see what effects low permeability paths have on air convection. It will also be of considerable interest to get results from other waste dumps to obtain a clearer picture of the variability of air permeability from system to system. This is particularly so of the Heath Steele Dumps, where oxygen concentration measurements indicate that convective or advective transport may be important.

Welcome Screen Search Report List

TABLE 1

Model	Question	Answers
Simple Homogeneous Model	Can diffusion through pore space support oxidation at a rate comparable with experiment?	Yes Expect high temp
2 Component Diffusion Model	What is the impact of including oxidation at the particle level?	Modified O_2 distribution Modified temperature distribution Total SO_4 essentially unchanged
Diffusion/Convection Model	How significant is convection?	Convection occurs Significance depends on geometry /air permeability
Diffusion/Convection Model	How significant is wind driven advection?	?

TABLE 2

PHYSICAL TRANSPORT MECHANISMS
WHICH NEED TO BE DESCRIBED

1. Oxygen transport into the heap by
   - diffusion as oxygen is consumed
   - advection due to air pressure gradients and temperature induced density changes

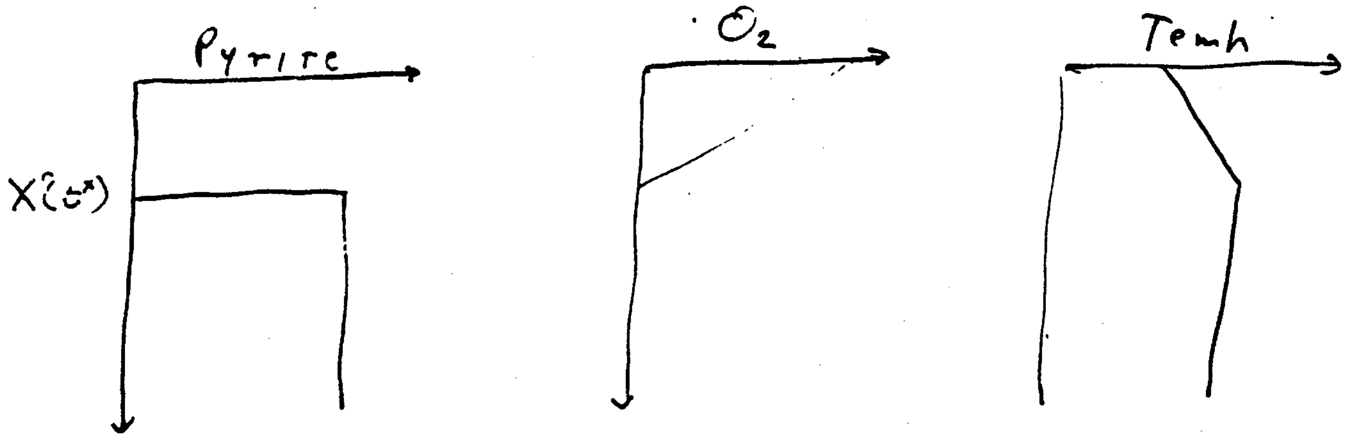
2. Oxygen usage by the pyritic material

3. Transport of water through the heap

4. Transport of heat generated by the oxidation of pyrite by
   - diffusion
   - advection

The description must include both the spatial and temporal variations in the above processes.

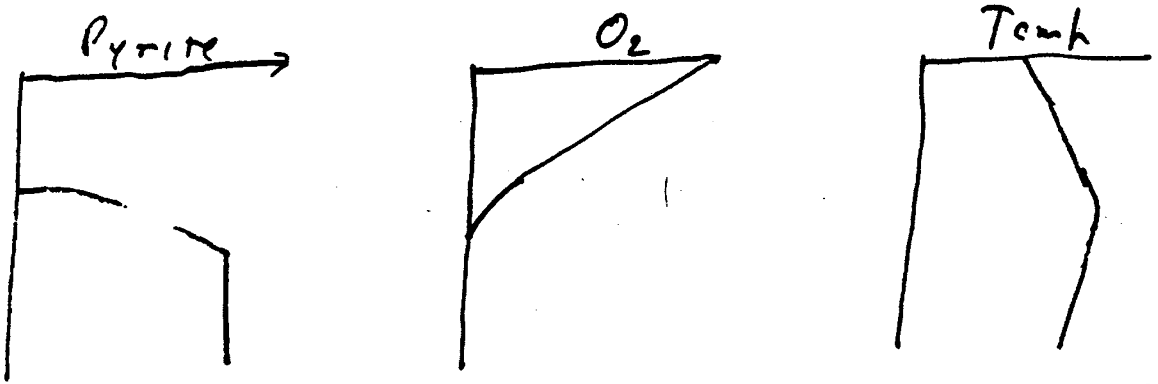
Figure 1a - Simple Homogeneous Model



$$X^*(t^*) = \left(2\,\frac{D_1 u_0}{\rho_s \varepsilon}\,t^*\right)^{1/2} \qquad X(t) = (2t)^{1/2} \qquad t^* = t\,L^2\,\frac{\varepsilon\rho_s}{D_1 u_0}$$

$$\tau_d = \frac{1}{2}$$

Figure 1b - Component Diffusion Model



$$t_d = \tau_c + \frac{1}{2} \qquad \tau_c = \frac{3}{2}\,\frac{\gamma D_2 (1-f) L^2}{D_1 a^2}$$

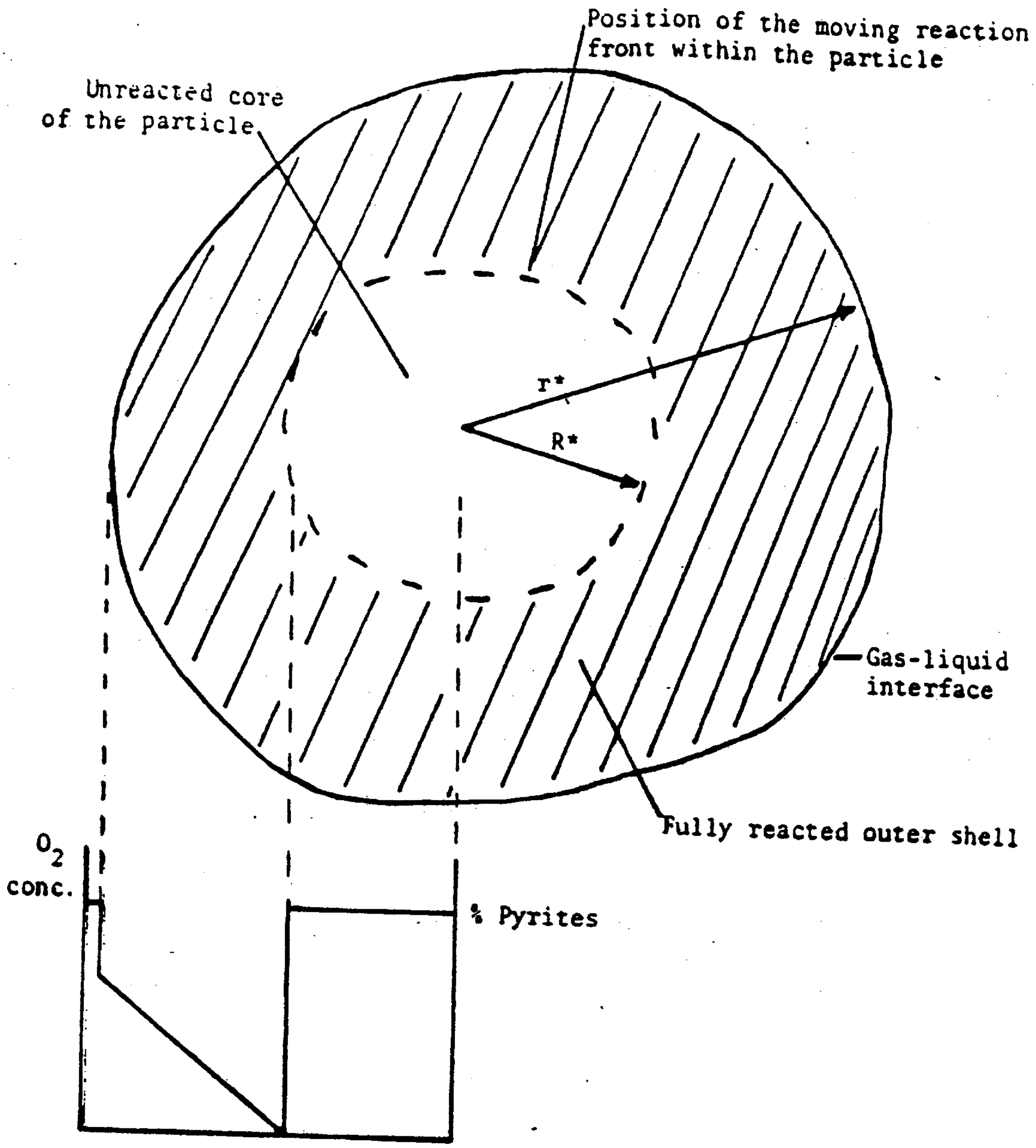


Figure 2 Schematic diagram of an oxidising particle of the dump.

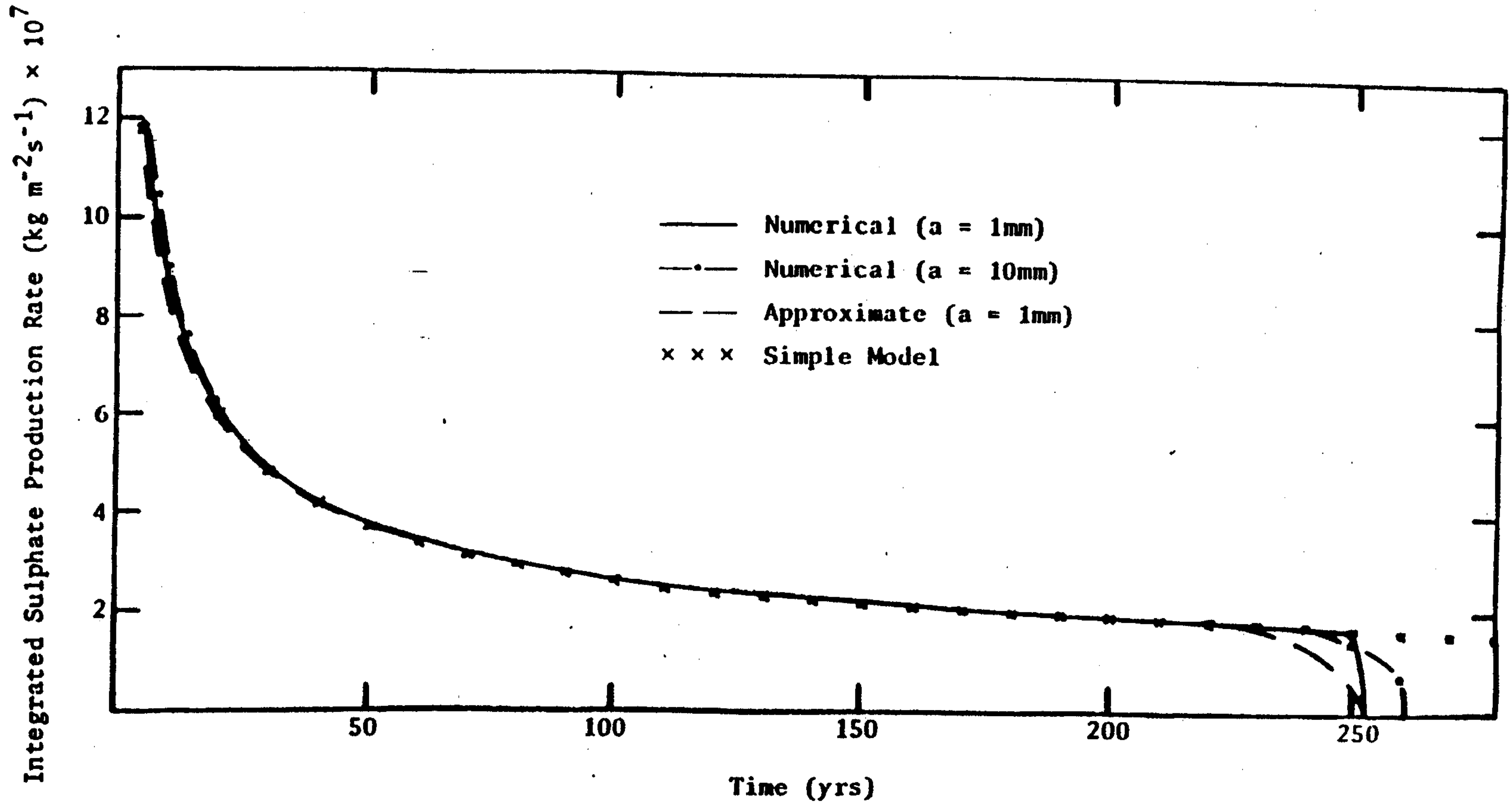


Figure 3 The integrated SO_4 production rate as a function of time after the creation of the waste rock dump.

Welcome Screen | Search | Report List

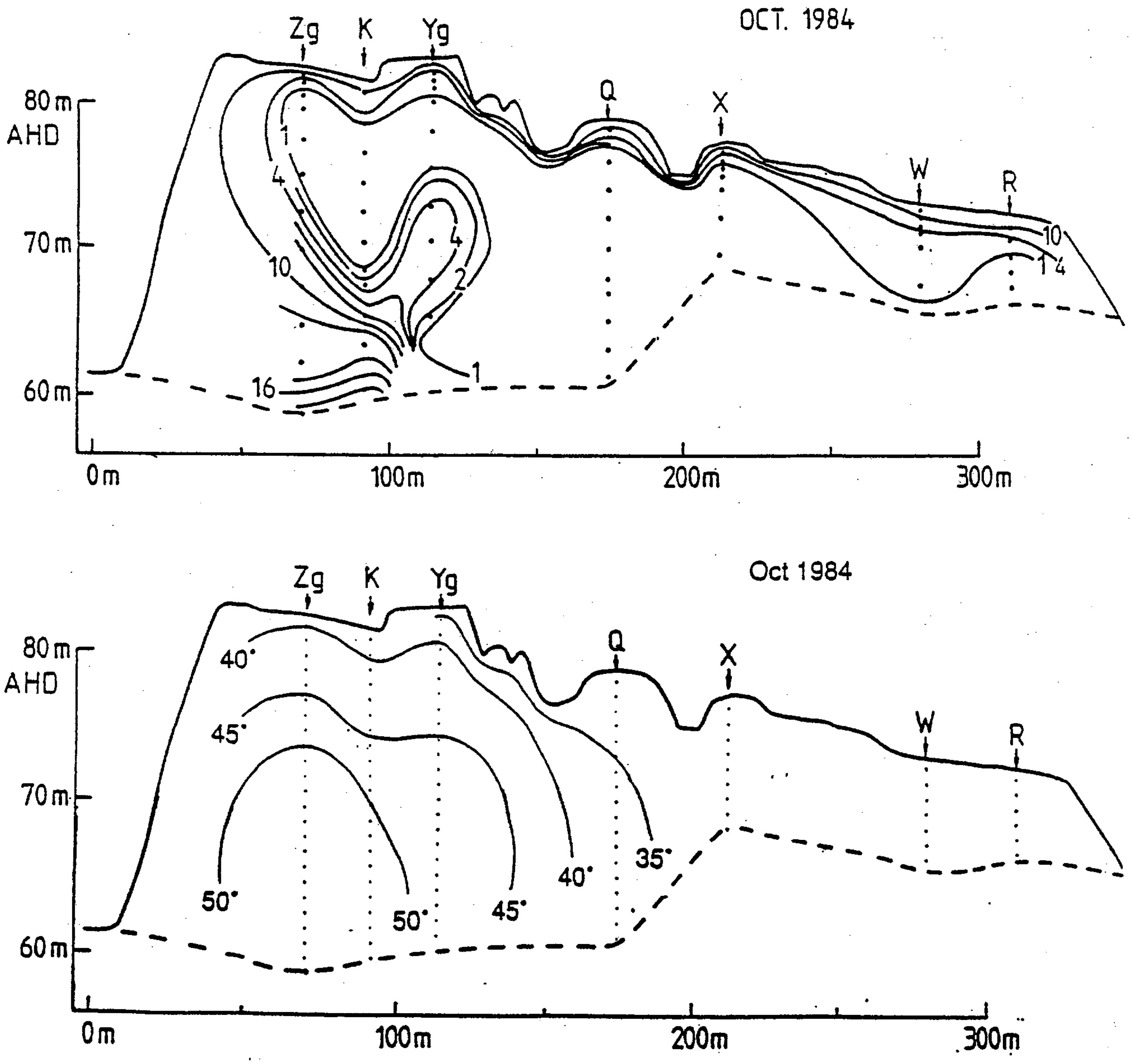


Figure 4: Measured oxygen concentrations and temperatures in the Intermediate mine overburden heap at Rum Jungle.

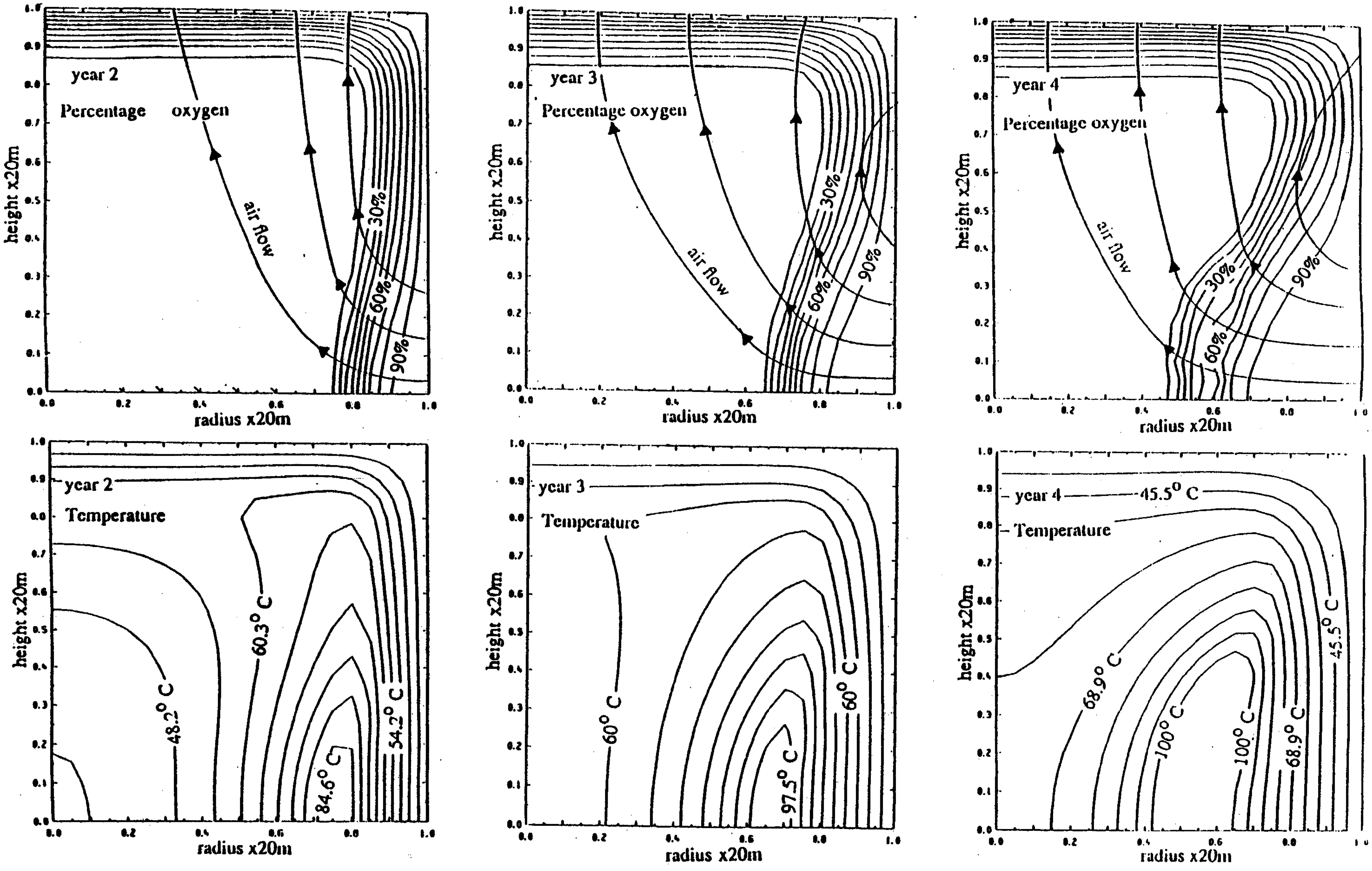


Figure 5: Oxygen content and temperature contours in a cylinrical heap at years 2,3 and 4. The permeability $K=10^{-10}$ m^2 and the particle size $a=0.005$ m. Arrowed solid lines indicate air flowpaths.

Welcome Screen | Search | Report List

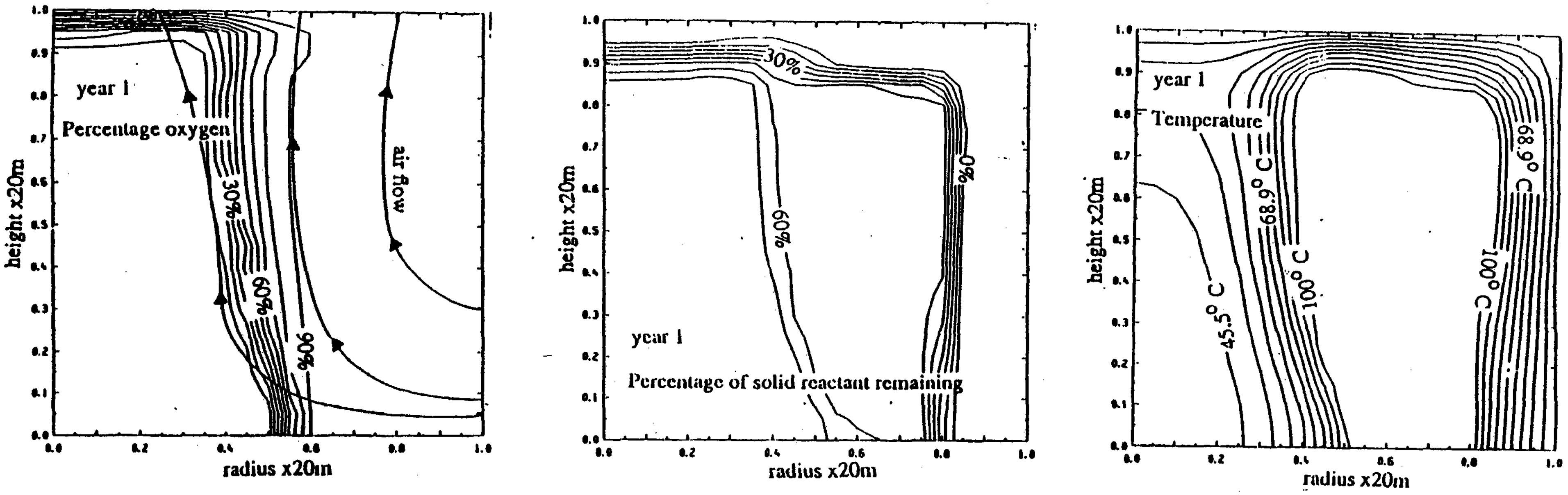


Figure 6: Oxygen content, solid reactant content and temperature at year 1 in a heap with permeability $K=10^{-9}\ m^2$ and particle size a=0.005 m.

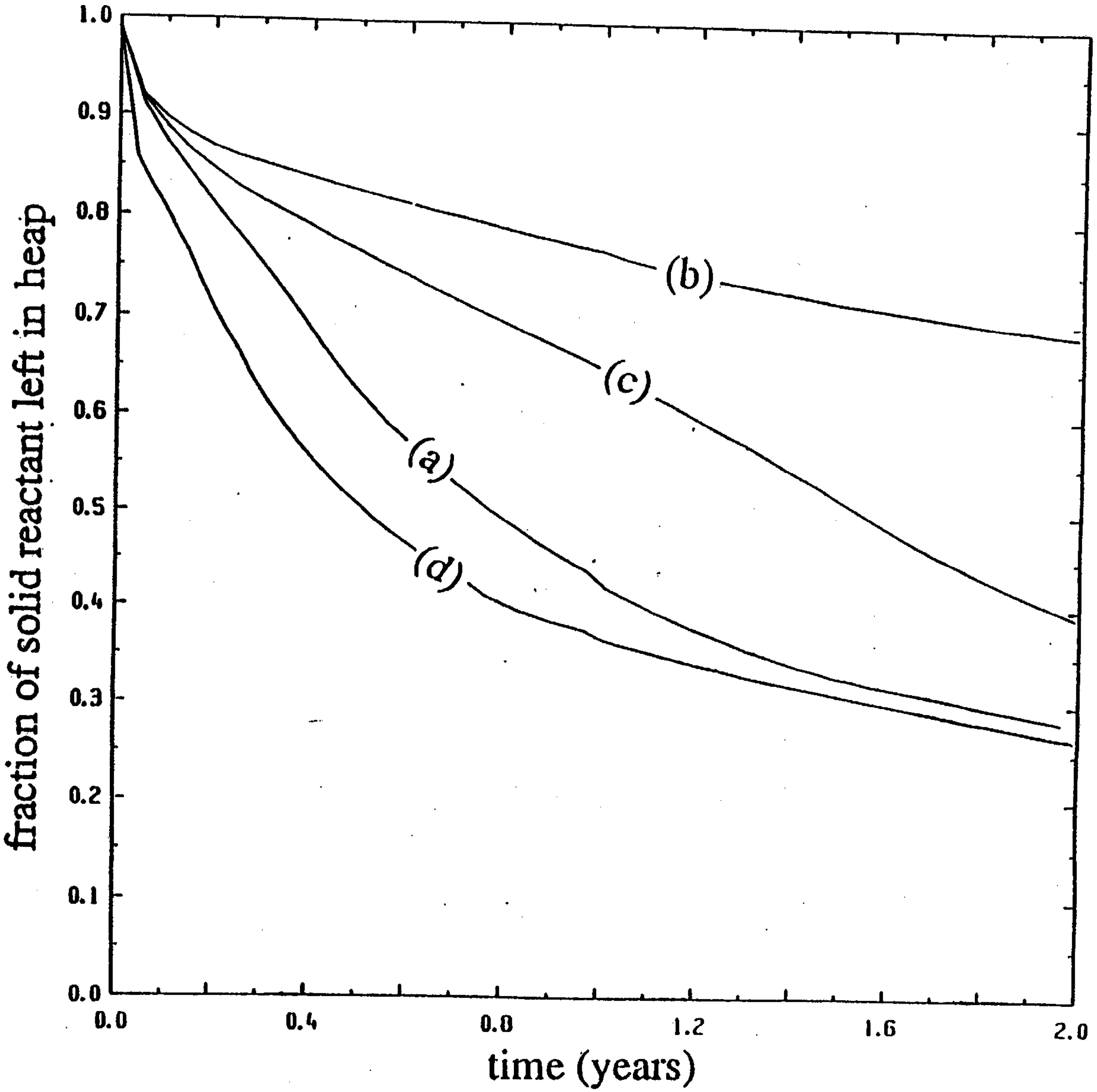


Figure 7 : Fraction of solid reactant left in the heap as a function of time. The cylindrical heap has a height of 20m, radius 20m and permeability $K=10^{-9}\ m^2$. The 4 curves correspond to; (a) no irrigation and particle size a=0.005 m, (b) irrigation rate 0.01 m/h and a=0.005 m, (c) irrigation rate 0.001 m/h and a=0.005 m, (d) no irrigation and a smaller particle size a=0.002 m.

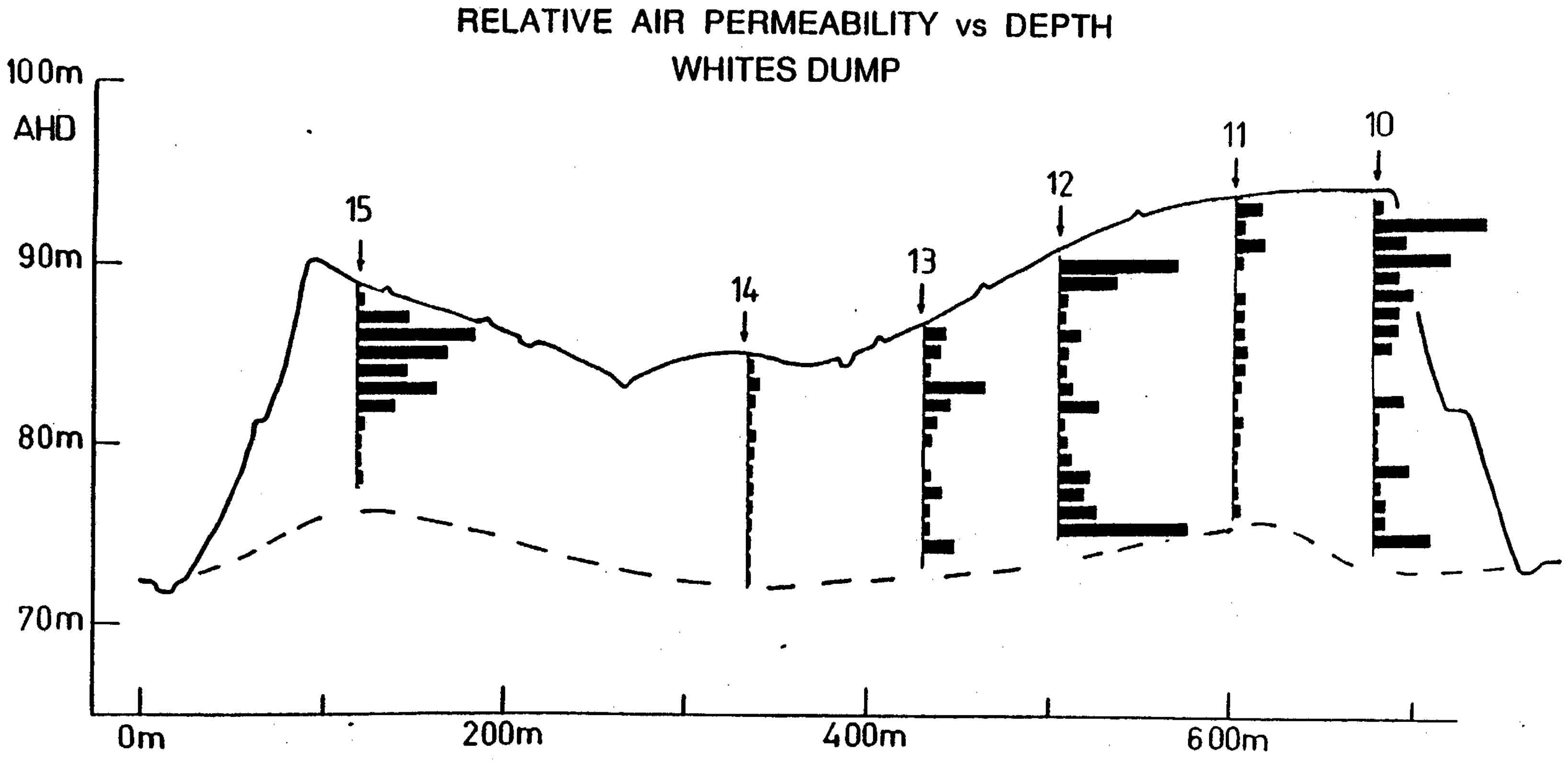

RELATIVE AIR PERMEABILITY vs DEPTH
WHITES DUMP
100m
AHD
90m
80m
70m
0m
200m
400m
600m
15
14
13
12
11
10

FIGURE 10

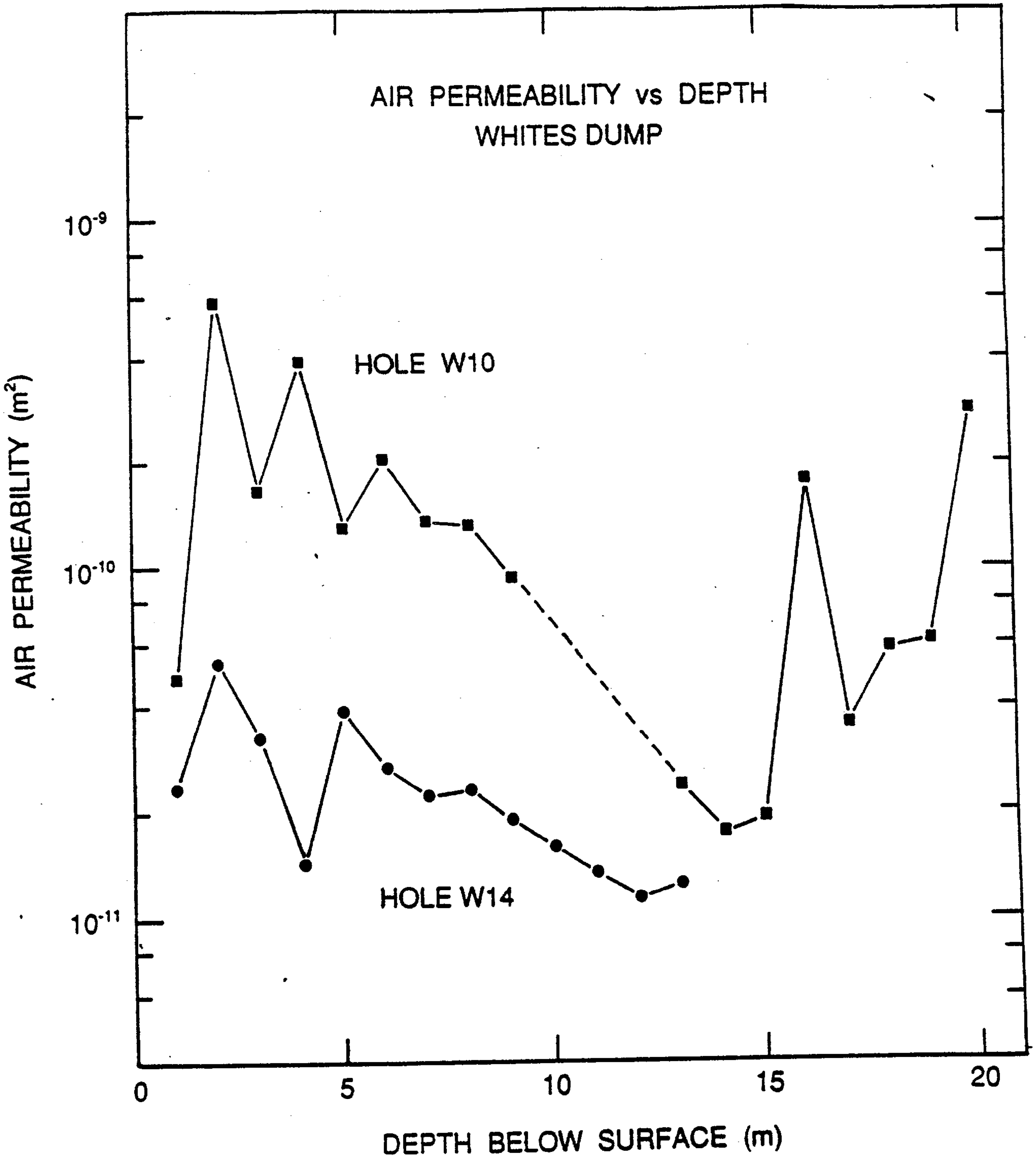

AIR PERMEABILITY vs DEPTH
WHITES DUMP
HOLE W10
HOLE W14
AIR PERMEABILITY (m²)
10⁻⁹
10⁻¹⁰
10⁻¹¹
0
5
10
15
20
DEPTH BELOW SURFACE (m)

FIGURE 11

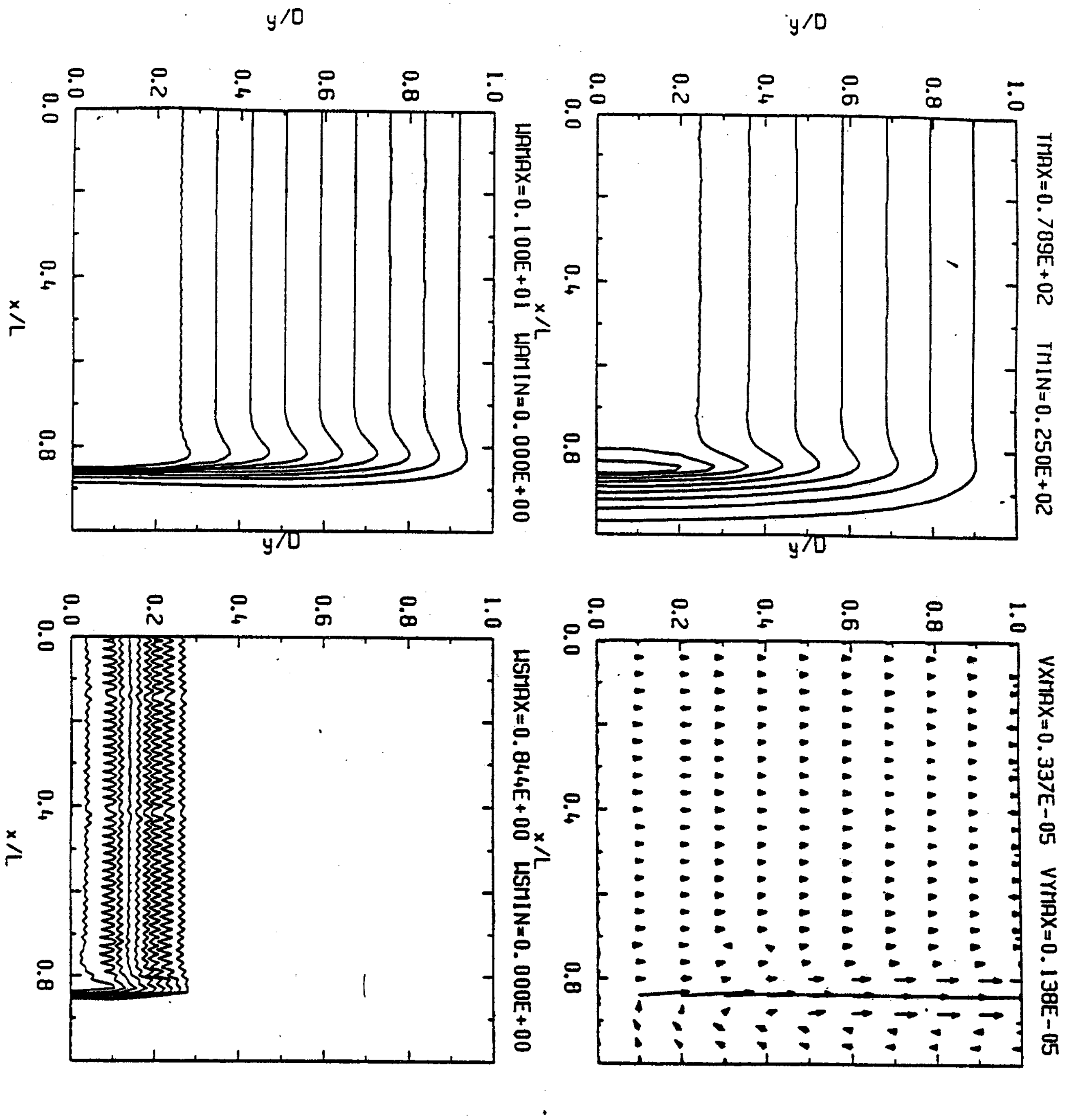


FIGURE 8: Oxygen, pyrite, temperature distributions and air flow field at 30 years in a planar dump of half length L=200m and height D=15m. The axis of symmetry is along x/L=0. Bottom left: Oxygen mass fraction (%). Bottom right: Mass fraction of pyrite remaining (%). Top left: Temperature (C) (ambient temperature = 25C). Top right: Air flow velocity vectors (m/s).

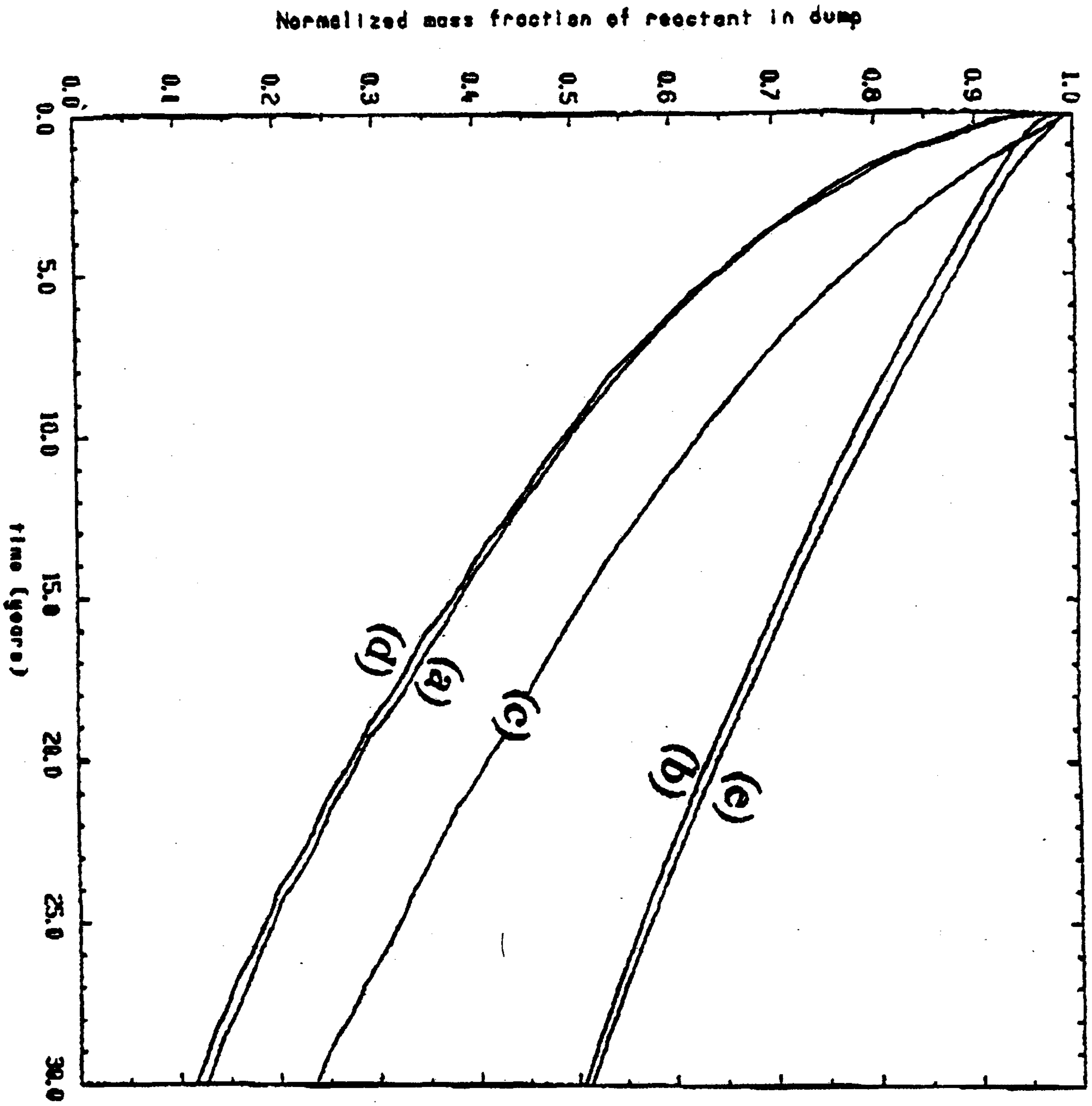


Figure 9 The mass fraction of pyrite remaining in the entire dump as a function of time for the 5 cases indicated in Table 3

TABLE 3 - Description of Case Studies

Case	Layer Thickness on Top (m)	Layer Thickness on Side (m)
a	0	0
b	10	10
c	2	2
d	10	0
e	0	10

Permeability of dump material = 10^{-10} m^2
Diffusion coefficient = 6.72×10^{-6} m^2 m^{-1}
Dump height = 15 m (without layer)
Dump length = 400 m (without layer)
Pyrite content = 1%

A question resulted why there is a step change in the pH predicted results. This is dominated by calcite, the site has been inactive for over 30 years.

The probabilistic runs give an idea of the standard deviation.

The ferrous iron concentration versus depth is a very similar plot. It is not to bad a run; the predicted results fall on a smooth curve whilst the field data bounce around, except for depths of more than three metres.

For the WA17 site, the pH-depth relationship produced a good agreement between the predicted and measured values. The predicted values are lower, which would indicate that more buffering capacity was available than was assumed.

The predicted ferrous iron concentrations versus depth were lower than the measured values, but generally a good fit was achieved.

A question resulted if the ferrous iron values were dictated by the oxidation rate and a discussion resulted. Dr. Scharer explained that total iron is dictated by the oxidation rate but the ferrous iron concentration is partitioned in the oxidation zone.

In the case of WA22, the oxygen concentration versus depth shows a good fit. The oxygen is depleted at depth's over 1 metre.

Mr. Halbert continued his presentation with some examples where the model is used to predict acid flux from a tailings area. At Nordic, the predicted graph shows a steady increase to 6,500 t/y of acid expressed as $CaCO_3$, and then falls off to a low level after 70 years. For comparison, a plot was made of the acid neutralized at the lime water treatment plant at the Nordic mine site. There is a steady rise since the treatment started. Calculations indicated that 45% of the acid is stored in the tailings site, only 25% is treated. The rest is neutralized by the addition of calcite. The expectation is that the amount of acid received at the treatment plant will start dropping off.

explained that any change in temperature with depth is masked by the fluctuations of temperature at the surface.

Mr. Halbert continued his presentation with some comparisons of model predictions to measurements in the field, i.e. the case of the Nordic tailings area in Elliot Lake. Slides were shown of the tailings areas. Mr. Halbert explained that the tailings are sulphidic uranium tailings. No buffering minerals are present due the sulphuric acid leach in the mill, but the tailings were neutralized in part with calcite. He showed the two test sites T3 and T5. T3 is a predominant slimes area, pyrite content 5%, whilst T5 is a sand area, pyrite content 10-11% A fairly good fit is obtained for the percent pyrite remaining versus time for T3, but the fit is not so good for T5. The tailing at T5 have a deeper water table.

A discussion resulted and Dr. Nicholson explained that the model is 'rough', grain size is used to calculate the moisture and this may result in the bad fit. He explained that one could override this and input moisture if this is available.

The pH fit (pH versus depth) is not as good, the pH is overestimated by the model in comparison to the field results. A discussion resulted. Dr. Nicholson indicated that when the sample is taken in the unsaturated zone below the oxygen level, the iron oxidizes in the sample and this results in a pH drop. Mr. Davé estimated that this is the case with all samples.

Mr. Halbert: The iron fit in mg/l versus depth is a good fit.

<u>Case of the Waite Amulet sulphide base metal tailings area</u>

This is a 40 ha area which was extensively sampled in recent times. The results of samples of two sites, WA17 & WA22 were compared with deterministic and probabilistic simulations. For the WA22 site, the pH-depth relationship produced a good fit. See Figures 3 & 4 of first referenced document.

QUESTION AND ANSWER PERIOD:

Dr. Yanful: Are you very satisfied with the calibration and validation work that you have done so far?

Mr. Halbert: He replied that this is really a comparison of field data with model results. There are many factors and each module needs to be calibrated and verified.

Dr. Nicholson: Perhaps we should have a simpler model to look at the effectiveness of covers. With regard to Dr. Yanful's question, there is room for improvement, especially the trace metals.

Dr. Yanful: Are you confident that the empirical formulae and the factors used are correct or do they have to be adapted if no fit is obtained and have you done that sufficiently so that the model is ready to go?

Mr. Halbert: Each model can continuously be corrected. Most of the questions will arise with some of the speciation work, conversion of the iron component.

Dr. Scharer: Dr. Scharer added that any model has this 'hocus pocus' because you have to do something when no data is available, as an example the conversion of cerisite to aluminite is purely kinetic in the model.

Dr. Nordstrom: He indicated that he can get very good results with respect to pH, i.e. to within .5 units, using real data, including all mineral reactions. The input is different, he uses the water chemistry.

Dr. Snodgrass: He commented that if the mass balances are known, then the pH can be calculated very well. He indicated that RATAP calculates the mass balances and calculates the pH. Various

Welcome Screen | Search | Report List

Next, Mr. Halbert showed a slide indicating the simulated effect of different covers on the acid generation rate as a function of the depth of the unsaturated zone. The cover material had identical properties as the underlying tailings. For one metre cover the acid generation rate is down by about 50%. Mr. Davé indicated that for a two metre cover the acid generation rate is still about 30% of the non-cover situation. Mr. Halbert confirmed that the process is slowed down, but not stopped.

Mr. Halbert ended his presentation by explaining the analysis carried out for five close-out options and the acid prediction with time.:

Option 1: original water level is left at 4.5 m below the surface
Option 2: the water level is raised by 1.5 metre
Option 3: the water level is raised by 3 metre to 1.5 metre below the surface
Option 4: the water level is left at the original level but a 3 metre de-pyritized tailings cap is applied
Option 5: as option 4, but the water level is raised by 4.5 metre

The prediction results show that over a 75 year period the total acidity increases steadily for each option, except for option 3, where the total acidity reaches a maximum and then drops off. There is no difference in acidity between option 1 and option 2, but the acidity is greatly reduced between options 2 and 3, and also between options 3 and 4. Option 5 produced virtually no acid.

A question resulted why for option 3 the curve showed a maximum, however this was not answered.

Dr. Steger added a comment related to the sometimes questionable accuracy of the field measurements.

Mr. Davé indicated that the initial layer is less certain due to addition of lime and the revegetation.

Dr. Nicholson: He repeated that the purpose of the Workshop is to determine what we are going to do about our modelling needs. The first thing to do is to take stock of the models we have here and get the understanding what to do with them.

Dr. Yanful: Dr. Yanful replied that he understands this, but 70 to 80% of the time was spent on RATAP and if ideally the objective was to look at various models, practically we only looked at RATAP.

Dr. Steger: He said that we have to be made aware of what we want and what we can afford. We must have all our objectives and resources in place.

Mr. Ferguson: Mr. Ferguson added that it is true that some of the other models were not discussed in as much detail as RATAP. He does not feel that RATAP had more time than it deserved because it was one of the focuses of this meeting. He felt that Dr. Nicholson's question, what are the tools, how are they useful, is a very important question. He was of the opinion that the question would be better addressed to the MEND Prediction Committee.

Mr. Phinney: Mr. Phinney requested to make a comment with respect to RATAP and its usefulness. He was of the opinion that RATAP will be very useful to predict what is going to happen to an existing site based on some measurements at the existing site to establish some reference points, and this was well demonstrated. He felt, however, that the same results could be obtained in a much simpler fashion. As far as new sites are concerned, there are easier ways and he did not see RATAP being useful.

Dr. Ritchie asked what models? and a discussion resulted between Mr. Phinney and Mr. Halbert regarding simpler models which can predict conditions for flooded tailings and the capabilities of RATAP for future sites.

packages were used to verify the code. He explained that RATAP tries to follow a model based measuring program. Everything is put into the model and then real data is used to calibrate the model.

Dr. Nicholson: One starts to see what the really important parameters are and one can then take the complications out of the model, simplify it. Example, if the temperature module is uncertain and not important it might be better to take it out.

Dr. Scharer: He added that the results of the model will be better if the input is more site specific. The more parameters we have measured in the field, the better our modelling results will be, example we can vary the initial concentration of pyrite layer per layer.

Dr. Nordstrom: The more parameters are measured in the field, the more unique the solution is to the processes that are happening. A model is no longer required if you have them all because you know what is going to happen.

Dr. Nicholson: He stated that he wants to get away from RATAP for a moment and said that there is a good appreciation of other models and approaches that are undertaken and asked what are the modelling needs and where are we going in the future? Which models should we use, a universal one or one which is specific for each purpose?

Dr. Yanful: Dr. Yanful indicated that it is not possible to get one tool that will do everything, but he wondered, as indicated earlier by Dr. Morin, what to do with RATAP. He summarised Dr. Morin's proposed recommendations (see third presentation: Dr. Morin, Morwijk Enterprises Ltd.) and asked what the approach will be.

Mr. Halbert explained why RATAP was developed in a probabilistic framework. The UTAP framework was used, but apart from that, each model has a certain built in incompleteness and imperfection which produces uncertainties in the output results. Also the input variables are uncertain, but bounds can be determined with confidence from consultation with researchers and practitioners of the different areas of specialization. Lastly, there is uncertainty about the future.

Mr. Halbert explained the concept of a probabilistic analysis. It consists of identifying probability distributions for each input variable to the model and inputting these distributions into the code. The program then selects at random a variable for each input parameter from its respective probability distribution and creates one output result. This procedure is repeated randomly as many times as necessary in order to create an output distribution of the results. The results are then analyzed in order to establish various measures of the distribution: minimum, maximum, arithmetic and geometric mean and standard deviation, measures of skewness and kurtosis. As a rule, the code is only run probabilistic at the end to do the final analysis.

Mr. Halbert showed a slide indicating the concept adopted for modelling a tailings area and indicated that up to 20 layers are included in the unsaturated zone and 2 layers in the saturated zone. Specific values for each layer can be inputted for a number of parameters, including porosity, water content, mineral content, as well as concentration values for various cations and anions. Usually, we do not have the information layer by layer but the ability is there to do it.

Some of the minerals that are included in the RATAP code include pyrite, pyrrhotite, chalcopyrite, sphalerite and arsenopyrite. The latter mineral was included in version BMT2. Some of the buffering minerals that are included in the RATAP code include calcite, cerussite and base aluminite. Also included are several chemical precipitates, gypsum, iron hydroxides, aluminum hydroxides, siderite, copper carbonate, copper-ferric hydroxide co-precipitate, ferric arsenic-ferric hydroxide co-precipitate, jarosite and copper-jarosite co-precipitate.

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

SENES CONSULTANTS LTD. - MR. BRUCE HALBERT

The presentation dealt with the development and description of RATAP.BMT and with the validation using tests at the Waite Amulet tailings deposit. Please refer to the following documents:

1. Modelling Chemical Reactions in Reactive Tailings Bruce E. Halbert, Jeno M. Scharer, William J. Snodgrass, Henry F. Steger, R.V. Nicholson, Jeanette M. Southwood found following these minutes.
2. A Research Report: Critical review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2), prepared for CANMET by Senes Consultants Ltd & Beak Consultants Ltd. found in the Appendix.
3. A Research Report: Adaptation of the Reactive Acid Tailings Assessment (RATAP) to Base Metal Tailings. Main Report, prepared for CANMET by Senes Consultants Ltd & Beak Consultants Ltd. found in the Appendix.
4. Application of the Reactive Acid Tailings Assessment Program to Pyritic Mine Tailings. B.E. Halbert, R.A. Knapp, J.W. Maltby and A.J. Vivyurka, Senes Consultants Ltd. and Rio Algom Ltd. found following these minutes.

Mr. Halbert began his presentation by giving some of the history of the development of RATAP, started five years ago, and stating RATAP's objectives:

- to investigate the factors and processes which control oxidization of sulphide minerals
- to simulate tailings pore water quality
- to simulate acid generation versus time
- to predict the long term acid flux from a tailings area
- to develop the ability to investigate the effects of acid generation of alternative close out concepts.

chemical exponential function and the query if this is a good way of doing it.

An other question resulted why oxygen did not appear in the formula. It was explained that oxygen was done in a separate part of the model.

The chemical reaction rate is a function of the pH, the temperature, the chemical energy of activation, the surface area of the sulphide particles, the partial oxygen pressure and the moisture content. See formula 2.13 of third referenced document.

The surface area is a function of the size distribution and this is included as a Paretto-type distribution. See formula 1 of first referenced document.

The rate of shrinkage of the particles is equal to the sum of the biological and chemical oxidation rates divided by the density of the particles.

A discussion resulted related to the sulphide particles and how much is free as compared to 'disseminated' particles. Mr. Davé was of the opinion that a lot of particles will have to be milled to be liberated, but Dr. Nicholson did not agree and from microscopic examinations felt that, for example with pyrite all particles are free. After the discussion, he admitted, however, that a correction factor should be included for some materials to account for the non-exposed sulphide particles.

Mr. Halbert continued his presentation by indicating the formula for the unreacted sulphide mineral at any time 't'. See formula 3 of first referenced document. Mr. Halbert discussed the temperature sub-routine and indicated that this has undergone several changes over time. The current model is based on energy transport. The change in temperature over time is evaluated as a function of the reaction rates, the conductive and convective transport and the heat capacity of the phases. The formula has not been verified but the results seem reasonable. The temperature is added to the background temperature.

A discussion resulted based on a question by Mr. Davé if the model predicted a rise in temperature. Temperature rises are 3 to 5 degrees C. Mr. Blowes

RATAP consists of six principal modules:

- initial inventory module
- kinetics module
- sulphide oxidation module
- oxygen transport module
- solute transport module
- speciation module.

Four basic sub-routines calculate temperature, pH, formation of hardpan and concentration of trace salts.

Each module calculates the following:

- initial inventory module: calculates the tailings mineralogy, the baseline tailings temperature, the tailings water and air content
- kinetics module: calculates the chemical and biochemical oxidation rates
- sulphide oxidation module calculates oxidation rates for each sulphide mineral
- oxygen transport module calculates the oxygen concentration with depth
- solute transport module calculates the new temperature profiles, the aqueous and solid phases mass balances, the pore water pH and the hardpan formation
- speciation module: calculates the concentration of all major (calcium sulphate, iron, etc.) and minor (copper, zinc and arsenic) elements.

With regard to the kinetics module, Mr. Halbert indicated that the total biological reaction rate is a function of the specific growth rate, the bacterial population density and the yield constant. The specific growth rate takes into account temperature, pH, phosphorous concentration, carbon dioxide and moisture. See formulae 2.10 and 2.11 of third referenced document.

A discussion resulted, starting with a question by Ms Pamela Friedrich, regarding the temperature expression in the specific growth rate formula, which is an usual

Welcome Screen | Search | Report List

Modelling Chemical Reactions in Reactive Tailings

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ABSTRACT

The control of acid mine drainage from tailings areas is widely recognized as the most serious environmental issue facing many base metal, gold and uranium mine operators today. While collection and treatment of acid mine drainage is commonly practiced at active mine sites, it is generally accepted that continuation of treatment practices for an indefinite period in the post operating phase is neither desirable nor practical. Besides problems associated with maintaining an effective treatment system after mining activities have ceased, the disposal of chemical treatment plant sludge produced from the neutralization of acid mine drainage is a major operational problem.

Recognizing the seriousness of this problem, the Canada Centre for Mineral and Energy Technology (CANMET), in the mid 1980's, initiated investigations into the factors and processes which control the oxidation of sulfide minerals and work on the development of a predictive modelling tool to simulate acid generation in mine tailings. The primary objective of this work was to provide a model for predicting the long-term potential of acid generation in tailings and for evaluating the effects on acid generation of alternative closeout concepts.

The model framework, known as the Reactive Acid Tailings Assessment Program (RATAP), was developed jointly by SENES Consultants Limited and BEAK

Dr. Robertson added that RATAP is not everything to all people and he made an analogy with different music instruments to achieve the same goals. A discussion resulted between Dr. Yanful and Dr. Nicholson related to the use of RATAP. RATAP will not solve all the problems, but it is useable now, why not use it.

Dr. Yanful: He again repeated his question related to the recommendations made by Dr. Morin, asking who is going to attend to these recommendations, and he asked everyone: what are we going to do with his recommendations?

Mr. Townsend: He suggested that RATAP should be made more user-friendly. It is a fine instrument and a simpler version could be produced.

Dr. Scharer: Dr. Scharer agreed that RATAP could be made more user friendly.

Dr. Snodgrass: He indicated that RATAP is programmer friendly.

* * * * * *

this model, known as RATAP.BMT2 (3), to the sulfide tailings at Waite Amulet in Quebec is discussed in this paper.

The mining and milling operation at Waite Amulet processed approximately 8.74 million tonnes of sulfide ore between 1929 and 1962. The mill produced a copper and zinc concentrate. Nearly 6 million tonnes of tailings were deposited in a 42 hectare site enclosed by a perimeter dam. An extensive research programme was initiated in 1985 by CANMET and the Noranda Research Centre to investigate the hydrogeology, hydrology, mineralogy, and geochemistry of this high sulfide tailings site.

THE RATAP.BMT MODEL

The concepts adopted for modelling a tailings area are illustrated on Figure 1. The tailings soil profile is subdivided into the unsaturated zone, capillary fringe and saturated zone. Conditions conducive to the oxidation of sulfide minerals are limited to the unsaturated zone and top layer of the capillary fringe due to the barrier posed by water to oxygen transport. Hence, the characteristics of the tailings mass in the top horizon may be subdivided into twenty layers with each layer having its own distinct physical and chemical properties. In contrast, the saturated zone, which is a reducing environment, is modelled as either a one or two layer system depending on the flowpath assumed for the tailings porewater. Precipitation entering the tailings is modelled to flow downward through the unsaturated zone and capillary fringe. On entering the saturated zone, a portion of the flow may be modelled as moving horizontally through the tailings mass and emerging as seepage passing through or beneath the perimeter dams while the remaining portion moves further downward into a subsurface aquifer beneath the tailings.

Oxidation of the sulfide minerals, which is assumed to be limited to the unsaturated zone, is modelled as the sum of biochemical and chemical oxidation rates. The factors which affect these rates have been extensively reviewed and summarized (4).

Pyrite and other sulfide minerals (pyrrhotite, chalcopyrite, sphalerite, and arsenopyrite) are considered as distinct, unconsolidated particles in the tailings. The cumulative size distribution is given by

Consultants Limited under contract to CANMET. The model was designed to predict, on a long-term basis, the rate and the extent of acid generation and concomitant major geochemical events brought about by the chemical and microbial oxidation of pyrite in uranium tailings. This model was subsequently adapted to base metal tailings by including other sulfide ores such as pyrrhotite, galena, and sphalerite (RATAP.BMT). The modular design of the code allowed these additions to be made to the original program with relative ease. Recently, RATAP.BMT has been expanded to incorporate the geochemistry of arsenic (RATAP.BMT2). The current version of the program can be run in a probabilistic or a deterministic manner.

The original version of the model has been calibrated and validated extensively on pyritic uranium tailings. Partial validation of the modified computer model (i.e. RATAP.BMT2) has been performed using field study data on the high sulfide tailings at Waite-Amulet in northeastern Quebec, some relevant data from pyritic uranium tailings investigations in the Elliot Lake area of northern Ontario, and laboratory observations.

INTRODUCTION

In the presence of oxygen or other oxidizing agents (ferric ion, for example), sulfide-containing minerals oxidize to soluble metal sulfates. Many of these oxidized minerals contribute to the acidic nature of mine drainage. The control of the acid mine drainage (AMD) from rock piles and tailings is widely recognized as a serious environmental issue at many mining properties. While collection and treatment of AMD is widely practiced, it is generally accepted that long-term treatment for an indefinite period past the operating phase is neither desirable nor practical. Besides the obvious problem of maintaining an effective treatment system at an abandoned mine site, the chemical sludges produced during treatment may pose a hazard as well.

Recognizing the seriousness of this problem, the Canada Centre for Mineral and Energy Technology (CANMET) initiated work in 1985 on the development of a predictive model to simulate acid generation by bacteria-assisted oxidation of pyritic uranium tailings. This original work, which was undertaken by SENES Consultants Limited and Beak Consultants Limited (1, 2), has been expanded to include sulfide minerals commonly found in base metal tailings. Application of transport into the tailings. At steady state, the diffusive transport is equal to the oxidation rate, i.e.:

$$D_e \frac{\delta^2 C}{\delta Z^2} = \frac{\delta M(t)}{\delta t} \qquad (4)$$

where

D_e = effective oxygen diffusivity through the tailings (m^2/month)
z = depth into the tailings (m)
t = time
c = oxygen concentration (moles/m^3)

The oxidation rate in Eq. 4 is an explicit function of oxygen. The model includes the simultaneous solution of Eq. 3 and Eq. 4 for evaluating the oxidation process.

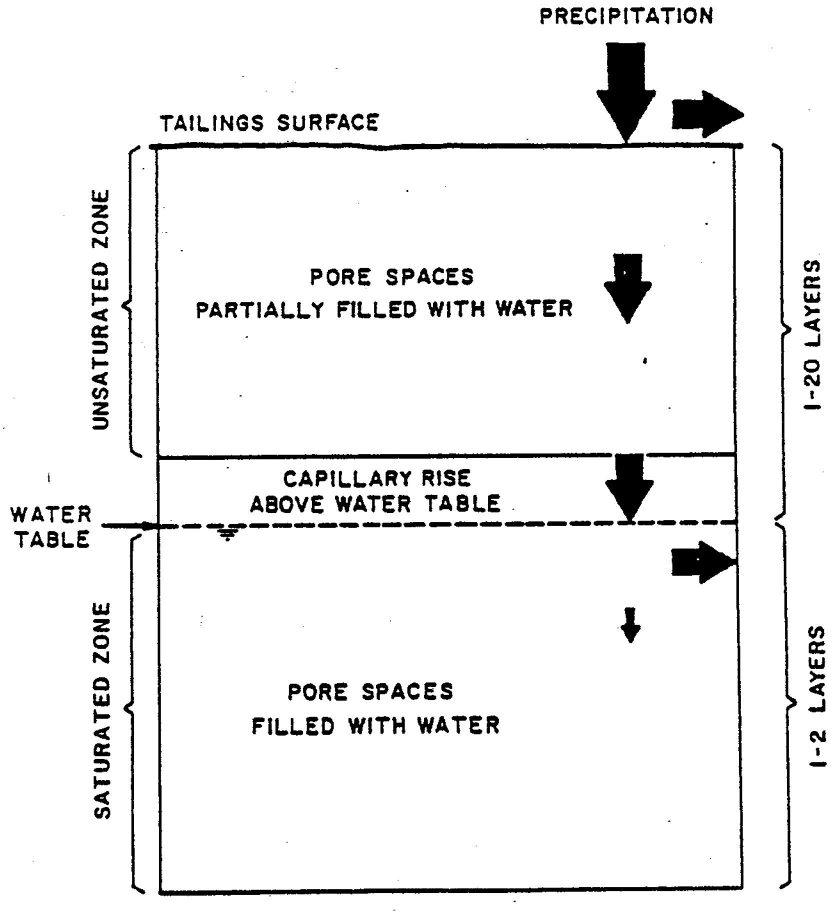

FIGURE 1: CONCEPT ADOPTED FOR MODELLING OF TAILINGS

a Paretto-type distribution function as follows:

$$F(r) = A\left(\frac{r}{R_{max}}\right)^{\alpha} - B\left(\frac{r}{R_{max}}\right)^{\beta} \qquad (1)$$

where

$F(r)$ = fraction of tailings having radius "r" or less.

R_{max} = maximum particle radius

The parameters A, B, α and β are fitted on the basis of sizing data and are subject to the following constraints:

$$A - B = 1.0, \quad \alpha \neq 1.0, \quad \beta \neq 1.0$$

Sulfide particle oxidation has been based on the concept of "shrinking radius" kinetics. Thus, the reaction rate is evaluated monthly as the sum of the biological and chemical oxidation rates:

$$k_t(t) = \frac{K_{Bio}(t) + K_{Chem}(t)}{\rho_p} \qquad (2)$$

K_{Bio} = biological oxidation rate per unit surface area (moles/(month.m^2))

K_{Chem} = chemical oxidation rate per unit surface area (moles/(month.m^2))

ρ_p = density of the sulfide mineral (moles/m^3)

It can be shown, that the mass of "unreacted" sulfide mineral per unit volume at any time "t" is given by the following expression:

$$M(t) = M_o \int_{\chi}^{R_{max}} \left\{ \left(\frac{r-\chi}{r}\right)^3 \left[A\left(\frac{\alpha}{R_{max}}\right)\left(\frac{r-\chi}{R_{max}}\right)^{\alpha-1} - B\left(\frac{\beta}{R_{max}}\right)\left(\frac{r-\chi}{R_{max}}\right)^{\beta-1} \right] \right\} dr \qquad (3)$$

where

$M(t)$ = unreacted sulfide mineral content (moles/m^3)

Mo = initial sulfide mineral content (moles/m^3)

χ = $\int_o^t k((t)\, dt$

The sulfate flux depends on the extent of oxygen

The first module, executed only once, is the initial inventory module which calculates for each layer the initial solids composition, the monthly soil temperature, the soil water content and soil air content. The kinetics module, the second module, calculates rate information (i.e. the chemical and biological oxidation rates) at each time step for the various layers. The calculated parameters transferred into the model for each layer are the soil temperature, water content, pH and oxygen concentration; the latter two parameters being estimates from the "previous month". The sulfide oxidation module is then employed to calculate simultaneously the extent of oxidation according to Eq. 3 and the rate of oxidation for each sulfidic mineral. The rate of oxidation, in turn, is used to evaluate the rate of oxygen consumption by considering the stoichiometry and kinetics of the process:

$$R_{O_2} = b\frac{\delta M}{\delta t} = b\left\{V_{Bio}\frac{C}{K+C} + V_{Chem}C\right\} \qquad (5)$$

where

b = stoichiometric oxygen requirement
V_{Bio} = volumetric biological oxidation rate (moles/(m^3.month))
V_{Chem} = volumetric chemical oxidation rate (moles/(m^3.month))

The oxygen module uses the above information together with data on the air-filled porosity of tailings to evaluate the oxygen content versus depth.

The next module, the solute transport module, is the heart of the program. This module directs the performance of several subroutines. Oxidation of sulfide minerals is highly exothermic. First, the temperature is evaluated interactively by a loop considering oxidation rates, thermal conductivity and heat capacity of solid and liquid phases. The temperature is evaluated as an increment above some background level. The next step in the transport model is the establishment of liquid and solid phase mass balances. Based on these balances, an "initial pH guess" is obtained and the pH calc and pH function subroutines are called to calculate actual pH by solving an ionic balance. Although the speciation affecting the pH calculation is performed implicitly in the pH code subroutine, detailed speciation is achieved in the speciation module. This module also affects the trace subroutines. In fact, trace is a collection of several subroutines, one each for each minor

The code comprises six main modules and five auxiliary subroutines as indicated on Figure 2. The main modules, in order of operation, are: initial inventory, kinetics, sulfide oxidation, oxygen transport, solute transport, and speciation. Four subroutines, namely the temperature, pH calculation, pH function and trace routines are called iteratively to evaluate the temperature effect, calculate the pH, and the trace metal concentrations in the porewater. A separate subroutine checks for the presence of hardpan by considering the extent of secondary mineralization.

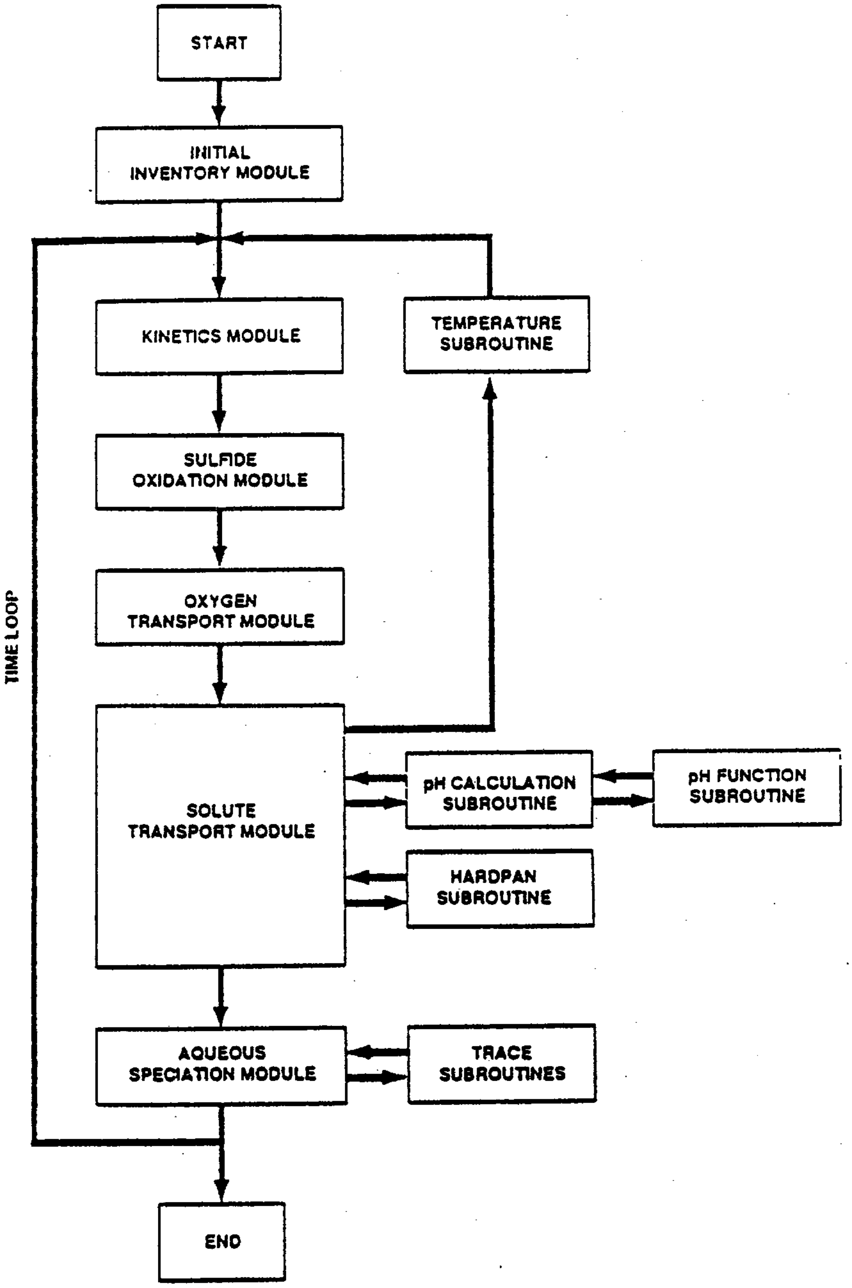

FIGURE 2: CONCEPTUAL FLOW DIAGRAM

deterministic run at each location and 25 probabilistic runs at each location. The results of these runs are discussed below.

The data from borehole WA22 was used to calibrate the model. Field data shows that the pH in the top 1 m of core rises sharply from 3.42 in the uppermost section to about 5.0 at 80 cm, then rises more slowly to a relatively constant value of about 6.4 (5). Predicted pH values agree well with measured values as indicated on Figure 3 for the deterministic model run and Figure 4.0 for the probabilistic model run. Both the deterministic and probabilistic model runs show more abrupt pH change with depth than is suggested by the field data.

There is good agreement between predicted and measured ferrous iron values as evidenced from the plots on Figures 5 and 6. The sharp reduction in the ferrous iron concentration between 2 and 3 metres below the tailings surface mimics the sharp rise in pH from about 4.5 to 6.5 - 7.0. This pH change contributes to the precipitation of dissolved ferrous iron as iron hydroxide.

The plot of the probabilistic model run includes error bars which span one standard deviation about the mean values. These error bars were calculated from the results of 25 probabilistic runs and represent the uncertainty in the predicted values due to uncertainty in the model input values, specified as distributions rather than constants. The large uncertainties predicted at a depth of 2 to 3 metres in the tailings pile are not unexpected but rather reflect the range in values which could be measured at this depth depending on the particular values selected for the input parameters.

The sampling program was conducted in the late fall of 1987, during a period of mixed snowfall and rainfall. The samples from WA17 were collected shortly after snowmelt had occurred, while samples from WA22 were collected through the unmelted snow cover (5). The unusual pH values in the near surface area suggest that the water expressed from the uppermost core at WA17 may reflect recently infiltrated rain or snow melt water. Below the top 100 cm the pH rises to a level between 5.0 and 6.0 (Figures 7 and 8), similar to those observed at WA22 (Figure 3). There is reasonable agreement between predicted and measured pH values, constituent. Currently, subroutines have been developed for copper from chalcopyrite, zinc from sphalerite, and arsenate and arsenite from arsenopyrite. The transport and speciation modules calculate properties for each individual layer. A subroutine called hardpan checks whether the porespace has been filled with secondary precipitates and, hence, whether a condition known as "hardpan" has developed.

Upon completion of these calculations, the program moves to the next time step and repeats the calculations for the kinetics through aqueous speciation modules.

The component modules described above are embedded within a probabilistic framework which permits the effect of uncertainty in the oxidation processes and model parameters on the rate and quantity of acid generation to be assessed. The uncertainty arises because of normal experimental error or because it is sometimes impossible to measure the influence of every variable. The probabilistic technique allows the full state of knowledge (or lack thereof) about the input parameters to be described in the form of subjective probability distributions. While this technique is very useful in evaluating the uncertainty in the model predictions and in assessing the sensitivity of the model output results to changes in the input parameters, the RATAP.BMT model can also be run in the more conventional deterministic mode. Deterministic model runs are made using nominal values of the input parameters. Experience suggests that it is generally preferable to limit the number of probabilistic runs because of the large amount of data which must be analyzed and interpreted and because the computer run time can take several hours.

RESULTS

Model validation using the Waite Amulet tailings as the test case involved running RATAP.BMT to predict pH and ferrous iron concentrations in the porewater and the oxygen concentration in the gaseous porespace at two locations. All input parameter values were held constant between the two locations with the exception of the depth to the water table which was set equal to 2.75 metres for WA17 and 6 metres for location WA22. While it was recognized that there were differences in the tailings characteristics between the two locations, there was insufficient basis for changing any of the parameter values. RATAP.BMT runs were performed for one

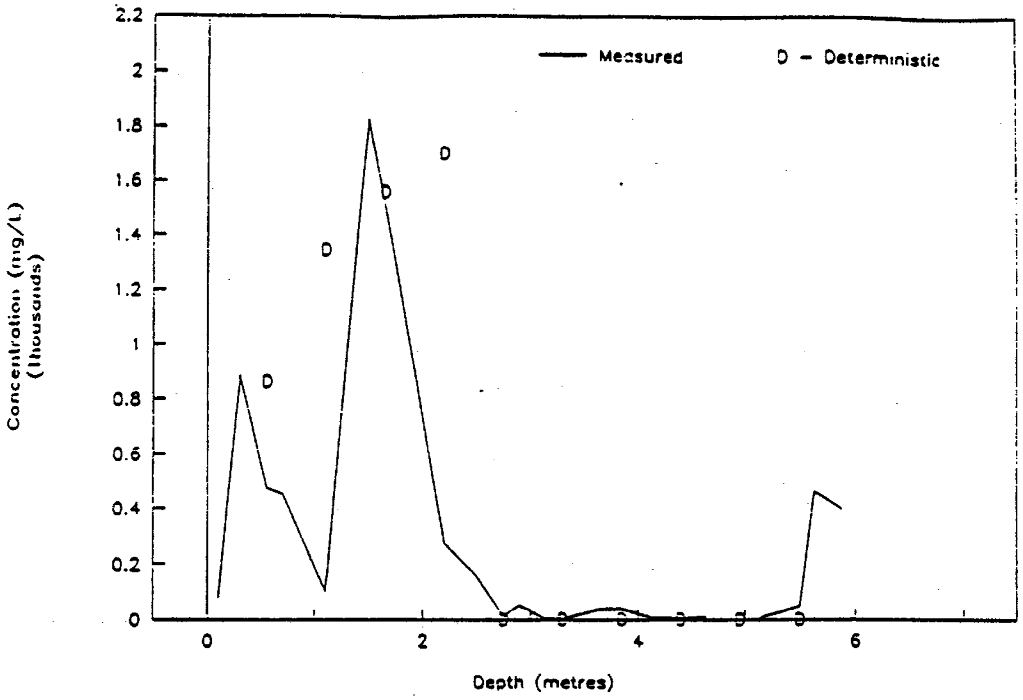

FIGURE 5: WA 22 - FERROUS IRON CONCENTRATION VERSUS DEPTH DETERMINISTIC RUN

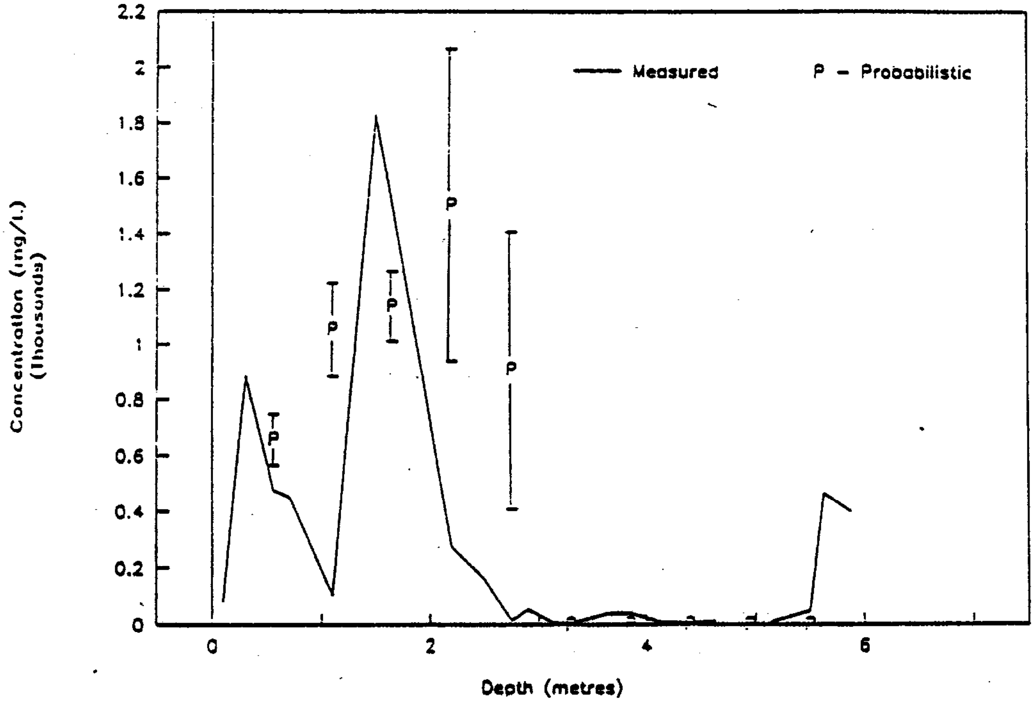

FIGURE 6: WA 22 - FERROUS IRON CONCENTRATION VERSUS DEPTH PROBABILISTIC RUN

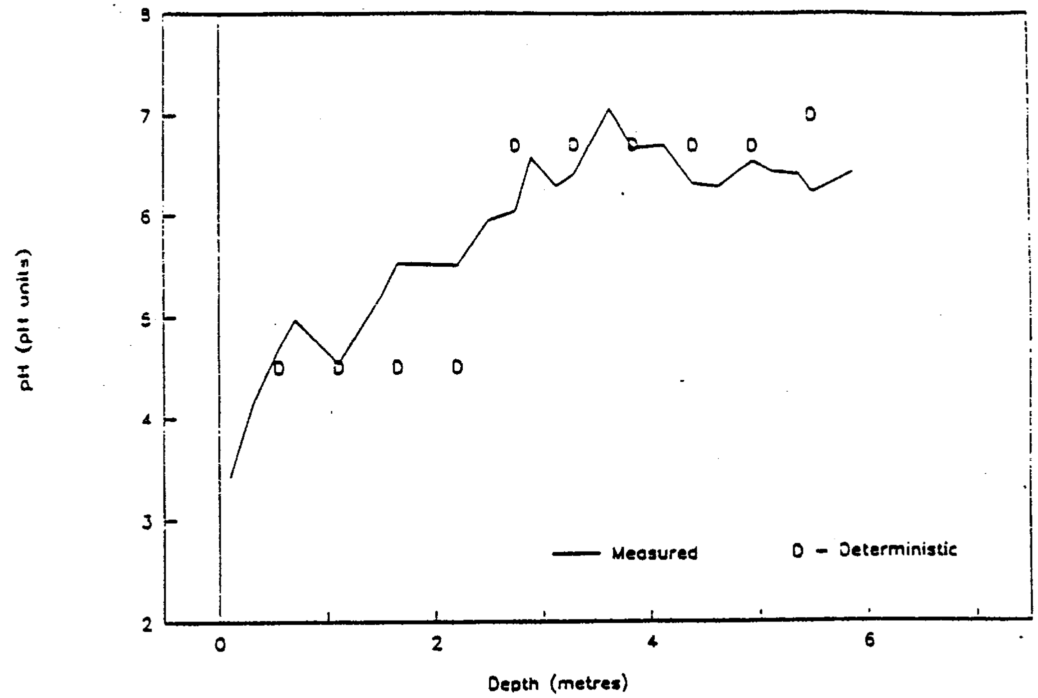

FIGURE 3: WA 22 - pH VERSUS DEPTH
DETERMINISTIC RUN

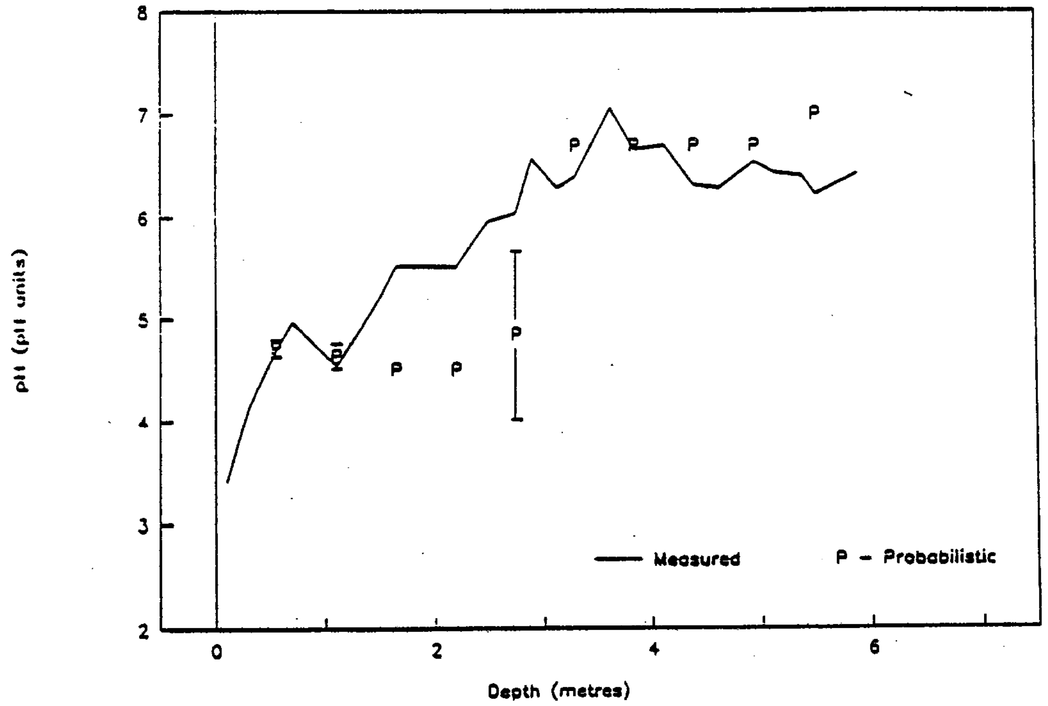

FIGURE 4: WA 22 - pH VERSUS DEPTH
PROBABILISTIC RUN

although the lower predicted values in this case suggest that more buffering capacity may have been available at this location than was assumed. The starting mineralogical composition at WA17 was assumed to be identical to WA22 since location specific data were not available. A better fit of observed and predicted values could have been obtained by adjusting some of the input parameter values.

The ferrous iron concentrations plotted on Figures 9 and 10 show that the predicted values agree well with the measured values. It is noted that the measured values at WA17 were significantly higher than measured at WA22, and the predicted values (deterministic and probabilistic) follow the same trend.

The diffusive transport of gaseous oxygen can be regarded as a rate limiting step. The porespace oxygen concentration reflects this process. In Figure 11, the predicted oxygen concentrations at borehole WA22 are compared with measurements. In general, the predictions agree well with measured values and the rapid decline of the oxygen concentration with depth reflects actively oxidizing tailings. Since the oxygen levels are dependent upon both the diffusive transport

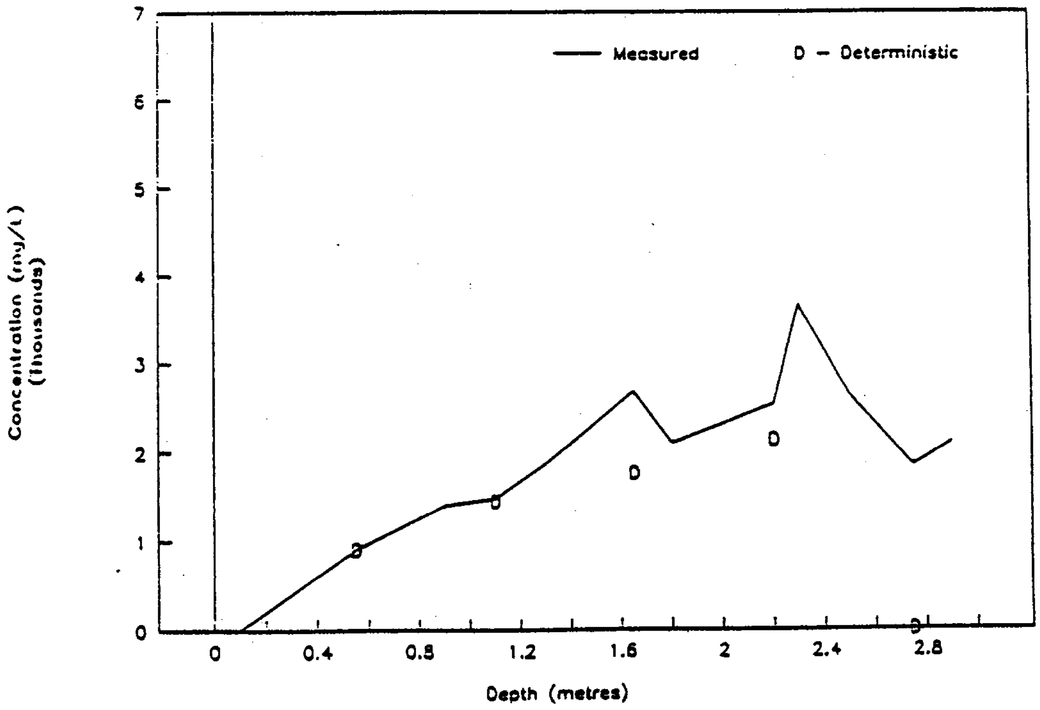

FIGURE 9: WA 17 - FERROUS IRON CONCENTRATION VERSUS DEPTH DETERMINISTIC RUN

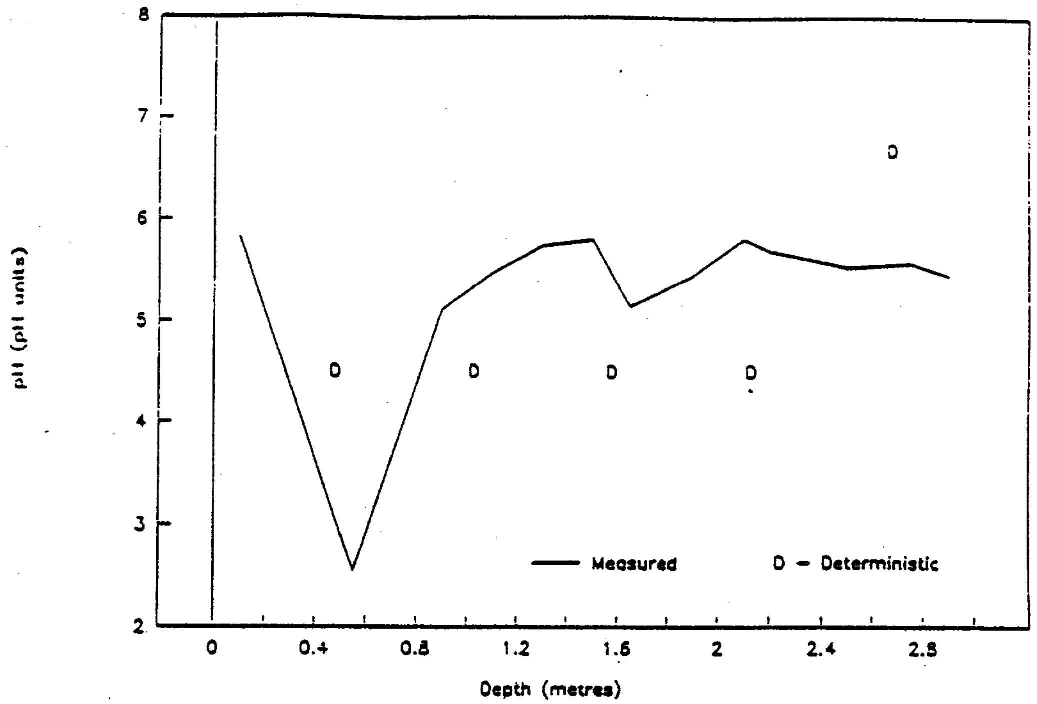

FIGURE 7: WA 17 - pH VERSUS DEPTH
DETERMINISTIC RUN

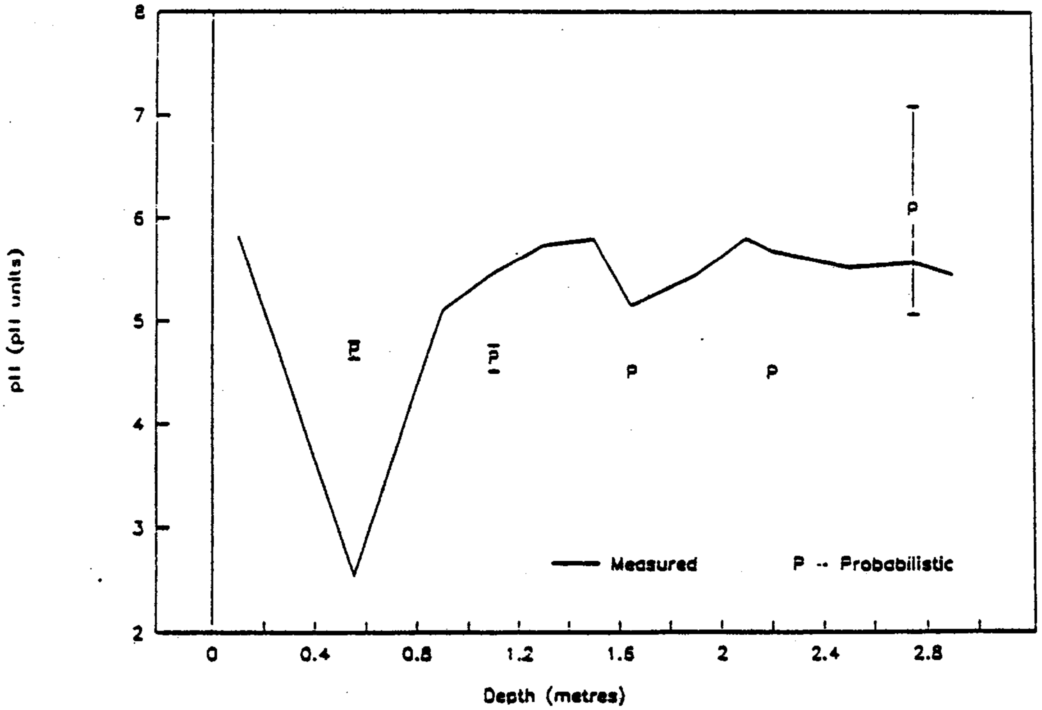

FIGURE 8: WA 17 - pH VERSUS DEPTH
PROBABILISTIC RUN

and the kinetic parameters, this agreement between model predictions and observations is perhaps the best "indicator" concerning the appropriateness of the model structure as well as the parameter values.

CONCLUSIONS

Mathematical models serve as useful predictive tools in assessing acid porewater generation from reactive tailings. The RATAP.BMT model is well suited for this purpose. In general a mechanistic (rather than empirical) modelling approach has been chosen. The sulfide oxidation process is based on "shrinking radius" kinetics and the acid flux estimation is based on particle size distribution. Mass balances are performed to take into account not only sulfide mineral oxidation, but also carbonate mineral interactions and secondary precipitation. The model has been successfully employed to predict acid fluxes in high sulfide base metal tailings (Waite Amulet) and sulfidic uranium tailings (Elliot Lake).

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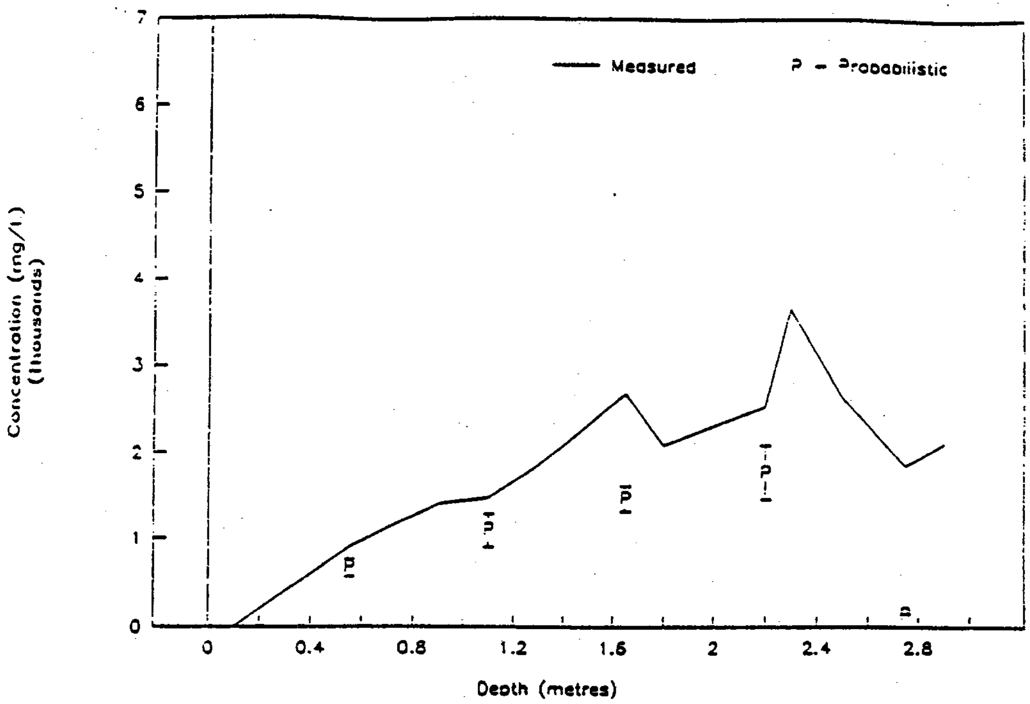

FIGURE 10: WA 17 - FERROUS IRON CONCENTRATION VERSUS DEPTH PROBABILISTIC RUN

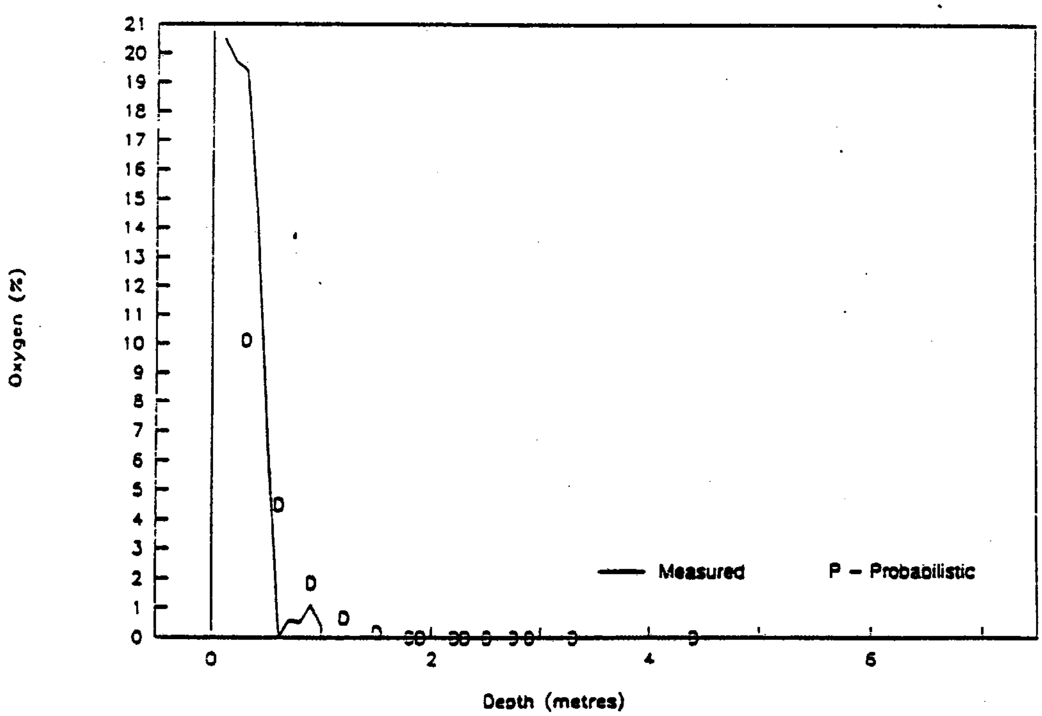

FIGURE 11: WA 22 - OXYGEN CONCENTRATION VERSUS DEPTH DETERMINISTIC RUN

Welcome Screen
Search
Report List

APPLICATION OF THE REACTIVE ACID TAILINGS ASSESSMENT PROGRAM TO PYRITIC MINE TAILINGS

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ABSTRACT

The Reactive Acid Tailings Assessment Program (RATAP) has been developed to analyze the effects of oxidation processes and variables on the rate and quantity of acid generated by the bacterial-assisted oxidation of sulfide minerals in mine tailings. The model allows the effects of various closeout strategies on the flux of total acidity from tailings areas to be evaluated. Acid generation is calculated as a function of both tailings characteristics, such as grain size, thickness of unsaturated zone, temperature, depth of tailings mass and time of year; and as a function of such mineralogical characteristics as pyrite, gypsum, calcite, basaluminite and geothite contents.

The code steps through time in monthly increments and typically is run for several decades on any application. It is structured into several modules to permit each component to be calibrated independently against data reported in the literature. In addition, the RATAP code was conceived in a probabilistic framework to allow the effects of uncertainties in the values of the input parameters to be investigated.

The RATAP model, which has been validated against field data on the Nordic tailings area in Elliot Lake, Ontario, showed good overall agreement between predicted values and field observations. The comparisons included pH values, several chemical and radiological species in both the aqueous and solid phases, and gaseous component concentrations.

The validated model has since been applied to other pyritic, uranium mine tailings areas at Elliot Lake to investigate the effects of closeout concepts on long-term acid generation. The results of model predictions for closeout options involving direct vegetation of the tailings surface, placement of a cover on the tailings and replacement of porous dams to raise the water table, have been evaluated and are discussed in this paper.

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accounts for many of these factors and is based upon principles of mass balance, geochemical kinetics or equilibria, where appropriate, and solution transport to estimate the pH and the acidity of tailings porewater.

The code comprises six modules as indicated on Fig. 2. The modules, in order of operation, are: initial inventory, kinetics, oxygen transport, pyrite oxidation, solute transport, and aqueous speciation. Because many of the processes are interdependent, the computational sequence involves several iterative solutions as suggested by the loops on Fig. 2. The computations are performed on a monthly basis and are repeated for each succeeding year over a user specified duration.

The first module, executed only once, is the initial inventory module which calculates for each layer the initial solids composition, the monthly soil temperature, the soil water content and soil air content. The kinetics module, the second module,

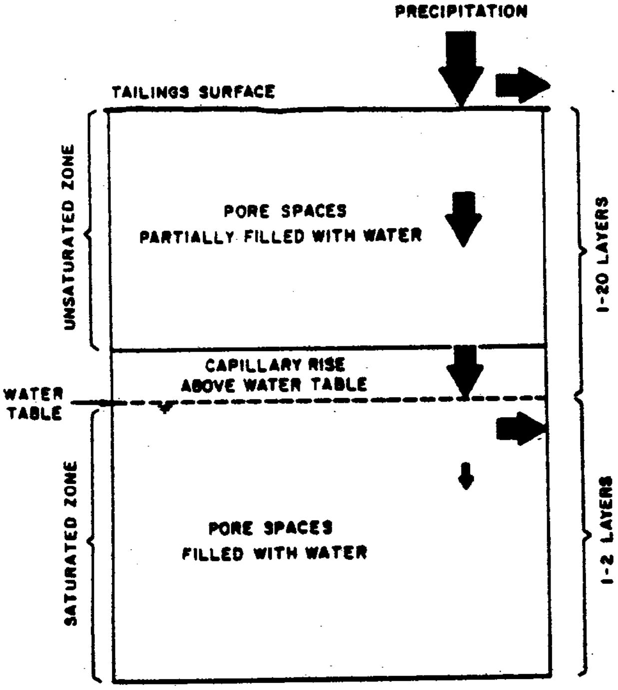

FIGURE 1: CONCEPT ADOPTED FOR MODELLING OF TAILINGS

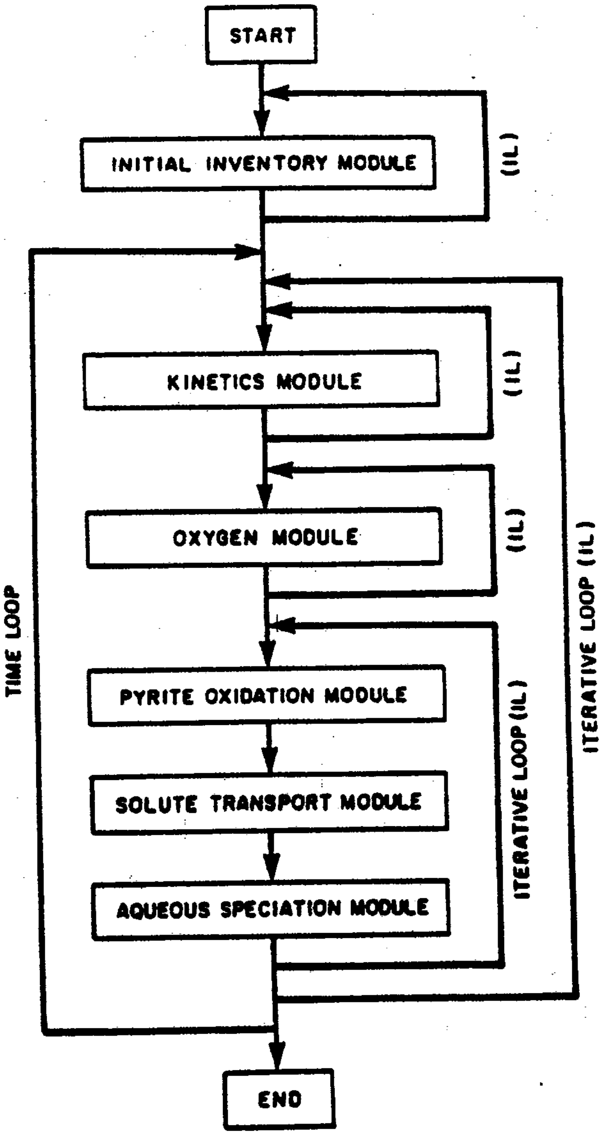

FIGURE 2: CONCEPTUAL FLOW DIAGRAM

Welcome Screen Search Report List

INTRODUCTION

Control of acid mine drainage from waste rock piles and tailings areas is widely recognized as the most serious environmental issue facing many coal, base metal and uranium mine operators today. While collection and treatment of acid mine drainage is commonly practiced at active mine sites, it is generally accepted that continuation of treatment practices for an indefinite period in the post operating phase is neither desirable nor practical. Besides the obvious problems associated with maintaining an effective treatment system after mining activities have ceased, the disposal of chemical treatment plant sludge produced from the neutralization of acid mine drainage is a major operational problem.

Recognizing the seriousness of this problem, the Canada Centre for Mineral and Energy Technology, initiated work in 1985 on the development of a predictive modelling tool to simulate acid generation by the bacterial-assisted oxidation of pyritic uranium mine tailings. The primary objective of this work was to provide a model for predicting the long-term potential of acid generation in tailings and for evaluating the effects on acid generation of alternative closeout concepts. This original work, which was undertaken by SENES Consultants Limited and Beak Consultants Limited (1986 and 1987) resulted in the development of the Reactive Acid Tailings Assessment Program (RATAP). A second version of the code was subsequently developed to include other sulfide minerals found in base metal tailings and has been given the acronym RATAP.BMT (SENES and Beak, 1988). The work presented in this paper however, relates to the application of the original version of RATAP on pyritic uranium mine tailings typical of those found in the Elliot Lake area of northern Ontario.

THE RATAP MODEL

The concepts adopted for modelling a tailings area are illustrated on Fig. 1. The tailings soil profile is subdivided into the unsaturated zone, capillary fringe and saturated zone. Conditions conducive to the oxidation of sulfide minerals are limited to the unsaturated zone and top layer of the capillary fringe due to the barrier posed by water to oxygen transport. Hence, the characteristics of the tailings mass in the top horizon may be subdivided into twenty layers with each layer having its own distinct physical and chemical properties. In contrast, the saturated zone, which is a reducing environment, is modelled as either a one or two layer system depending on the flowpath assumed for the tailings porewater. Precipitation entering the tailings is modelled to flow downward through the unsaturated zone and capillary fringe. On entering the saturated zone, a portion of the flow may be modelled as moving horizontally through the tailings mass and emerge as seepage passing through or beneath the perimeter dams while the remaining portion moves further downward into a subsurface aquifer beneath the tailings.

The rate and quantity of acid generated from the biochemical oxidation of sulfide minerals is dependent on a host of factors which have been extensively reported in the literature and were reviewed in an earlier report by SENES (1984). The RATAP code

Beak (1986) and showed good agreement for all those parameters which could be tested. Space does not permit review of this calibration work in this paper.

Once the RATAP model development and calibration work was completed, the validity of the model predictions were tested by comparison to field data collected at the Nordic tailings site in Elliot Lake, Ontario. The tailings were deposited between 1957 and 1968 and typically contained between 3 to 8% pyrite. Several geochemical and hydrogeological investigations have been undertaken at the site in the intervening years. The data selected for comparison purposes are those reported by Smyth (1981) on two sampling stations located about 0.75 km apart and designated as T3 and T5. The tailings at location T3 are predominantly slimes and the water table at this station varies between 6 and 6.5 m below the surface. At location T5 tailings are coarse grained and the water table is at a depth of 4 to 4.5 m.

To initiate a model validation run, certain site specific information was required to characterize the tailings as laid down at the cessation of operations in 1968. Specifically, input data were required for each tailings type on the initial pyrite content, depth to water table, number of layers and thickness of each layer, tailings porosity, tailings residual water content, coefficient of moisture content and air entry value. The input values employed for all other input parameters were determined from the literature or from other field investigations in the Elliot Lake areas.

The RATAP model provides output data on a range of solid, aqueous and gaseous phase parameters. Model predictions are presented here however for only the key parameters. Figure 3 presents a comparison of predicted and measured pyrite values at locations T3 and T5 twenty years after tailings disposal ceased. The initial pyrite content assumed for the two locations was 6% and 11% respectively. The plots show reasonably good agreement between predicted and observed values and indicate that a substantial amount of pyrite remains above the water table at both locations.

Good agreement between predicted and measured pH values was also found at both locations (see Fig. 4). The sharp gradients in the predicted values occur when particular buffering systems are calculated to be depleted. In contrast the field data suggest that the porewater may be influenced by residual solids of the buffering species which tend to smooth out the transition. The low pH values at location T5 indicate that more extensive oxidation is occurring in the coarse tailings than in the slimes fraction at T3. This observation is expected since the coarse tailings have a lower moisture content which permits a greater oxygen flux into the tailings which, in turn, supports more complete biochemical oxidation of the sulfide minerals.

Measured and predicted total dissolved iron levels in the tailings porewater in the unsaturated zone are presented on Fig. 5. Again model predictions are seen to be in good agreement with the field data. The low iron concentrations predicted at shallow depth for location T3 occurs because pyrite is predicted to be depleted from the upper tailings horizons after twenty years of oxidation.

calculates rate information (i.e. the chemical and biological oxidation rates and the oxygen consumption rate) at each time step for the various layers. The calculated parameters transferred into the model are the soil temperatures, water contents, pH values and oxygen concentrations; the latter two parameters being estimates. The oxygen consumption rate information is then employed in the oxygen transport module, the third module, to calculate the oxygen profile. The oxygen module requires data on the volumetric air content of the soil, in addition to the rate information.

The next three modules (i.e. the pyrite oxidation, solute transport and aqueous speciation modules) are all run in sequence for each layer. The pyrite oxidation module imports the biological and chemical rates of pyrite oxidation and the oxygen concentrations. The pyrite module then adjusts the rates to include the effect of oxygen concentration giving an overall rate of pyrite oxidation. The solute transport and aqueous speciation module use the rate of pyrite oxidation to calculate the acid flux and pH respectively. The solute transport and aqueous speciation routines are solved simultaneously.

The pH and oxygen concentrations required for the kinetics module are estimated initially using values from the previous time step. These values are then refined twice by being fed back into the kinetics model and recalculating new values. Test calculations have shown that an acceptable convergence of all parameter values is achieved in three iterations. Upon completion of these calculations, the program moves onto the next time step and repeats the calculations for the kinetics through aqueous speciation modules.

The component modules described above are embedded within a probabilistic framework which permits uncertainty in the oxidation processes and model parameters on the rate and quantity of acid generation to be assessed. The uncertainty arises because of normal experimental error or because it is sometimes impossible to measure the influence of every variable. The probabilistic technique allows the full state of knowledge (or lack thereof) about the input parameters to be described in the form of subjective probability distributions. While this technique is very useful in evaluating the uncertainty in the model predictions and in assessing the sensitivity of the model output results to changes in the input parameters, the RATAP model can also be run in the more conventional deterministic mode. Deterministic model runs are made using nominal values of the input parameters. Experience suggests that it is generally preferable to limit the number of probabilistic runs because of the large amount of data which must be analyzed and interpreted and because the computer run time can take several hours.

MODEL CALIBRATION AND VALIDATION

The individual components of each module were calibrated using laboratory and/or field data whenever possible. Additionally, more comprehensive chemical speciation models were used to confirm RATAP model predictions of individual chemical species concentrations. The comparisons are fully documented in the report by SENES and quantity of acid generated unless the cover application results in a rise in the water table within the basin.

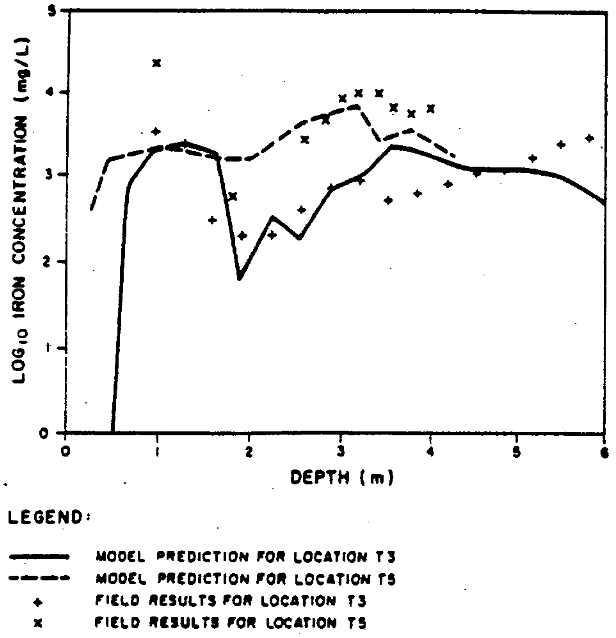

FIGURE 5: MODEL vs. FIELD IRON CONCENTRATION NORDIC TAILINGS AREA

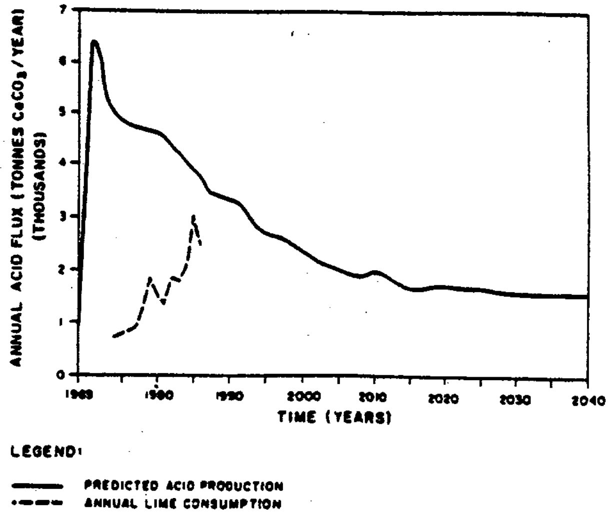

FIGURE: 6: ANNUAL ACID PRODUCTION FROM NORDIC TAILINGS AREA

The predicted effects on the total quantity o acidity produced at a representative tailings site in Elliot Lake of five closeout options are illustrated on Fig. 8. The tailings are assumed to be contained in a rock rimmed valley setting with pervious dams at the low points. The closeout options evaluated in this application included:

Option 1 - the tailings basin would be closed out with no remedial work excepting the grading, shaping and vegetation of the tailings surface. The depth to the water table was assumed to be more than 4.5 m below the tailings surface.

Option 2 - replace perimeter dams with new structures which include seepage cutoff to original ground. This option causes the water table to rise to within 3 m of the surface.

Option 3 - replace perimeter dams with new structures which include complete seepage cutoff to bedrock. This option causes the water table to rise to within 1.5 m of the surface.

Option 4 - apply a 3 m cap of depyritized tailings to the entire tailings surface and leave the existing perimeter dams intact. With this option the water table remains essentially at the same level as in the base case (Option 1).

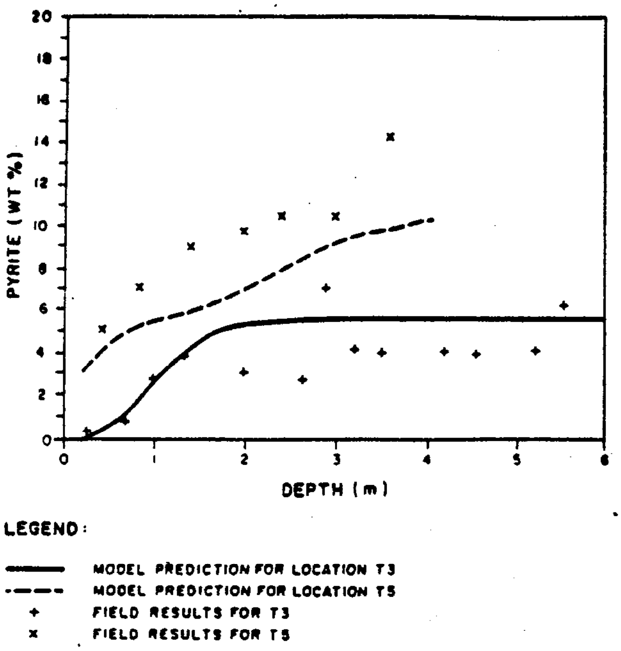

FIGURE 3: MODEL vs. FIELD PYRITE CONTENT NORDIC TAILINGS AREA

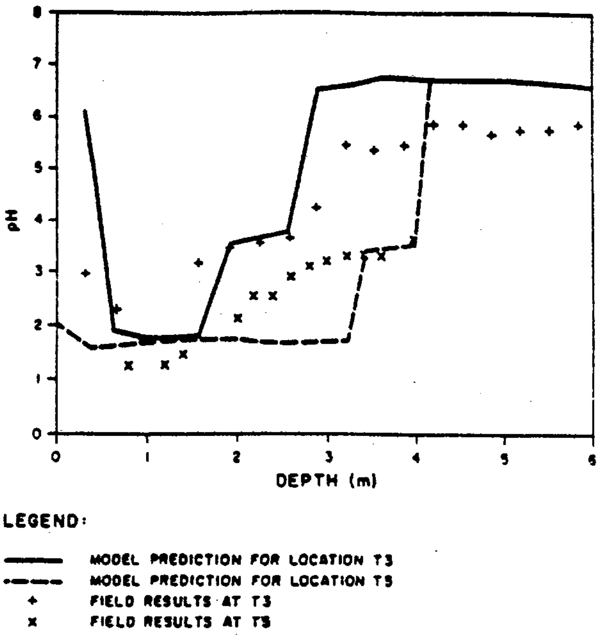

FIGURE 4: MODEL vs. FIELD pH VALUES NORDIC TAILINGS AREA

MODEL APPLICATION

As a test of the RATAP model, predictions of acid generation in the Nordic tailings were made for a timeframe spanning the period from 1969 to 2041. The model predictions are plotted on Fig. 6 together with data on lime consumption at the Nordic treatment plant. Analysis of the data indicated that approximately 90,000 tonnes of acid have been produced at the Nordic site to date. Of this amount, it is estimated that 25% has been neutralized at the lime treatment plant, 45% remains in storage in the tailings porewater and sand aquifer underlying the site, and 30% has been neutralized by the buffering capacity of the tailings and sand aquifer. As of 1988, the rate of acid being generated was approaching the rate of acid release from the system. Although the rate of acid production is declining and currently is at about one-half the rate predicted for the early 1970's, acid generation will continue well into the 21st century because of the large inventory of pyrite remaining to be oxidized.

The RATAP model has also been applied on several of the tailings areas at Elliot Lake to evaluate the potential benefits of closeout options in reducing acid generation. One concept which has been discussed on numerous occasions involves the application of a cover of earthen material or depyritized tailings. The effect on the acid generation rate of cover material is illustrated on Fig. 7 as a function of the depth of the cover material and the depth to the unsaturated zone in the pyritic tailings. For this evaluation, it was assumed that the cover material (soil or depyritized tailings) had the same physical characteristics as tailings. The results demonstrate that cover application will reduce the acid generation rate substantially but does not necessarily impact upon the total

Welcome Screen Search Report List

SUMMARY

RATAP has proven to be a useful analytical tool for assessing the rate and quantity of acid generation in pyritic tailings. Comparison of predicted concentrations for several solid, aqueous and gaseous phase constituents against data collected in the field at several monitoring stations on tailings areas in Elliot Lake has generally shown excellent agreement.

The model has been successfully applied as a planning tool to assess the benefits of short- and long-term tailings management options and to develop alternative reclamation or closeout strategies. Application of RATAP to the Elliot Lake situation has provided a basis for assessing the need for remedial measures at non-operating properties, for assessing the extent and duration of acid generation and the long-term need for treatment, and most importantly, for comparing the environmental and cost effectiveness of remedial measures and reclamation proposals.

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Welcome Screen | Search | Report List

Option 5 - apply a 3 m cap of depyritized tailings to the entire tailings surface and replace the perimeter dams with new structures which include complete seepage cutoff to bedrock. This option results in the water table rising into the cover material thus flooding the pyritic tailings.

The results shown on Fig. 8 indicate little difference between Options 1 and 2 over the simulation period. Over the longer term the total acidity curves for these two options would diverge as there is a lesser depth of pyritic tailings available to be oxidized with Option 2. The divergence of the acidity curve for Option 3 from the curves for Options 1 and 2 after the first decade reflects the fact that a lesser depth of pyritic tailings is available to be oxidized with Option 3. The acidity curve for Option 4 reflects the influence on the rate of oxidation of lower temperatures with increasing depth in the pile, as well as, the effects of the cover material on oxygen diffusion. While the cover material influences the rate of oxidation, the total quantity of acidity produced in the longer term with Option 4 would be greater than that predicted for Option 3. With Option 5, the effect of raising the water table into the cover material is to essentially eliminate acid generation.

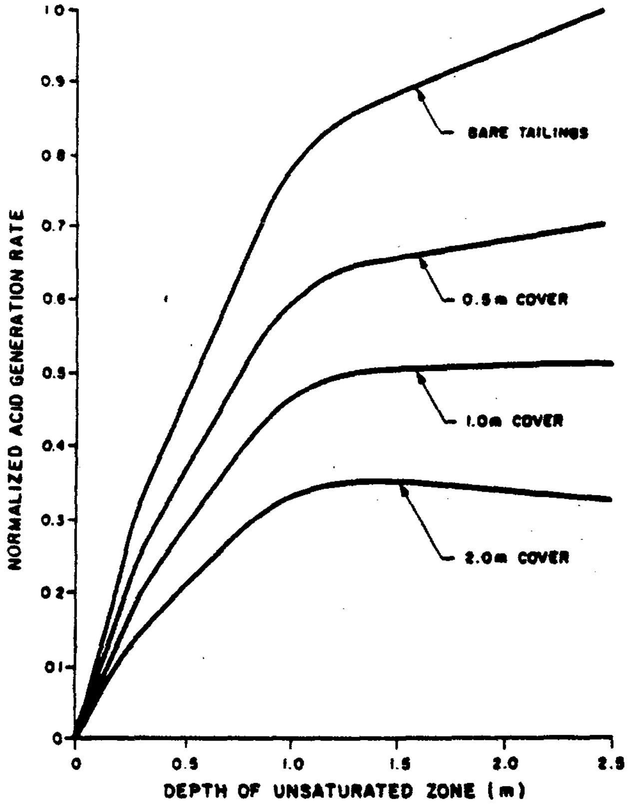

FIGURE 7: THE EFFECTS OF SOIL COVER ON ACID GENERATION RATES

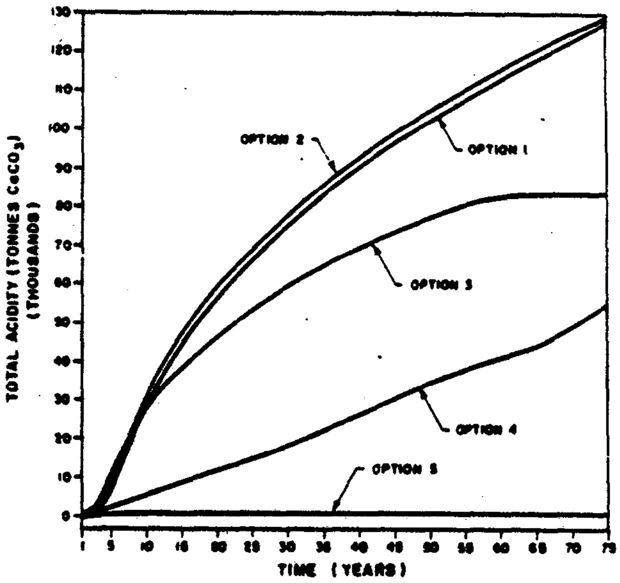

FIGURE 8: PREDICTED TOTAL ACIDITY vs. TIME FOR FIVE TAILINGS CLOSEOUT OPTIONS

WORKSHOP ON MODELLING OF REACTIVE TAILINGS
SPONSORED BY THE MEND PREDICTION COMMITTEE

SUMMATION AND CONCLUSIONS

Mr. Keith Ferguson announced that the MEND Prediction Committee had met on the Wednesday night and had taken the decision to recommend to CANMET to release RATAP in its present form. He said that most of the people in the group have indicated that they want to get RATAP. Some changes will be recommended to improve the documentation and to improve the user friendliness.

Dr. Henry Steger closed the formal part of the meeting by expressing his thanks to all participants for coming to this Workshop. He apologized for the rush of its organization, which was due to the fact that the GAC-MAC Annual Meeting was held in Vancouver. Participants to this Acid Mine Drainage Conference like Ms Marie Collin and Mr Björn Sodermark of Sweden, and Dr. Ian Ritchie of Australia could then easily attend this Workshop. He also thanked Ms Patricia Erickson and Dr. Kirk Nordstrom for coming and presenting the U.S.A.'s point of view. He indicated that all participants will receive a copy of the minutes and Executive Summary of this Workshop.

He offered a copy of the Appendices to RATAP to those who wished it. He thanked especially Ms Mary Paddon for the successful organization of the Workshop.

Dr. Henry Steger wondered if this type of activity, as suggested by Dr. Ernest Yanful, should be pursued in the future and suggested that we give this question some thought.

Dr. Nicholson commented that, if RATAP is released, someone should organize short courses on using the model.

Dr. Henry Steger again thanked everyone and adjourned the Workshop.

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Welcome Screen Search Report List

A RESEARCH REPORT PREPARED UNDER
CONTRACT #15SQ-2344-7-9208:

ADAPTATION OF THE REACTIVE ACID TAILINGS ASSESSMENT PROGRAM (RATAP) TO BASE METAL TAILINGS

MAIN REPORT

Prepared for

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March 1988

Welcome Screen | Search | Report List

ABSTRACT

The objective of this study was to adapt the Reactive Acid Tailings Assessment Program (RATAP), a model developed for sulfidic uranium tailings, to base metal tailings. The model developed, the Reactive Acid Tailings Assessment Program for Base Metal Tailings, Version 1 (RATAP.BMT1), provides an estimate of the upper and lower limits of acid generation by bacterially-assisted oxidation of pyrite, pyrrhotite, chalcopyrite and sphalerite. In addition, it calculates the aqueous concentration of zinc and copper. Two options are available for calculating copper concentrations in the oxidizing zones due to the uncertainties in solid phase geochemistry.

The model was conceived as several modules which could each be calibrated independently against data reported in the literature. The integrated model was applied to field data from the Waite Amulet tailings site in Quebec. A good calibration was achieved between the predicted values and field observations for solid phase concentrations of sulfide minerals, aqueous concentrations (pH) and gaseous concentrations (oxygen) in the unsaturated zone. The calibration was incomplete, as no data are available on the aqueous concentration of copper, zinc and sulfate in the unsaturated zone, the dynamics of hardpan formation or on tailings temperature.

Deterministic simulations using the calibrated model indicated a high degree of dependency between tailings temperature, oxygen content and overall rate of oxidation. The results also indicated large temperature increases of up to 100 °C, in the surface layers when sulfide oxidation rates were high.

Probabilistic techniques were employed to estimate the limits of acid generation at the Waite Amulet tailings site. The maximum monthly acid flux for location WA-20 occurred during June of year 2 , and had a mean of 17 $mol.m^{-2}.yr^{-1}$ with upper and lower limits of 3 and 78 $mol.m^{-2}.yr^{-1}$, respectively. The cumulative acid loading at the site over a 24 year span is estimated to be 1970 $mol.m^{-2}$ with upper and lower limits of 180 and 4300 $mol.m^{-2}$.

SOMMAIRE

Le but de cette étude a été d'adapter le Programme d'Evaluation des Résidus Acide Réactifs (PERAR), un modèle élaboré pour les résidus d'uranium sulfureux, aux métaux communs. Le modèle mis sur pied, le Programme d'Evaluation des Résidus Acides Réactifs pour les résidus de métaux communs, Version 1 (PERAR.RMC1), permet d'estimer le maximum et le minimum d'acide généré par l'oxydation bactérienne de la pyrite, la pyrrhotine, la chalcopyrite et la fausse galène. De plus, il permet de déterminer les concentrations en dilution du zinc et du cuivre. Il existe deux options de calcul des concentrations de cuivre dans les zones d'oxydation en raison des incertitudes qui existent dans le géochimie en phase solide.

Le modèle a été conçu comme un ensemble de plusieurs modules qui peut être testé indépendamment en regard des données provenant des études publiées sur le sujet. Le modèle intégré a été appliqué aux données réelles provenant des résidus de Waite Amulet au Québec. Une bonne concordance a été obtenue entre les valeurs théoriques prévues et les observations faites sur le terrain pour les concentrations de sulfates en phase solide, les concentrations en dilution (pH) et les concentrations gazeuses (oxygène) dans la zone non saturée. Il ne s'est agi là que d'une concordance incomplète, étant donné qu'il n'existait pas de données sur les concentrations en dilution du cuivre, du zinc et du sulfate dans la zone non saturée, ni sur la dynamique de formation de la croûte, pas plus que sur la température des résidus.

Des simulations déterministes à l'aide du modèle une fois testé ont indiqué un haut degré d'interdépendance entre la température des résidus, la teneur en oxygène, et le taux global d'oxydation. Les résultats ont également indiqué de fortes hausses de température pouvant atteindre 100° C dans les couches de surface lorsque les taux d'oxydation des sulfates étaient élevés.

Des techniques utilisant les probabilités ont servi à estimer les limites de génération d'acide au site de Waite Amulet. L'écoulement maximum mensuel d'acide pour l'emplacement WA-20 est survenu en juin de la 2ème année, avec une moyenne de 17 $mol.m^{-2}.an^{-1}$ et des limites inférieures et supérieures de 3 et 78 $mol.m^{-2}.an^{-1}$, respectivement. La charge cumulée d'acide au site pendant une période de 24 ans est estimée d'être 1970 $mol.m^{-2}$, avec des limites inférieures et supérieures de 180 et 4300 $mol.m^{-2}$.

Welcome Screen Search Report List

ACKNOWLEDGMENTS

This work was funded by a research contract from the Canadian Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources, Government of Canada to SENES Consultants Limited and Beak Consultants Limited. The project manager for this study was Mr. B. Halbert (SENES). The co-authors of the report included Dr. B. Snodgrass (Beak), Mr. J.D. Phyper (SENES), Dr. R. Nicholson (Beak), Dr. J. Scharer (SENES) and Mrs. C. Hallam (SENES).

SENES Consultants Limited were responsible for the development of the temperature model, modifications to the initial, kinetic, oxygen, sulfide, speciation and transport modules and calibration of the model with data from Waite Amulet. Beak Consultants Limited developed the trace module and assisted in the calibration of the model.

The cooperation and the assistance provided by the scientific authority, Mr. H. Steger, is gratefully acknowledged.

NOTICE

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TABLE OF CONTENTS

Welcome Screen | Search | Report List

Table of Contents cont'd

Table of Contents cont'd

Table of Contents cont'd

Welcome Screen Search Report List

Table of Contents cont'd

Table of Contents cont'd

Table of Contents cont'd

Page

Welcome Screen | Search | Report List

LIST OF FIGURES

List of Figures, cont'd.

List of Figures, cont'd.

Follows Page

List of Figures, cont'd.

LIST OF TABLES

Welcome Screen | Search | Report List

List of Tables, cont'd.

1.0 INTRODUCTION

1.1 Scope of Work

As part of a research investigation supported by the National Uranium Tailings Program (NUTP), SENES Consultants Limited and Beak Consultants Limited (1986 developed the Reactive Acid Tailings Assessment Program (RATAP). The RATAP model was developed to provide an estimate of the upper and lower limits of the rate and quantity of acid generation by the bacterially-assisted oxidation of pyrite and other sulfide minerals present in uranium mill tailings.

The RATAP model is based upon principles of mass balance and employs geochemical kinetics or equilibria where appropriate and solution transport to estimate the pH and the acidity of porewater. A probabilistic technique is used to analyze the effects of oxidation processes and variables on the rate and quantity of acid generation. The model employs algorithms derived from theoretical and experimental considerations. In conjunction with the development of the model, uncertainties in the model coefficients and parameters that influence acid generation were evaluated and described by selected probability distributions.

The stated objective of this research work, undertaken for the Canada Centre for Mineral and Energy Technology (CANMET), was to adapt the RATAP model to base metal tailings, i.e. the Reactive Acid Tailings Assessment Program for Base Metal Tailings (RATAP.BMT).

The RATAP.BMT model comprises several modules: initial inventory; temperature; kinetics; oxygen transport; sulfide oxidation; solute transport; aqueous speciation; and trace metals. Detailed descriptions of the functions of the various modules are provided in the appendices. In the main report, an overview of the model, its method of coding, and results of the simulations are summarized.

In the initial inventory module, values for parameters which are assumed to

Welcome Screen Search Report List

be independent of any particular year, are calculated; e.g. background temperature in the tailings as a function of depth. The kinetics module determines the biological and chemical rates of sulfide oxidation whereas the oxygen transport module calculates the oxygen profile. In the sulfide oxidation module, the influence of oxygen on the rate of bacteria-assisted sulfide oxidation is incorporated into the computation of the amount of sulfide which is oxidized. The sulfides of primary importance were pyrite, pyrrhotite, chalcopyrite, and sphalerite. The solute transport and aqueous speciation modules calculate the aqueous and solid phase concentrations of various species (e.g. calcium and sulfate), the tailings porewater pH, and the acid flux leaving the tailings over time. Lastly, the trace metal module calculates the aqueous and solid phase concentrations of zinc and copper.

The individual components of each module were calibrated using actual laboratory and/or field data whenever possible. Overall model calibration studies were conducted using field data for the Waite Amulet tailings in Quebec and the Nordic uranium tailings site in Elliot Lake, Ontario. The model was also validated using field data from the Nordic uranium tailings site. The calibration/validation against Nordic field data was conducted as part of the development of the original RATAP model. In addition, the models' calculations were also compared against the results of simulations using the MINTEQ model which is a member of the MINEQL family of computer speciation programs that are capable of computing equilibrium with solids (Felmy et al., 1984).

Following model calibration and validation, the RATAP.BMT model was run probabilistically, using data characteristic of the Waite Amulet tailings, to assess the limits on the rate and quantity of acid generation from base metal tailings and to estimate the aqueous concentration of trace metals (zinc and copper). This information was then used to develop recommendations on those areas where emphasis should be placed in future research work.

1.2 Report Organization

This report is divided into the following sections:

Chapter 2	Model Development presents a summary of the biological, chemical, and geochemical theory and the influence of physical factors. It summarizes the equations and associated algorithms including the call sequence of modules over time at different layers and the information flow between modules.
Chapter 3	Model Calibration compares the results of model calculations with field data collected at the Waite Amulet tailings site. The comparison includes pyrite and pyrrhotite concentrations, porewater pH, and gaseous phase oxygen profiles.
Chapter 4	Model Predictions presents a summary of the parameters employed in the modules and their probabilistic distributions. The chapter presents the results of a probabilistic model simulation for a reference sulfidic tailings.
Chapter 5	Conclusions and Recommendations presents an overall summary of the model's ability to predict the bacteria-assisted oxidation of sulfide minerals in base metal tailings. Deficiencies in the model and information gaps in the input parameters are also discussed.
Appendices A-H	The individual modules are described in detail in Appendices A through H. The information presented includes theoretical background, algorithms, and parameter distributions.

2.0: MODEL DEVELOPMENT

2.1 Overview of RATAP.BMT1

The RATAP.BMT1 model is divided into two parts: control modules and component modules. Control modules provide the infrastructure for the probabilistic analysis of the component modules. These modules are responsible for 1) the random selection of values from specified input parameter distributions, 2) performing statistical analyses on user-specified input and calculated parameters and 3) managing the information transfer between modules. A detailed description of the control modules is presented in Volume 2 of the SENES (1986) report.

Eight component modules are employed in the computer code, each performing a specific task. The modules, in order of execution, are: initial inventory, temperature, kinetics, oxygen transport, sulfide oxidation, solute transport, aqueous speciation, and trace metals. The tailings profile employed in the component modules is subdivided into distinct zones and a transition zone as indicated on Figure 2.1. In the unsaturated zone and capillary fringe, one to twenty layers are employed whereas in the saturated zone, one or two layers are used. The exact number of layers is specified in the input file.

Besides being divided into unsaturated and saturated zones, the tailings is also divided into oxidation and reduction zones. Oxidation is assumed to occur in the unsaturated zone above the hardpan. Reduction occurs below the hardpan and in the saturated zone.

Figures 2.2 outlines the call sequence of the modules over time for the various layers. Information transferred between the modules is also identified on the figure. The first module, executed only once, is the initial inventory module which calculates, for each layer, the initial solids composition, the monthly background tailings temperature and the tailings water content and air content. The monthly estimates are assumed to be repeated for each succeeding year.

FIGURE 2.1

CONCEPT ADOPTED
FOR MODELLING OF TAILINGS

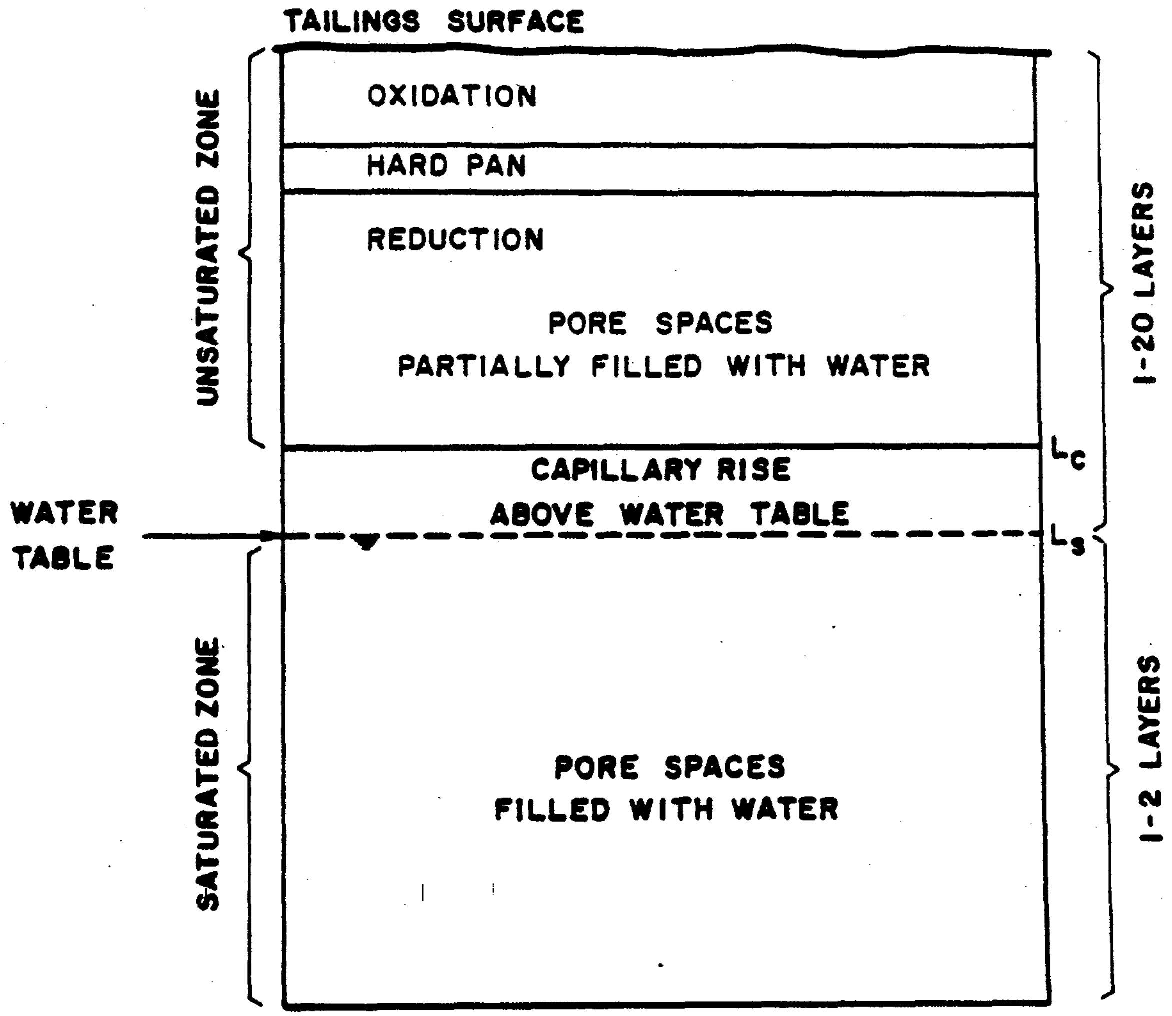
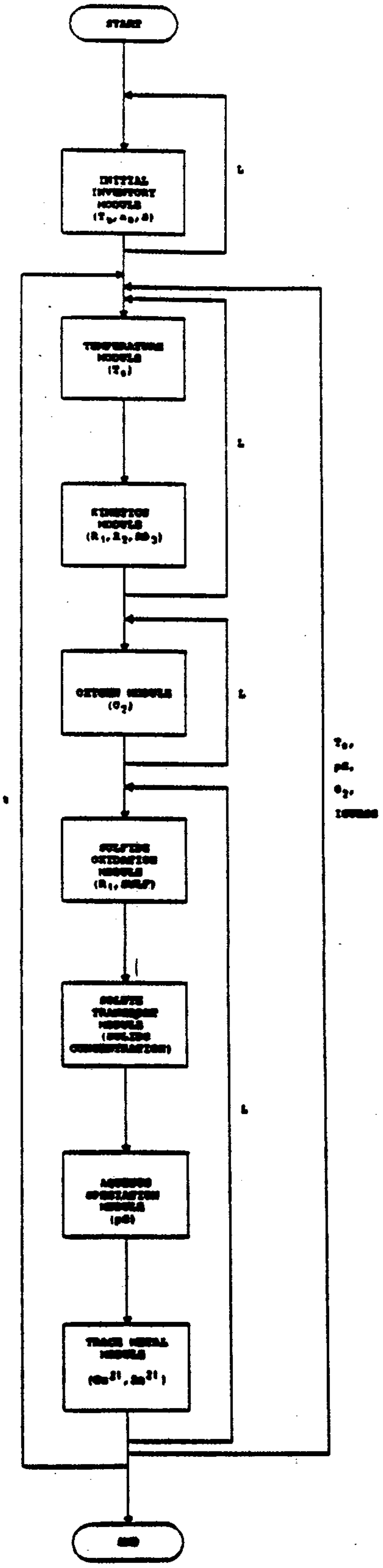


FIGURE 2.2

CONCEPTUAL FLOW DIAGRAM



In the temperature module, the second module, the overall tailings temperature is estimated as the background tailings temperature plus the incremental increase in temperature resulting from sulfide oxidation. The temperature module transfers the overall tailings temperature to the kinetics module, the third module, which calculates rate information (the chemical and biological oxidation rates and the oxygen consumption rate), at each time step for the various layers. The oxygen consumption rate information is then employed in the oxygen transport module, the fourth module, to calculate the oxygen profile. The oxygen module requires data on the volumetric air content of the tailings in addition to the rate information.

The next four modules (i.e. the sulfide oxidation, solute transport, aqueous speciation and trace metal modules) are all run in sequence at time t for each layer. The sulfide oxidation module imports the biological and chemical rates of oxidation for pyrite, pyrrhotite, chalcopyrite and sphalerite and the oxygen concentrations. The sulfide module then adjusts the rates to include the effect of oxygen concentration. The solute transport and aqueous speciation modules use the rates of sulfide oxidation to calculate the acid flux and pH, respectively. The solute transport and aqueous speciation routines are solved simultaneously.

The trace metal module calculates the aqueous concentration of zinc and copper and the solid phase concentrations of copper carbonate, copper hydroxide, coprecipitated copper with iron hydroxide, copper-jarosite and sphalerite.

The pH, temperature and oxygen concentrations required for the kinetics module are estimated initially using values from the previous time step. These values are then refined seven times by being fed back into the modules and recalculating new values (see Figure 2.2). Test calculations showed that an acceptable convergence of all parameter values was achieved in eight iterations. The values for tailings temperature, oxygen content and overall rate of oxidation fed back into the model during iterations three through eight are the geometric means of the previous two iterations. (Refinement of the convergence method may be required to reduce the computer run time.) Upon completion of these calculations, the program moves onto time period t+1 and repeats temperature through aqueous speciation modules calculations.

The following sections briefly outline the individual modules.

2.2 Initial Inventory Module

In the initial inventory module, initial values for those parameters that are dependent on more than one input are calculated. The parameters can be divided into two broad groups; geochemical parameters and physical parameters. This module is also used to define a cover over the tailings. A cover is defined as material placed over the tailings to reduce acidic discharges, e.g. depyritized tailings, clay, etc.

2.2.1 Geochemical Parameters

The geochemical parameters include an initial estimate of the porewater pH, the aqueous phase concentrations and the solid phase concentrations. The pH estimate is a function of the particular scenario being analyzed, e.g. calcite present or calcite absent.

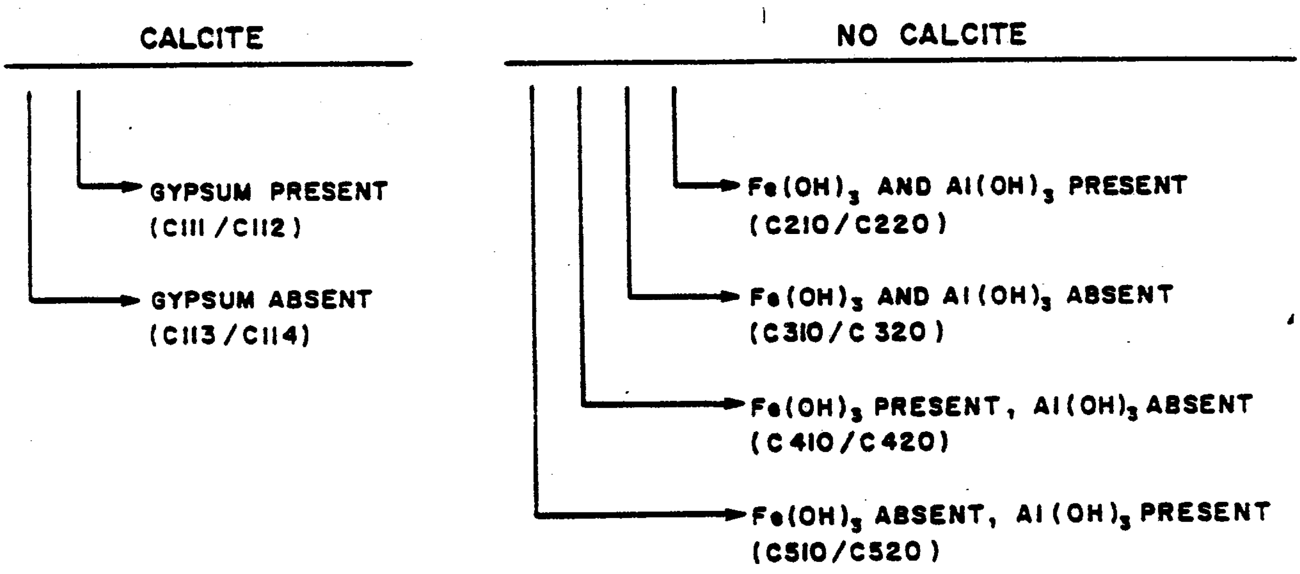
pH

The porewater pH is estimated by solving the electroneutrality equation. The concentration of other solution ions is estimated from mass balance principles if a solid phase involving the ion is not present, or from chemical equilibrium, if a controlling solid phase is present.

If a particular solid phase which buffers pH is present, the solution pH can be estimated within a narrow range. Hence, the computational procedure can be greatly simplified by employing several pH equations, each applicable for only a particular pH range. Each pH equation is a simplification of the electroneutrality equation; Figure 2.3 presents the various solid phase scenarios for which the pH was determined.

FIGURE 2.3

pH COMPUTATIONAL SCENARIOS



NOTE:

C210 / C220 DENOTES CASE 210 (UNSATURATED ZONE)
AND CASE 220 (SATURATED ZONE)

For conditions where calcite is present (i.e. Case 111 to 114), an exact analytical solution is used to calculate the pH of the tailings porewater. An initial value of 6.5 is assigned, however, to start the program off.

For conditions in which calcite is absent, the computational nature of the electroneutrality equation requires that an iterative approach be used to calculate the pH. The secant convergence method is used to solve for the porewater pH. This approach requires two initial estimates of the porewater pH, preferably within 0.5 pH units of the actual pH in order to reduce computational time and instability problems.

For cases where basaluminite is present (i.e. Cases 210/220 and 510/520), initial pH estimates of 4.0 and 3.9 are employed. Similarly, the starting pH for cases in which basaluminite is depleted (i.e. Cases 310/320 and 410/420) is 2.4 and 2.5.

Aqueous Concentrations

In estimating the initial aqueous concentrations of calcium and sulfate, it is assumed that the effect of sulfide oxidation at time zero is minimal. Accordingly, the initial concentration of dissolved calcium and sulfate ions is estimated assuming equilibrium. This gives:

$$[SO_4^{2-}] = [Ca^{2+}] = (K_{CaSO_4}/f_2^{\,2})^{0.5} \qquad (2.1)$$

where

$[SO_4^{2-}]$ = concentration of SO_4^{2-} ($mol.L^{-1}$)

$[Ca^{2+}]$ = concentration of Ca^{2+} ($mol.L^{-1}$)

K_{CaSO_4} = solubility equilibrium constant for $CaSO_4$ ($mol^2.L^{-2}$)

f_2 = activity coefficient for a divalent ion

The initial solid phase concentrations are calculated using the following equation:

$$C_{si} = \rho_t X_{fi}/M_{wi} \qquad (2.2)$$

where

C_{si} = concentration of component i in the solid phase ($mol.m^{-3}$)
ρ_t = tailings bulk density ($g.m^{-3}$)
X_{fi} = mass fraction of component i in the tailings ($g.g^{-1}$)
M_{wi} = molecular weight of component i ($g.mol^{-1}$)

2.2.2 Physical Parameters

The physical parameters estimated in the initial inventory module are the background tailings temperature and water content.

Background Temperature

To estimate background tailing temperatures, the following expression was fitted to experimental data reported by Grenier and Bigu (1983) for the Stanrock tailings management site:

$$T(X,t) = T_m + A_o[\sin(w(t-\ell) - X/d)] \exp(-X/d) \qquad (2.3)$$

where

A_o = empirical coefficient (K)
w = radial frequency = $2\pi/12$ mth (mth^{-1})
d = dampening depth (m)
X = actual depth of layer (m)
T_m = yearly mean temperature (K)
t = time period (mth)
ℓ = phase-shift constant; a function of the month that represents $t = 1$ (mth)
$T(X,t)$ = background tailings temperature at depth X at time t (K)

Water Content

The water content for each layer in the unsaturated zone is determined using the following expression:

$$n_w = (h_e/h)^{X_{sc}} \; (n_t - n_r) + n_r \qquad (2.4)$$

where

h_e = capillary head

n_t = the maximum water content, i.e. porosity $(m^3_{void} \cdot m^{-3}_{tail})$

n_r = the residual water content $(m^3_{water} \cdot m^{-3}_{tail})$

n_w = the water content of the tailings $(m^3_{water} \cdot m^{-3}_{tail})$

h = height above water table (m)

X_{sc} = soil coefficient; is the material dependent constant that is referred to as the grain size distribution parameter

The form of this equation was developed by Hillel (1980) using experimental measurements for clays and sands. It is assumed that for a 10 to 100 year simulation period, the water content profile remains at steady state from month to month.

In the saturated zone, the water content is set equal to the porosity:

$$n_w = n_t \qquad (2.5)$$

2.2.3 Tailings Cover

In addition to the distinction between unsaturated zone and saturated zone, a further distinction can be made between tailings and cover material. For conditions where a cover is present, the initial solid phase concentrations of calcite and pyrite (depyritized tailings cover) are calculated using Equation (2.2).

Welcome Screen Search Report List

The net infiltration rate employed in the model when a cover is present may be distinctly different than that for the tailings. Hence an appropriate net infiltration rate should be used when evaluating cover options. The HELP model developed by the U.S. Army Corps of Engineers (Schroeder et al, 1984) is recommended as a tool to estimate the infiltration rates through various cover materials.

2.3 Temperature Module

In the Temperature Module, the overall temperature of a particular layer, i.e. background temperature and temperature increase due to sulfide oxidation, is determined. The tailings temperature was determined by first estimating the temperature with no heat conduction and then incorporating heat conduction.

2.3.1 Tailings Temperature (Excluding Conduction)

The tailings temperature (i.e. excluding conduction in the tailings) can be estimated by:

$$T_n^* = \frac{R_{i,j} \quad Q_j \; - \; H_{vap,i} \; (V_n - V_{n-1})}{L_n \quad C_{pw}} + T_{sb} \qquad (2.6)$$

where

T_{sb} = background tailings temperature calculated in the initial module

T_n^* = tailings temperature excluding conduction (K)

R = reaction rate of sulfide ($mol.m^{-3}.mth^{-1}$)

Q = heat of reaction ($J.mol^{-1}$)

H_{vap} = heat of vaporization ($J.mol^{-1}$)

V = flux of water vapour ($mol.m^{-2}.mth^{-1}$)

C_{pw} = heat capacity of water ($J.mol^{-1}.K^{-1}$)

L = flux of water ($mol.m^{-2}.mth^{-1}$)

n = node

i = layer number

j = reaction number

2.3.2 Tailings Temperature

The tailings temperature, including conduction, was estimated from:

$$T_n = M_t\, C_{pt}\, T_n^* - K_{soil}\, dx\, (T_{n+1} - T_{n-1}) \;/ (M_t\, C_{pt}) \qquad (2.7)$$

where

T_n = tailings temperature (K)

M_t = mass of tailings in layer (g)

C_{pt} = heat capacity of the tailings ($J.g^{-1}.K^{-1}$)

K_{soil} = conductivity of tailings ($J.m^{-1}.mth^{-1}\ K^{-1}$)

dx = thickness of layer (m)

n = layer number

The soil temperature at the mid-depth of a particular layer can be estimated from:

$$T_s = (T_n + T_{n-1})/2.0 \qquad (2.8)$$

2.4 Kinetics Module

In the kinetics module, the rates of chemical and microbial oxidation of sulfide tailings are calculated. These rates are a function of several environmental parameters.

2.4.1 Microbial Oxidation

The rate of bacteria-assisted sulfide oxidation, R, is a function, f, of several biological and environmental parameters (Hoffmann *et al.*, 1981; Halbert, *et al.*, 1983; Jaynes *et al.*, 1984; SENES, 1984). It may be stated by the following expression:

$$R = f(X_p,\ Y_{x/s}, pH,\ T,\ P_{O2},\ P_{CO2},\ S,\ [N],\ [P],\ E_a,\ A,\ [I]) \qquad (2.9)$$

where

R = rate of microbial oxidation ($mol.m^{-2}.mth^{-1}$)

X_p = bacterial population density (g biomass per m^2 sulfide surface area)

$Y_{x/s}$ = growth yield coefficient (g biomass per mol sulfide)

pH = measure of hydronium concentration

T = tailings temperature (K)

P_{O2} = oxygen partial pressure (atm)

P_{CO2} = carbon dioxide partial pressure (atm)

S = degree of saturation ($m^3_{water}.m^{-3}_{void}$)

$[N]$ = nitrate or ammonia concentration ($mol.m^{-3}$)

$[P]$ = phosphorous concentration ($mol.m^{-3}$)

E_a = biological energy of activation ($cal.mol^{-1}$)

A = surface area of sulfide (m^2)

$[I]$ = inhibitor concentration ($mol.m^{-3}$)

In the above expression the value of X_p is known with some degree of certainty for pyrite. For the other sulfides, it is back calculated from rate information.

The overall reaction rate can be expressed as:

$$R_1 = - \frac{u \ X_p}{Y_{x/s}} \qquad (2.10)$$

where

R_1 = the specific biologicaal reaction rate ($mol.m^{-2}_{tailings}.mth^{-1}$)

u = the specific growth rate (mth^{-1})

A multiplicative expression for the specific growth rate was selected which takes into account temperature, pH, phosphorous concentration, carbon dioxide and moisture content:

$$u = u_{max} \left[\exp(C_k) \underbrace{(\exp(-E_a/R_g T))}_{\text{Temperature}} (1 + \underbrace{10^{2.5-pH} + 10^{pH-4.0}}_{\text{pH}})^{-1} \right.$$

$$\left. \underbrace{\left(\frac{[P]}{L_p + [P]}\right)}_{\text{Phosphorus}} \underbrace{\left(\frac{1.3\ P_{CO2}}{10^{-4} + P_{CO2}}\right)}_{\text{Carbon Dioxide}} \underbrace{\quad S \quad}_{\text{Moisture}} \right] \tag{2.11}$$

where

u_{max} = maximum specific growth rate observed (mth^{-1})
L_p = limiting phosphorus concentration ($mol.m^{-3}$)
R_g = universal gas constant ($cal.mol^{-1}.\ K^{-1}$)
C_k = constant which sets $u = u_{max}$ at optimal conditions

The effect of limiting oxygen concentration was not incorporated in the above equation because of the sequence of calculations, i.e. kinetics module first then oxygen module. The effect of oxygen concentration is included in the sulfide oxidation module.

The multiplicative form of the expression is assumed for convenience. It has not, to our knowledge, been unambiguously proven, but is widely used and is assumed to be applicable here.

The constant C_k is set equal to u_{max} at optimal conditions. It is calculated from the following expression:

$$C_k = \ln \left[(\exp(E_a/R_g\ T_{opt}))\ (1+10^{2.5-pH} + 10^{pH-4.0}) \right.$$

$$\left. \left(\frac{[P]}{L_p + [P]}\right) \left(\frac{1.3\ P_{CO2}}{10^{-4} + P_{CO2}}\right) \quad S \right]^{-1} \tag{2.12}$$

Welcome Screen Search Report List

For the optimal conditions of:

pH = 3.25

T_{opt} = 303 K

E_a = sulfide specific

R_g = 1.987 $cal.mol^{-1}.K^{-1}$

$[P]$ = 2.3 $mol.m^{-3}$

L_p = 1.29×10^{-3} $mol.m^{-3}$

P_{CO2} = 3.2×10^{-4} atm

S = 1.0 $m^3_{water}.m^{-3}_{void}$

The value of C_k is only changed when E_a is altered because other "optimum conditions" are invariant.

2.4.2 Chemical Oxidation

The chemical rate of sulfide oxidation in is a function of several environmental parameters:

$$R = f\ (pH,\ T,\ E_c,\ A,\ P_{O2},\ S) \qquad (2.13)$$

where

E_c = chemical energy of activation ($cal.mol^{-1}$)

The specific rate of chemical oxidation from pyrite has been expressed in the literature (McKay and Halpern, 1958) by the following expression:

$$R_2 = r_c\ P_{O2} \qquad (2.14)$$

where

R_2 = the specific rate of chemical oxidation ($mol.m^{-2}.mth^{-1}$)

r_c = chemical rate coefficient ($mol.m^{-2}.mth^{-1}.atm^{-1}$)

P_{O2} = partial pressure of oxygen (atm)

The chemical rate coefficient is described by:

$$r_c = k_c \exp(-E_c/R_g T) \quad (2.15)$$

where

T = absolute temperature (K)

R_g = universal gas constant (1.987 $\text{cal.mol}^{-1}.\text{K}^{-1}$)

k_c = chemical rate constant ($\text{mol.m}^{-2}.\text{mth}^{-1}.\text{atm}^{-1}$)

The effect of pH was not included in equation (2.14). Employing experimental data on pyrite oxidation from Smith and Shumate (1970), the following pH expression was developed.

$$f_p = 0.25\ (\text{pH})^{0.70} \quad (2.16)$$

where

f_p = pH factor (dimensionless)

Their data indicated that at a pH of 7.0, $f_p = 1.0$ and at pH of 2.0, $f_p = 0.4$.

The chemical rate of pyrite oxidation used in this work then is:

$$R_2 = f_p\ r_c\ P_{O2} \quad (2.17)$$

It has been assumed that the chemical oxidation of pyrrhotite, chalcopyrite and sphalerite can also be expressed by Equation (2.17).

2.5 Oxygen Module

As indicated in Section 2.4, low oxygen concentrations can limit the rate of sulfide oxidation. The oxygen profile of the tailings is calculated in the oxygen module. This information is, in turn, employed in the calculation of the overall rate of sulfide oxidation.

There are two mechanisms by which oxygen mass transport through a porous medium occurs: advection and diffusion. In the unsaturated zone of tailings, the diffusive transport of oxygen through the air phase is the dominant transfer mechanism. In the capillary fringe and saturated zones of the tailings, the dominant transfer mechanism is advection of oxygen dissolved in the infiltrating porewater. The physical properties of each layer in the gas filled or non-gas filled tailings zones are used to determine whether gaseous diffusion or advection dominates. The models are described below.

2.5.1 Effective Diffusivity

Diffusive transport is a function of the effective gaseous diffusivity coefficient. The effective gaseous diffusivity (D_e) of the tailings is calculated using the following expression experimentally determined from Nordic field data (Reardon and Moddle, 1985):

$$D_e = 52.56 \left(\frac{n_a - 0.05}{0.95} \right)^{1.7} \qquad (2.18)$$

where

n_a = volumetric air content of the tailings ($m^3_{air} \cdot m^{-3}_{total}$)
D_e = effective diffusivity of oxygen ($m^2 . mth^{-1}$)

This expression has a lower limit of 0.05 $m^3_{air} \cdot m^{-3}_{total}$ for n_a.

2.5.2 Diffusive Transport

The rate of response of the oxygen profile to changes in gaseous diffusion with time is relatively quick, i.e. in the order of hours compared to slower changes induced by variations in pH and temperature. Accordingly, it is appropriate to assume that the oxygen profile through the gaseous pore spaces of the tailings is at steady state in each monthly time step. This permits the development of analytical solutions for each layer. These equations are coupled to adjoining layers through the appropriate boundary conditions.

There are three possible conditions in each layer which affect the final differential equations and hence their mathematical solution. When sulfides are present, zero-order oxygen consumption kinetics are used at high oxygen concentrations ($P_{O2} > 0.01$ atm) and first order consumption kinetics at low oxygen concentrations. This reflects the fact that oxygen consumption is independent of oxygen concentration at high oxygen concentrations. When sulfides are absent, no consumption of oxygen occurs.

For the first-order consumption reaction at steady state, the analytical solution for flux across any interval where concentrations are know at the boundaries is given as (Carslaw and Jaeger, 1959):

$$F_t = D_e \; (U\ C_1 \cosh\ (U\ dX) - UC_2)/\sinh\ (U\ dX) \qquad (2.19)$$

and

$$F_b = D_e \; (U\ C_1 - U\ C_2 \cosh\ (U\ dX))/\sinh\ (U\ dX) \qquad (2.20)$$

F_t = flux at top of the boundary layer ($mol.m^{-2}.mth^{-1}$)

F_b = flux at the bottom of the boundary layer ($mol.m^{-2}.mth^{-1}$)

C_1 = the oxygen concentration in the upper boundary layer ($mol.m^{-3}$)

C_2 = the oxygen concentration in the lower boundary layer ($mol.m^{-3}$)

U = square root of the ratio of the reaction rate constant (bulk) to the effective diffusivity of the layer $(K_b/D_e)^{0.5}$ (m^{-1})

dX = thickness of a layer (m)

D_e = effective diffusivity through the tailings ($m^2.mth^{-1}$)

K_b = bulk reaction rate constant (mth^{-1})

For a zero-order consumption reaction at steady-state, the fluxes across the layer interfaces are:

$$F_t = R\ dX/2 + D_eC_1/dX - D_eC_2/dX \qquad (2.21)$$

and

$$F_b = -R\ dX/2 + D_e C_1/dX - D_e C_2/dX \qquad (2.22)$$

where

R = zero-order rate constant ($mol.m^{-3}.mth^{-1}$)

When no sulfides are present, the diffusive flux is simply expressed by Fick's first law:

$$F = D\ (C_1 - C_2)\ /\ dX \qquad (2.23)$$

where

F = the flux of oxygen across the top boundary ($mol.m^{-2}.mth^{-1}$)

The effective diffusivity coefficient, D_e, is estimated from equation (2.18). The zero-order reaction rate constant is estimated from the biological and chemical reaction rate constants as:

$$R = X_{O2}\ (R_1 + R_2) \frac{\alpha_p}{V_g} \qquad (2.24)$$

where

R = zero-order reaction rate constant ($mol.m^{-3}.mth^{-1}$)
R_1 = biological reaction rate constant ($mol.m^{-2}.mth^{-1}$)
R_2 = chemical reaction rate constant ($mol.m^{-2}.mth^{-1}$)
α_p = sulfide surface area per unit volume tailings ($m^2.m^{-3}$)
V_g = volume of gas per unit volume of tailings ($m^3.m^{-3}$)
X_{O2} = stoichiometric conversion factor

2.5.3 Advection Transport

In water saturated soil, the gaseous diffusivity is small. The major transport route for oxygen is via infiltrating water. This advective flux, however, is small relative to transport by gaseous diffusion in the unsaturated zone. It provides a boundary condition at the water table and can be expressed as:

$$F = V\,C_w\,K_H \qquad (2.25)$$

where

C_w = the concentration of oxygen (in solution) at the air-water boundary ($mol.m^{-3}$)
V = the rate of infiltration of water ($m.mth^{-1}$)
K_H = Henry's law constant ($m^3.m^{-3}$)

2.5.4 Overall Mathematical Solution

Oxygen transport and oxygen consumption are described by coupling the various solutions at the appropriate boundaries. Different combinations of consumption in adjoining layers give different analytical solutions for each interface dependent upon the conditions involved. This results in 6 possible equations that can apply to the top boundary, 6 equations for intermediate boundaries and 3 equations for the bottom boundary.

The general equation that applies to all conditions has a linear algebraic form which, in matrix notation, is:

$$\underline{\mathbf{A}}\,\underline{\mathbf{C}} = \underline{\mathbf{W}} \qquad (2.26)$$

where

$\underline{\mathbf{A}}$ = the matrix of coefficients ($m.mth^{-1}$)
$\underline{\mathbf{C}}$ = the concentration of oxygen with depth ($mol.m^{-3}$)
$\underline{\mathbf{W}}$ = the loading term ($mol.m^{-2}.mth^{-1}$)

$\underline{\mathbf{A}}$ is an nxn matrix, and $\underline{\mathbf{C}}$ and $\underline{\mathbf{W}}$ are nx1 matrices. There are up to 3 coefficients in each row of $\underline{\mathbf{A}}$ having a non zero value. The values of these coefficients change due to the 15 different conditions possible. The $\underline{\mathbf{A}}$ matrix is tridiagonal with the dominant diagonal containing the A coefficients for the middle interface and the upper and lower diagonals containing the upper and lower interface coefficients respectively. The mathematical solution for C is found by simultaneous solution of the N equations where N equals the number of interfaces or layers.

2.6 Sulfide Oxidation Module

In the sulfide oxidation module, the depletion of pyrite, pyrrhotite, chalcopyrite and sphalerite in the tailings is calculated. The effects of oxygen concentration, sulfide surface area and the kinetic rate constants are employed in the calculation of the overall reaction rate.

The overall reaction rate for sulfide oxidation can be expressed as:

$$\frac{dM}{dt} = \frac{-A_s}{V} (R_{1b} + R_2) \tag{2.27}$$

where

M = moles of sulfide per unit volume of tailings ($mol.m^{-3}$)

R_{1b} = biological specific reaction rate per unit area of sulfide ($mol.m^{-2}.mth^{-1}$)

R_2 = chemical specific reaction rate per unit area of sulfide ($mol.m^{-2}.mth^{-1}$)

A_s = surface area of sulfide (m^2)

V = volume of tailings (m^3)

t = time (mth)

2.6.1 Rate Limitation due to Oxygen Concentration

The biological reaction rate constant defined above, R_{1b}, is effectively a "material" constant and is independent of oxygen concentration. The net biological oxidation rate is equal to this "material" constant times an oxygen factor. The limiting effect of oxygen on the biological specific reaction rate can be included in equation (2.27) by replacing the term R_{1b} with:

$$R_{1b} = R_1 \frac{P_{O2}}{L_o + P_{O2}} \qquad 2.28)$$

where

P_{O2} = partial pressure of oxygen (atm)
L_o = limiting oxygen partial pressure (atm)
R_{1b} = oxygen influenced biological specific reaction rate $(mol.m^{-2}.mth^{-1})$

This equation includes the influences of oxygen concentration using a Monod type expression. It is essentially equivalent to the zero order and first order rate expressions used in the oxygen model: it has a value equivalent to the zero order constant (R_1) at high oxygen concentrations and equivalent to the first order rate constant $k_b = R_1/L_o$ at low oxygen concentrations where $L_o = 0.01$.

The chemical term, R_2 in equation (2.27), incorporates a first order oxygen dependence:

$$R_2 = f_p\, k_c\, P_{O2} \qquad (2.29)$$

where

k_c = sulfide specific chemical rate constant $(mol.m^{-2}.mth^{-1}.atm^{-1})$
R_2 = chemical specific reaction rate $(mol.m^{-2}.mth^{-1})$
f_p = pH dependence factor

Oxygen dependence of sulfide oxidation upon the chemical and biological kinetics results in a mixed dependence which is neither Monod nor first order. For the purpose of this study it has been assumed that the overall oxygen dependence is a Monod expression.

2.6.2 Effect of Particle Size Distribution

As oxidation proceeds, the surface area of individual sulfide particles decreases. The rate at which the sulfide particle "shrinks" due to dissolution by oxidation is given by the following expression:

$$\frac{dM}{dt} = + \left(\rho_s \frac{A_s}{V} \right) \frac{dr}{dt} \qquad (2.30)$$

where

ρ_s = moles of sulfide per volume of sulfide ($mol.m^{-3}$)

r = average radius of sulfide particles (m)

M = moles of sulfide per unit volume of tailings ($mol.m^{-3}$)

V = volume of tailings (m^3)

A_s = total surface area of sulfide particles (m^2)

The expression assumes that the sulfide particles are spherical.

The overall rate of the oxidation of a particular sulfide, e.g. pyrite, pyrrhotite, chalcopyrite or sphalerite, can be determined by combining equations (2.27) and (2.30):

$$- \left(\frac{\rho_s}{V} A_s \right) \frac{dr}{dt} = \frac{A_s}{V} (R_{1b} + R_2) \qquad (2.31)$$

$$- \frac{dr}{dt} = \frac{R_t}{\rho_s} \qquad (2.32)$$

where

R_t = overall specific reaction rate, (i.e. $R_{1b} + R_2$) ($mol.m^{-2}.mth^{-1}$)

Integration of equation (2.32) by assuming that R_t is constant for the time period "0 to t" yields:

Welcome Screen | Search | Report List

$$r = r_o - \left(\frac{t\ R_t}{\rho_p}\right) \qquad (2.33)$$

which can be expressed alternatively as:

$$r = r_o - k_o\ t \qquad (2.34)$$

where

r_o = initial radius of particle (m)
k_o = rate constant for oxidation ($m.mth^{-1}$)

Substitution of a term for the concentration of sulfide remaining, moles of sulfide per m^3 of tailings, as a function of surface area and time gives:

$$M_{r,t} = M_{r,O}\ \left(\frac{r - k_o\ t}{r_o}\right)^3 \qquad (2.35)$$

for $r \geq k_o\ t$.

The initial radii of sulfide grains in tailings, however, are not of a uniform size, but have various sizes. The radii can be described by the following size distribution density function:

$$f(r) = \frac{x\alpha}{r_m}\left(\frac{r}{r_m}\right)^{\alpha-1} + \frac{y\beta}{r_m}\left(\frac{r}{r_m}\right)^{\beta-1} \qquad (2.36)$$

where

$f(r)$ = size distribution density function
r_m = maximum radius of particles (m)
x, y, α, β = Paretto distribution function coefficients ($x + y = 1$)

Substituting the above expression for particle radii, equation (2.36) into equation (2.35) and integrating results in the following polynomial expression:

$$M_t = M_o \left[1 + a_1 \left(\frac{k_o\, t}{r_m} \right)^{\alpha} + a_2 \left(\frac{k_o\, t}{r_m} \right)^{\beta} + a_3 \left(\frac{k_o\, t}{r_m} \right) + a_4 \left(\frac{k_o\, t}{r_m} \right)^{2} + a_5 \left(\frac{k_o\, t}{r_m} \right)^{3} \right] \tag{2.37}$$

where

M_o = initial pyrite concentration in moles per unit volume of tailings ($mol.m^{-3}$)

r_m = the initial maximum radius and $k_o\, t \leq r_m$

$$a_1 = -x \left(1 - \frac{3\alpha}{\alpha - 1} + \frac{3\alpha}{\alpha - 2} - \frac{\alpha}{\alpha - 3} \right)$$

$$a_2 = y \left(1 - \frac{3\beta}{\beta - 1} + \frac{3\beta}{\beta - 2} - \frac{\beta}{\beta - 3} \right)$$

$$a_3 = -\left(\frac{3x\alpha}{\alpha - 1} - \frac{3y\beta}{\beta - 1} \right)$$

$$a_4 = \frac{3x\alpha}{\alpha - 2} - \frac{3y\beta}{\beta - 2}$$

$$a_5 = -\left(\frac{x\alpha}{\alpha - 3} - \frac{y\beta}{\beta - 3} \right)$$

Once the sulfide concentration has been determined, the relationship between surface area and volume of tailings can be calculated for any time by differentiating equation (2.34) to give:

$$\alpha_p = \frac{-M_o}{\rho_p\, r_m} \left[a_1 \alpha \left(\frac{k_o\, t}{r_m} \right)^{\alpha - 1} + a_2 \beta \left(\frac{k_o\, t}{r_m} \right)^{\beta - 1} + a_3 + 2a_4 \left(\frac{k_o\, t}{r_m} \right) + 3a_5 \left(\frac{k_o\, t}{r_m} \right)^{2} \right] \tag{2.38}$$

2.7 Solute Transport Module

In the solute transport module, the mass transport of aqueous species via percolating water, the formation and dissolution of hardpan, and a solids balance are determined. The particular algorithms employed in the

Welcome Screen | Search | Report List

calculations are a function of the presence or absence of various minerals such as calcite, gypsum and solids containing aluminum and iron.

The solute transport model assumes that water infiltrates vertically down through the unsaturated zone to the saturated zone in a plug flow manner. From the saturated zone, water flows horizontally to surface water and vertically downward to deep subsurface flow (i.e. groundwater). Transport calculations depend on two types of dissolution mechanisms: kinetically-controlled dissolution, and equilibrium controlled dissolution. Evidence available from the literature justifies the assumption that the dissolution of sericite and pyrite is kinetically controlled and that the dissolution of calcite, gypsum, basaluminite and geothite is equilibrium controlled for the monthly-time-scales of interest here (Beak, 1985).

<u>Mass Balances</u>

For elements like potassium leached from sericite, the mass balance equation gives:

$$[K_i] = \frac{q_{i-1}\ [K_{i-1}] + f_K \cdot r_{ser} \cdot V_i}{q_i} \qquad (2.39)$$

where

$[K_i]$, $[K_{i-1}]$ = the potassium concentration in water leaving layer i and layer i-1, respectively ($mol^{-1}.L$)

q_i, q_{i-1} = the flow rate leaving layer i and layer i-1, respectively ($L.mth^{-1}$)

r_{ser} = the sericite dissolution rate (mol sericite.m^{-3} tailings.mth^{-1})

f_K = the stoichiometry factor (mol potassium released. mol^{-1} sericite dissolved)

V_i = the volume of layer i (m^3)

Welcome Screen | Search | Report List

The term $f_K \cdot r_{ser} \cdot V_i$ is the source of potassium from sericite dissolution ($mol.mth^{-1}$).

A mass balance on sericite gives the following equation for the solid phase:

$$[Ser_t] = [Ser_{ti-1}] - r_{ser}\ dt \qquad (2.40)$$

where

$[Ser_t]$ = the mass inventory of sericite at time t ($mol.m^{-3}$)
dt = the elapsed time between t-1 and t (mth)

These two equations are applicable for kinetically controlled dissolution. Provided that no other solid phase exists, equation (2.39) is applicable for aluminum by substituting $[Al_T]$ for [K] and the stoichiometric factor (mole Al released per mole sericite dissolved). Here $[Al_T]$ is the total aqueous concentration of Al, including solution complexes. Where basaluminite exists or thermodynamic formation is predicted, then equilibrium conditions control the aqueous ionic concentration of aluminum $[Al_i]$. Basaluminite ($Al_4(SO_4)(OH)_{10}$) was used here to describe solubility controls for Al. This choice was based on the findings of Dubrovsky <u>et al</u>. (1985) for the Nordic tailings which suggested that this solid phase better describes the observed solution concentrations than does the $Al(OH)_3$ solid phase. In this case:

$$[Al_i] = \frac{1}{f_3}\left(\frac{10^{KBAS - 10pH}}{f_2\ [SO_4^{2-}]}\right)^{0.25} \qquad (2.41)$$

where

$[Al_i]$ = the aqueous ionic concentration of aluminum ($mol.L^{-1}$)
f_2, f_3 = activity coefficients for 2+ and 3+ sericite species
$[SO_4^{2-}]$ = the solution sulfate concentration ($mol.L^{-1}$)
KBAS = the power for the basaluminite solubility constant.

Because the ionic concentration of aluminum is a function of pH and sulfate concentration, its value is simultaneously obtained with the solution of the equation for pH (see below).

For an element such as aluminum which dissolves and which may participate in formation of another solid, the solid's mass balance is:

$$[BAS]_t = [BAS]_{t-1} + (q_{i-1}\,[Al_T]_{i-1} + f_{Al}\,r_{ser}\,V_i - q_i\,[Al_T]_i)\,dt \qquad (2.42)$$

where

$[BAS]_t$ = the basaluminite concentration ($mol.m^{-3}$)
f_{Al} = the aluminum sericite stoichiometry factor
$[Al_T]_{i-1}$ = the total aqueous aluminum concentration in layer i-1 ($mol.m^{-3}$)

For other elements such as Fe^{3+}, Ca^{2+}, SO_4^{2-}, similar equations are used to solve for the aqueous concentrations and inventories, dependent upon whether or not a solid phase exists at equilibrium with solution. The only changes involved are formulation of the equilibrium relationship analogous to equation (2.41) (Fe^{3+} with geothite; Ca^{2+} with gypsum and calcite; and SO_4^{2-} with gypsum) and of the presence or absence of a kinetic term in equation (2.42).

The mass balance for Fe^{3+} and Fe^{2+} has an added complicating factor for sulfide oxidation (excluding sphalerite); in a net sense a portion of the sulfide oxidized forms Fe^{3+} while the remainder forms Fe^{2+}. This occurs because Fe^{3+} is formed by bacterial oxidation but is reduced to Fe^{2+} during the dissolution of sulfide. This results in a source for Fe^{3+}:

$$Source_{Fe3} = (0.02 + P_{O2}{}^{1/2}).R_{sulf}.\,V_i \qquad (2.43)$$

and the source for Fe^{2+}:

$$Source_{Fe2} = \left(\frac{0.46 - P_{O2}{}^{1/2}}{0.48}\right).R_{sulf}.V_i \qquad (2.44)$$

These are empirical relationships based on laboratory data.

Welcome Screen Search Report List

Under reducing conditions ($P_{O2} = 0$), sulfide (excluding sphalerite) can be dissolved by Fe^{3+} entering a tailings layer with infiltrating rainwater. The net overall reaction results in an additional source term for Fe^{2+} and a sink term for Fe^{3+} under reducing conditions. The equations are:

$$Source_{Fe2} = -Sink_{Fe3}$$

$$= -K_{Fe3}\ [Fe^{3+}_{T}]\ \frac{L_{O2}}{L_{O2} + P_{O2}}\ \exp\left[\frac{-E_{a2}}{1.987}\left(\frac{1}{T} - \frac{1}{298}\quad V_i\right)\right] \tag{2.45}$$

where

K_{Fe3} = the reaction rate constant (mth^{-1})
E_{a2} = the activation energy of the reaction ($cal.mol^{-1}$)
T = the ground temperature (K)

Hardpan

Due to reduced pH effects during oxidation and the chemical nature of base metal sulfides, the dissolved base metal species are more likely to re-precipitate than iron from pyrite. In addition, incongruent re-precipitation of alkaline earth and transition metals can also take place. The extent of these precipitation reactions may be large enough to cement the tailings particles and fill the void space with solids. As the pore space is being plugged, the permeability of the tailings to water is greatly reduced. It has been observed that these precipitates attach to the surface of the solids and in a relatively short time a hardpan develops that prevents any further downward movement of the groundwater.

The formation of hardpan is assumed to be caused by $Fe(OH)_3$ precipitates filling the tailings pore air spaces and hence restricting infiltration.

The volume of precipitate in a layer is estimated from:

$$V_p = \frac{Fe(OH)_3\ M_w\ V_t}{D_{FeOH3}} \tag{2.46}$$

Welcome Screen | Search | Report List

where

V_p = volume of $Fe(OH)_3$ precipitate (m^3)

$Fe(OH)_3$ = solid phase concentration of $Fe(OH)_3$) ($mol.m^{-3}$)

M_w = molecular weight of $Fe(OH)_3$ ($g.mol^{-1}$)

V_t = volume of layer (m^3)

D_{FeOH3} = density of $Fe(OH)_3$ ($g.m^{-3}$)

As precipitates form, the volumetric air content of a layer diminishes:

$$n_a = ((n_t - n_w)\ A_{tail}\ 0.05 - (V_p - V_{po}))/(A_{tail}\ 0.05) \qquad (2.47)$$

where

n_a = air content of tailings ($m^3.m^{-3}$)

n_w = water content of tailings ($m^3.m^{-3}$)

n_t = porosity of tailings ($m^3.m^{-3}$)

V_{po} = initial volume of $Fe(OH)_3$ precipitates (m^3)

A_{tail} = cross sectional area of the tailings (m^2)

0.05 = thickness of hardpan layer (m)

When the volumetric air content of a layer reaches 0.05 $m^3_{air}.m^{-3}$ tailings as a result of precipitation, hardpan is assumed to occur.

A series of material balances are used to keep an inventory of precipitated ferric hydroxide at various depths in the tailings.

2.8 Aqueous Speciation Module

The main purpose of the speciation module is the calculation of the pH and the acid flux. The calculation of pH is based upon the principle of electroneutrality. For the ions of concern in this equation, it is:

$$10^{-pH} + 2[Ca^{2+}] + ALUM + IRON + 2[Fe^{2+}] + [K^+] = [HCO_3^-] + SULF - [NO_3^-] \qquad (2.48)$$

where

$$\mathrm{ALUM} = (3 + 2\ f_3\ \mathrm{CAlOH}\ 10^{pH}/f_2 + f_3\ \mathrm{CAlOH_2}\ 10^{2pH}/f_1 + + f_3\ \mathrm{CAlOH_3}\ 10^{3pH} + f_3\ f_2\ \mathrm{CAlSO4}\ [SO_4^{2-}]/f_1\ [Al^{3+}] \qquad (2.49)$$

$$\mathrm{IRON} = (3 + 2\ f_3\ \mathrm{CFeOH}\ 10^{pH}/f_2 + f_3\ \mathrm{CFeOH_2}\ 10^{2pH}/f_1 + + f_3\ \mathrm{CFeOH_3}\ 10^{3pH} + f_3\ f_2\ \mathrm{CFeSO_4}\ [SO_4^{2-}]/f_1)\ [Fe^{3+}] \qquad (2.50)$$

$$\mathrm{SULF} = (2 + f_2\ 10^{-pH}/(\mathrm{CHSO_4}\ f_1))[SO_4^{2-}] \qquad (2.51)$$

where

CAlOH, $\mathrm{CAlOH_2}$, $\mathrm{CAlOH_3}$, $\mathrm{CAlSO_4}$,
CFeOH, $\mathrm{CFeOH_2}$, $\mathrm{CFeOH_3}$, $\mathrm{CFeSO_4}$ = thermodynamic complexation constants
f_1, f_2 and f_3 = activity coefficients

All chemical concentrations refer to layer i whether or not explicitly subscripted with "i". The terms 'ALUM','IRON', and 'SULF' refer to solution complexes of aluminum, iron and sulfate, respectively, which have a charge. For 'ALUM' and 'IRON', the respective complexes in equations (2.49) and (2.50) are the 3+ (Al^{3+}, Fe^{3+}), 2+ ($AlOH^{2+}$, $FeOH^{2+}$), 1+ ($Al(OH)_2^+$, $Fe(OH)_2^+$ and sulfate, $AlSO_4$, $FeSO_4$) complexes. For sulfate, equation (2.51), the respective species are SO_4^{2-} and HSO_4^-.

The $[Al^{3+}]$ is estimated from the solubility constant and pH if the solid phase is present, and from $[Al_T]$ (solution mass balance) and pH if no solid phase is present. $[Fe^{3+}]$ is estimated similarly. $[Ca^{2+}]$ and $[SO_4^{2-}]$ are estimated from equilibrium considerations if gypsum is present and from solution mass balance if it is absent. If calcite is present, $[Ca^{2+}]$ is estimated from gypsum equilibria and $[HCO_3^-]$ is estimated from the following expression for tailings layers which are not fully saturated:

$$[HCO_3^-] = \frac{K_H\ K_1\ P_{CO2}}{f_1\ 10^{-pH}} \qquad (2.52)$$

where

K_1 = the dissociation constant for carbonic acid ($mol.L^{-1}$)
K_H = solubility constant for carbon dioxide ($mol.L^{-1}.atm^{-1}$)
P_{CO_2} = the partial pressure of carbon dioxide (atm)
$[HCO_3]$ = the bicarbonate concentration ($mol.L^{-1}$)

For saturated tailings layers,

$$[HCO_3^-] = \frac{K_1}{f_1\ 10^{-pH} + K_1} C_T \qquad (2.53)$$

where

C_T = the total inorganic carbon concentration in solution, calculated by mass balance ($mol.L^{-1}$)

The pH is calculated by finding the root of equation (2.48) (i.e. where the L.H.S. equals the R.H.S.) using an iterative search technique.

The two routines, transport and speciation, are solved simultaneously depending upon which solid phases are present. Generally, solution mass balance calculations are made first, the pH is estimated and then the remaining mass balance calculations are made (for solid phases and solution phases if a solid phase completely dissolves during a time step).

2.9 Trace Metal Module

In the trace metal module, the aqueous concentrations of zinc and copper are calculated. The following assumptions are employed:

1) Copper and zinc are trace metals. This means that, for all conditions, other ions such as iron (II), iron (III), calcium, aluminum and sulfate control solution chemistry, including solution pH. Accordingly, the behaviour of copper and zinc is mediated by these ions.

2) Under aerobic conditions, porewater concentrations of copper are controlled by one of the four following solids:
   - copper carbonate ($CuCO_3$);
   - copper hydroxide ($Cu(OH)_2$);
   - coprecipitated copper with iron hydroxide; and
   - copper-jarosite.

3) Under anaerobic conditions, porewater concentrations of copper are controlled by covelite, (Copper sulfide, $CuS_{(s)}$).

4) Under aerobic conditions, there are no secondary mineral phases which could control zinc concentrations. Accordingly, only oxidative dissolution, transport and adsorption processes will mediate zinc concentrations.

5) Under anaerobic conditions, porewater concentrations of zinc are controlled by sphalerite (ZnS).

6) Under aerobic conditions,all sulfur in porewater is present as sulfate.

7) Under anaerobic conditions, sulfur in porewater is present as both sulfate and sulfide ions. Sulfate concentrations are assumed to be controlled by mass balance considerations or by gypsum if sufficient porewater calcium is present. Sulfide ions concentrations are assumed to be controlled by mass balance consideration or by pyrrhotite equilibrium when pyrrhotite is present.

2.9.1 Copper Concentrations in Oxic Porewater - Option 1

It is possible that copper concentrations would be controlled by any one of four minerals. It is doubtful, however, that the porewater copper concentrations would be controlled simultaneously by more than one phase. Accordingly, it is assumed that copper concentrations are controlled by only one mineral phase at any time; if other minerals are present, it is assumed

Welcome Screen | Search | Report List

that they are at equilibrium with the porewater but subjected only to dissolution processes. Their dissolution may be kinetically controlled but a lack of appropriate data preclude considering such possibilities in this study.

The following equations are used to define copper concentrations.

1) If the pH is greater than 9, and copper hydroxide present:

$$[CU^{2+}] = \frac{KCuOH2}{[OH^{-}]^{2}} \qquad (2.54)$$

where

$[Cu^{2+}]$ = aqueous copper concentration ($mol.L^{-1}$)

$[OH^{-}]$ = aqueous hydroxide concentration ($mol.L^{-1}$)

KCuOH2 = solubility constant for copper hydroxide $(mol.L^{-1})^{2}$

2) If the pH is greater than 6 and less than 9, if copper carbonate is present and if the pCO_2 level is approximately $10^{-3.5}$ atm:

$$[Cu^{2+}] = \frac{KCuCO3}{[CO_3{}^{2-}]} \qquad (2.55)$$

where

$[CO_3{}^{2-}]$ = aqueous carbonate concentration ($mol.L^{-1}$)

KCuCO3 = solubility constant for copper carbonate $(mol.L^{-1})^{2}$

4) If the pH is less than 3 and copper jarosite present, then

$$[Cu^{2+}] = \left(\frac{KCUJAR}{[OH^{-}]^{6}\ [SO_4^{2-}]}\right)^{0.25} \qquad (2.56)$$

where

$[SO_4^{2-}]$ = aqueous sulfate concentration ($mol.L^{-1}$)

[KCUJAR] = solubility constant for copper-jarosite (assumed to be bronchaniete)

Welcome Screen | Search | Report List

For the above three pH ranges, the total copper concentration, Cu_T, is defined by:

$$CUT = [Cu^{2+}]\ CUCOMP \tag{2.57}$$

$$CUCOMP = 1 + CCuSO_4\ .\ [SO_4^{2-}] + CCUHS3.(HS^-)^3)$$

where

$CCUSO_4$ = complexation constant for copper sulfate

CUT = porewater concentration of total copper ($mol.L^{-1}$)

and the change in solid phase concentration is defined by:

$$CUSOL_t = CUSOL_{t-1} + [(q_{i-1}\ .\ CUT_{i-1} - q_i\ CUT_i) + (RCUS + RCU)\ .\ V_t]\ dt//V_t \tag{2.58}$$

where

CUSOL = the solid phase concentration of $Cu(OH)_2$, $CuCO_3$, or CU-jarosite ($mol.m^{-3}$)

RCUS = oxidation dissolution rate of Covelite (CuS) ($mol.m^{-3}.mth^{-1}$)

RCU = dissolution rate of other solid phases of copper not controlled by precipitates-dissolution equilibrium ($mol.m^{-3}.mth^{-1}$)

If the pH is greater than 3 and less than 6 and an iron hydroxide solid phase is present, then:

$$CUTT = [q_{i-1}\ CUT_{i-1}\ dt + (RCUS + RCU)\ dt\ V_t + CUTT_t\ .VT_t - q_i\ CUT_i\ dt]/V_t \tag{2.59}$$

$$[Cu^{2+}] = \frac{CUTT}{CuCOMP + \frac{1}{DCUPRCE} \times \frac{[FEOOH]}{[Fe^{3+}]}} \tag{2.60}$$

$$CUT = [Cu^{2+}]\ {*CUCOMP} \tag{2.61}$$

$$[CUPREC] = ([Cu^{2+}]\ .\ [FeOOH])/(DCUPREC.[Fe^{3+}]) \tag{2.62}$$

where

CUTT = total amount of copper in coprecipitated, adsorbed and porewater phases ($mol.m^{-3}$)

V_t = volume of layer (m^3)

dt = time increment, 1 month

If the solid phase in a particular pH range is not present, then the total copper and Cu^{2+} concentrations are calculated based on mass balance. That is:

$$CUT = [CUT_{i-1} \cdot q_{i-1} + (RCUS + RCU)\ V_t\ dt]/q_i \tag{2.63}$$

$$[Cu^{2+}] = CuT/CUCOP \tag{2.64}$$

If the porewater concentration resulting from mass balance is supersaturated with respect to the particular phase, then the phase is allowed to precipitate to define $[Cu^{2+}]$ and CUT is then calculated.

2.9.2 Copper Concentrations in Oxic Porewater - Option 2

In Option 2, antherite and copper sulfate are assumed to control copper dissolution in the pH ranges 0 to 3 and 3 to 6, respectively.

1) If the pH is greater than 3 and less than 6:

$$[Cu^{2+}] = \frac{KANTL\ [H^+]^4}{[SO_4^{2-}]\ f_2^4} \tag{2.65}$$

$$CUT = [Cu^{2+}] * cucomp \tag{2.66}$$

where

KANTL = solubility constant for antherite $(mol.L^{-1})^{-2}$

$[SO_4^{2-}]$ = aqueous sulfate concentration ($mol.L^{-1}$)

f_2 = activity coefficient for 2+ species

2) If the pH is less than 3:

$$[Cu^{2+}] = \frac{KCuSO_4}{f_2^2\ [SO_4^{2-}]} \qquad (2.67)$$

where

$KCuSO_4$ = solubility constant for copper sulfate $(mol.L^{-1})^2$

2.9.3 Copper Concentration in the Anoxic Porewater

Copper concentrations in the porewater are controlled by covelite. If the mineral is present, the copper concentration is equal to:

$$Cu^{2+} = \frac{KCURED^{0.5}}{[Fe^{2+}]} \qquad (2.68)$$

and the mass balance upon the solid sulfide phase, CUS, results in:

$$CUS_t = CUS_{t-1} + (q_{i-1}\ CuT_{i-1} - q_i\ CUT_i)/V_t \qquad (2.69)$$

where

CUS = copper sulfide concentration $(mol.m^{-3})$

q = infiltration rate $(L.mth^{-1})$

If the mineral is not present, Cu^{2+} is defined by mass balance as:

$$CUT_i = CUT_{i-1} \cdot q_{i-1}/q_i \qquad (2.70)$$

and Cu^{2+} is defined by the complexation formula. A subsequent check is made to ascertain that the porewater is not supersaturated with respect to CuS. If it is, copper sulfide is allowed to precipitate.

2.9.4 Zinc System in Oxic Zone

For zinc in the oxic zone, there were no solid phases identified as probable controllers of porewater concentrations of zinc. Accordingly, mass transport controls zinc concentrations. This results in the following equations:

$$ZNTT_t = ZNTT_{t-1} + RZnS\ dt + (q_{i-1}\ (ZnT)_{i-1} - q_i\ (ZnT)_i)/V_t \qquad (2.71)$$

$$[Zn^{2+}] = \frac{ZnTT}{ZnFACT} \qquad (2.72)$$

$$ZnT = ZNCOMP\ .\ [Z_n^{2+}] \qquad (2.73)$$

where

$$ZnFACT = ZNCOMP + \frac{KDZN.BULKD}{POROS}$$

ZNTT = total zinc concentration in solution and sorbed phases ($mol.l^{-1}$)

ZNT = total zinc concentration in solution ($mol.L^{-1}$)

ZNCOMP = $1 + CZNSO_4\ (SO_4^{2-}) + (HS^-)^2\ CZNHS2 + (HS^-)^3\ CZNHS3$ ($mol.L^{-1}$)

$CZnSO_4$ = complexation constant for the reaction $Zn^{2+} + SO_4^{2-} = ZnSO_4$ ($L.mol^{-1}$)

KDZN = the adsorption coefficient for zinc onto the solids ($m^3.g^{-1}$)

BULKD = the dry solids below solids density of the box ($g.m^{-3}$)

POROS = porosity of the box ($m^3_{void}.m^3_{tailing}$)

2.9.5 Zinc System in the Anoxic Zone

If sphalerite is present, the zinc concentration in the porewater is equal to:

$$[Zn^{2+}] = \frac{KZnS}{[S^{2-}]} \qquad (2.74)$$

and

Welcome Screen | Search | Report List

$$ZnT = [Zn^{2+}]\ ZNCOMP \tag{2.75}$$

The mass balance results in:

$$ZnS_{t+1} = ZnS_t + (q_{i-1}\ ZnT_{i-1} - q_i\ ZnT_i)/V_t \tag{2.76}$$

If sphalerite is not present, the zinc concentration is defined by mass balance as:

$$ZnT_i = q_{i-1}\ ZnT_{i-1}/q_i \tag{2.77}$$

$$[Zn^{2+}] = \frac{ZnT_i}{ZNCOMP} \tag{2.78}$$

If the solution is supersaturated with respect to sphalerite, the solid is allowed to precipitate resulting in an adjustment to the concentration of ZnT_i and Zn_i.

3.0 MODEL CALIBRATION

3.1 Background Information

The Waite Amulet tailings were selected for the model calibration study since these tailings have been under investigation since 1985 as part of the Reactive Acid Tailings Stabilization (RATS) program, a jointly funded program between the federal government and industry. Hydrogeochemical investigations at the site were begun in 1985 and preliminary results of the studies have been the subject of two reports to date (Siwik, 1986; Siwik et al., 1987).

The Waite Amulet tailings basin, located 20 km north of Noranda-Rouyn, Quebec, was operated between 1929 and 1962 and contains about 5.9 million tonnes of massive sulfide tailings. The tailings area is a conventional above-ground stack covering 41 hectares.

Over its operating life, the Waite Amulet mill processed copper and zinc ore with a minor silver/gold content from ten orebodies. During the latter 1950's, a pyrite concentrate was also produced. Because of the variability in the mill feed sources, the tailings have a highly variable composition. A typical feed analysis for the Waite Amulet and West Macdonald orebodies is provided in Table 3.1.

3.2 Description of the Tailings Area

3.2.1 Physical Features

The Waite Amulet tailings areas is a conventional stack, constructed by spigotting from perimeter dams. The tailings occupy some 41 hectares, with an average height of approximately 8 to 10 metres. The surrounding topography in the area slopes gently to the south and west. The tailings surface, in contrast, slopes from south to north and varies in thickness from 15 m on the south to 2 m on the north. The basin is underlain with clayey soils of variable depth and bedrock.

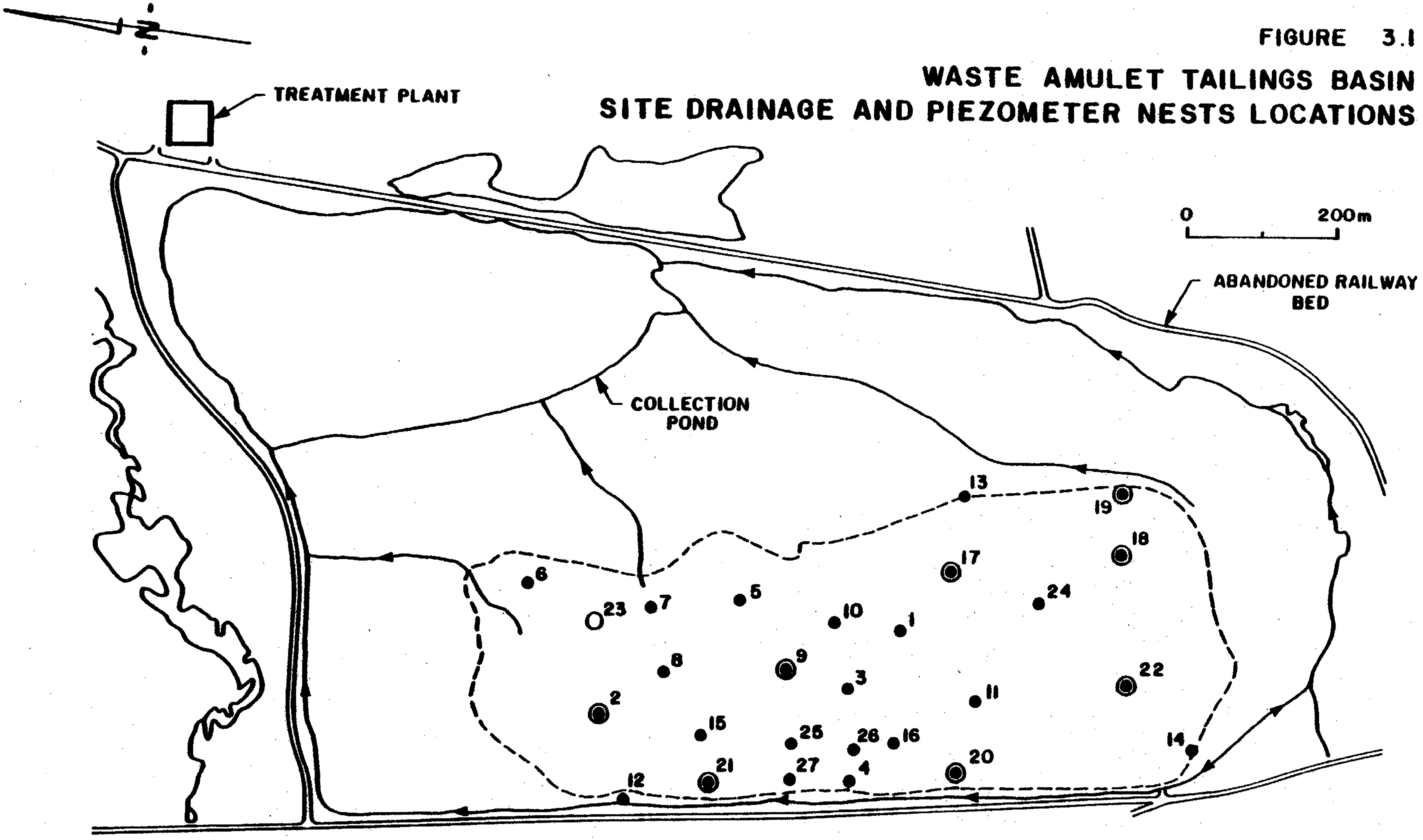


FIGURE 3.1

WASTE AMULET TAILINGS BASIN
SITE DRAINAGE AND PIEZOMETER NESTS LOCATIONS

LEGEND:

- - - - BOUNDARY OF MAIN TAILINGS AREA
← DIRECTION OF SURFACE WATER FLOW
○ CORE SAMPLE
● PIEZOMETER NEST

Welcome Screen Search Report List

Table 3.1

WAITE AMULET AND WEST MACDONALD ORE AND TAILINGS CHARACTERISTICS (1956)

	Composition		
	Waite Amulet Ore	West Macdonald Ore	Combined[1] Tailings
Cu %	3.89	0.13	0.16
Zn %	3.95	2.41	0.26
S %	18.91	46.47	12.82

Note:

[1] In 1956, a pyrite concentrate was being produced which lowered the sulfide content in the tailings.

Seepage streams, which exit from the perimeter dams, are collected in drainage ditches which discharge into a collection pond northwest of the basin where they are intercepted and treated. Surface runoff from the tailings reports to the north end of the tailings basin and flows with the seepage streams to the collection pond (see Figure 3.1).

3.2.2 Hydrogeological Characteristics

The depth to the water table is highly variable. The water table is lowest at the south end and highest at the north end of the basin where the tailings are fine grained. The water table is also mounded along the north-south axis and slopes downward towards the perimeter dykes on the east and west sides. Water table depths range from less than 1 m in the north to more than 5 m in the south.

Hydraulic conductivities, as expected, are lowest in the fine grained tailings and highest in the south and around the perimeter spigotted coarse tailings dykes. Values range from 10^{-6} to 10^{-3} cm s^{-1}.

Porewater velocities range from 0.4 cm yr^{-1} to 5 m yr^{-1} within the pile, and increase to as much as 35 m yr^{-1} across the tailings dams. The permeable nature of the dams and the fact that the basin is underlain with clayey subsoils suggest that most of the seepage exits through the perimeter dams.

An extensive amount of porewater quality information has been collected. Analytical results for 10 samples collected from the saturated zone in December 1985 are presented in Table 3.2. The location of the piezometer nests indicated on Table 3.2 are shown on Figure 3.1.

The data indicate a general increase in pH and decrease in the concentrations of most contaminants with depth. Because the pH is near neutral in the saturated zone, the concentrations of several of the metal ions, notably copper, lead and zinc, are low. The iron concentration perhaps shows the sharpest decrease with depth suggesting that iron, which is being transported

Table 3.2

ANALYTICAL RESULTS OF 10 POREWATER SAMPLES COLLECTED 5 DECEMBER 1985

		Piezometer Sample Location (Piezometer Nest - Piezometer Number)									
		2-1	11-1	11-2	11-3	20-1	20-2	22-1	22-2	22-3	22-4
Depth	(m)	6.96	8.64	6.17	3.99	6.14	4.06	11.7	9.30	8.08	7.72
pH		6.8	7.0	6.8	5.5	7.5	6.3	7.0	7.0	6.1	5.7
Eh		244	214	242	302	404	294	189	194	224	294
Ec field	(us)	-	2100	4900	-	-	-	-	2200	4500	3600
Ec lab	(us)	3080	2950	5800	8000	1250	6700	2500	3600	6000	6000
Temp field	(^{o}C)	-	4	6	-	-	-	-	5	5	5
Temp lab	(^{o}C)	18	15.5	16.5	18	16	17	25	21	21	21
Acidity	(mg/L)	44	40	336	5400	40	12	139	54	598	1500
Alkalinity	(mg/L)	160	90	90	-	500	44	530	184	40	24
Al	(mg/L)	0.25	0.26	0.31	0.71	0.04	0.38	0.14	0.26	0.30	0.48
Ca	(mg/L)	369	91	498	416	-	453	292	457	531	496
Co	(mg/L)	<0.00	<0.00	0.68	15.6	<0.00	5.30	<0.00	0.00	2.11	4.33
Cu	(mg/L)	<0.00	<0.00	<0.00	<0.03	<0.001	0.02	0.01	<0.00	<0.00	0.01
Fe	(mg/L)	10.0	6.60	198	3940	1.97	1480	23.5	9.32	671	1410
K	(mg/L)	<0.00	61.9	146	67	<0.00	336	-	70.3	73.8	55.6
Mg	(mg/L)	51.7	107	1380	781	20.4	1430	143	371	1290	958
Mn	(mg/L)	1.54	0.61	951	73	0.63	19.4	0.65	0.52	9.7	14.9
Na	(mg/L)	589	1040	61.3	268	422	87.6	-	219	61.4	28.7
Ni	(mg/L)	0.09	0.04	0.18	0.71	<0.00	0.30	0.11	0.11	0.23	0.44
NH_4	(mg/L)	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00	<0.00
Pb	(mg/L)	0.15	0.06	0.27	1.54	0.04	0.59	0.13	0.18	0.40	0.58
Zn	(mg/L)	0.10	0.02	0.07	1.54	<0.00	0.35	0.06	0.02	0.15	0.36
SO_4	(mg/L)	3060	3120	1020	14700	626	2200	2640	4370	9820	9380

Note:

From Siwik (1986).

into the saturated zone from the unsaturated zone, is precipitating out of solution.

In contrast, results of an investigation into the water quality of the unsaturated zone of the tailings indicated low pH conditions and high redox potential (Blowes and Cherry, 1987). The results of this work have not been fully reported to date.

3.3 Field Data for Calibration

3.3.1 General

In order to calibrate the RATAP.BMT model, the field data collected at Waite Amulet were reviewed to identify piezometer nests at which a complete range of mineralogical, water chemistry and oxygen profile data had been collected. It was found that solid phase, aqueous phase and gaseous phase data had been collected at only one location, that being nest WA-20. Since solid phase data is the most important information to have in calibrating RATAP.BMT1, the data for WA-20 have been used. However, this nest is not ideally located as it resides on the bench of the tailings dam on the west side of the basin as indicated on Figure 3.1. The porewater quality data collected at this location is quite likely influenced by horizontal flow through the dams.

3.3.2 Mineralogy

The pyrite, pyrrhotite and related mineral content of the tailings solids at WA-20 are summarized in Table 3.3. The water table at this site is approximately 2.2 m below ground surface although it is expected to fluctuate seasonably since this piezometer nest is located in the perimeter dam.

As shown on Table 3.3, oxidation would appear to have reduced the near surface sulfide levels. At the surface, sulfides are almost depleted and increase in content with depth. Below a depth of 2 m the extent to which sulfide mineral oxidation has occurred is not clear. The pyrite and pyrrhotite data for the

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TABLE 3.3

PYRITE AND PYRRHOTITE PROFILES FROM CORE WA-20*
(FRACTION 37 um)

Sample		WA20-1	WA20-2	WA20-3	WA20-4	WA20-5	WA20-6	WA20-7	WA20-8	WA20-9	WA20-10
Depth (metres)		0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
Pyrite	%	0.3	2.1	5.4	2.9	3.5	5.9	45.5	25.5	21.4	62.5
Pyrrhotite	%	0	0.1	1.1	5.9	17.2	6.5	10.8	3.0	13.7	14.1
Pyrite & Pyrrhotite[3]	%	0.4	3.9	7.7	9.9	22.0	14.3	57.2	29.1	35.8	77.7
Geothite	%	14.2	1.4	5.1	8.1	5.8	7.3	2.8	6.3	3.1	1.1
Magnetite/hematite[2]	%	46.8	43.6	10.4	13.5	37.9	7.5	12.7	19.4	18.6	7.5
Silicates[1]	%	38.5	51.2	76.4	66.5	22.0	63.6	21.5	40.1	39.7	11.3
Altered pyrrhotite	%	0.0	0.1	0.4	2.0	12.2	7.3	5.8	5.1	2.9	2.4

<u>**Note**</u>:

* Condensed from Table 3 of Petruk and Pinard (1986). Quantities are in wt. %.
1. Quartz, K-fledspar, chlorite, amphibole and pyroxene
2. Reported as magnetitie/hematite
3. Pyrite and pyrrhotite mainly

2.1 m sample depth suggest that there has been much less oxidation at this depth than at the shallower sampling stations. The data for the samples at 2.4 and 2.7 m, on the other hand, indicate a much lower pyrite content at both stations and a much lower pyrrhotite content at the 2.4 m depth than at the 2.1 m depth. The district differences noted in the pyrite and pyrrhotite contents at these stations suggest that there was considerable variation in the mineralogy of the tailings as they were laid down.

The shallow samples contain elevated levels of magnetite/hematite and geothite, likely oxidation products from sulfide oxidation. The trend in concentration with depth for these constituents, as expected, is the reverse of sulfide minerals.

3.3.3 Geochemistry

Geochemical data collected on porewater samples from the unsaturated and saturated zones at WA-20 are summarized in Table 3.4.

While the data are not complete for all sample depths, they do indicate definite trends. For example, the pH data indicate much lower values in the upper unsaturated zone than in the saturated zone where the pH is near neutral. The oxygen profile shows a rapid decline in the unsaturated zone, as expected, due to consumption from oxidation of sulfide minerals. The elevated dissolved ferrous iron content also suggests that sulfide mineral oxidation is ongoing. As previously discussed, the iron level in the saturated zone (see Table 3.2) is much lower, presumably due to the formation of iron precipitates. The electrical conductance and specific conductivity data confirm that the dissolved solids levels are much higher in the unsaturated zone than in the saturated zone again suggesting that some dissolved constituents have precipitated out of solution as the porewater moves downward through the tailings mass.

Welcome Screen | Search | Report List

Table 3.4

GEOCHEMICAL RESULTS

(Location WA-20)

Water Content	Depth (m)	pH	Eh (mv)	S.Cond. (mS/cm)	Fe^{2+} (mg/L)	O_2 (%)	CO_2 (%)	SO_4 (mg/L)
Unsaturated	.1	2.3	686	12.8	58.5	19.7	<0.02	-
Unsaturated	.2	-	-	-	-	13.1	0.05	-
Unsaturated	.3	4.6	650	16.6	6650	7.6	0.07	-
Unsaturated	.4	-	-	-	-	4.3	<.02	-
Unsaturated	.5	4.35	649	16.6	3560	4.0	0.3	-
Unsaturated	.7	4.35	501	18.5	4430	-	-	-
Unsaturated	.9	4.30	582	17.9	4250	-	-	-
Saturated	1.4	-	-	-	-	-	-	-
Unsaturated	2.2	-	-	-	-	-	-	-
Saturated	4.06	6.3	294	2.5	-	-	-	2200
Saturated	6.14	7.5	404	6.7	-	-	-	640

3.4 Comparison of Model Calculations to Field Data

In the following section model predictions of solid phase species concentrations (pyrite and pyrrhotite), aqueous concentrations (pH) and gaseous concentrations (oxygen) in the unsaturated zone are compared to field data.

3.4.1 Solid Phase Species

Pyrite

Figure 3.2 presents the predicted and measured pyrite content of the tailings solids. The model predicts a sharp depletion front at approximately 0.8 m. The field data, indicate less distinctly defined front but also are seen to be quite variable. In terms of the amount of pyrite oxidized (i.e. the area under the curves), the measured and predicted amounts are in good agreement.

Altering the moisture content of the tailings, e.g. increasing the residual water content, would have increased the slope of the pyrite profile. It would also, however, alter the pyrrhotite front, Figure 3.3, which is in good agreement with the measured pyrrhotite values.

Pyrrhotite

The predicted and measured pyrrhotite contents are presented on Figure 3.3. The measured pyrrhotite levels at depths greater than 1.0 m are seen to be quite variable. Nevertheless, the data show that good agreement exists between the measured and predicted values.

FIGURE 3.2

PREDICTED AND MEASURED PYRITE PROFILES
FOR WAITE AMULET
(WA - 20)

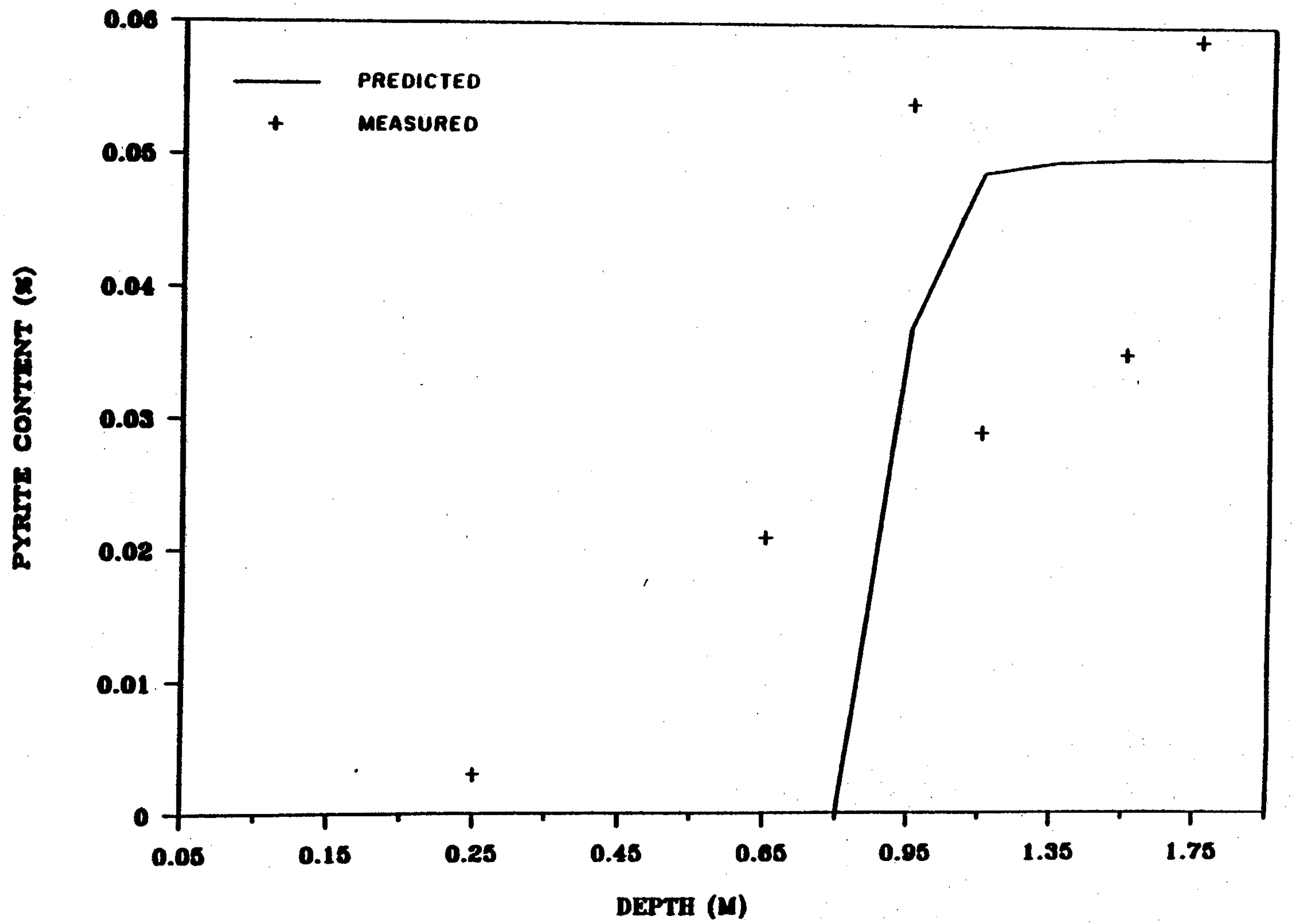
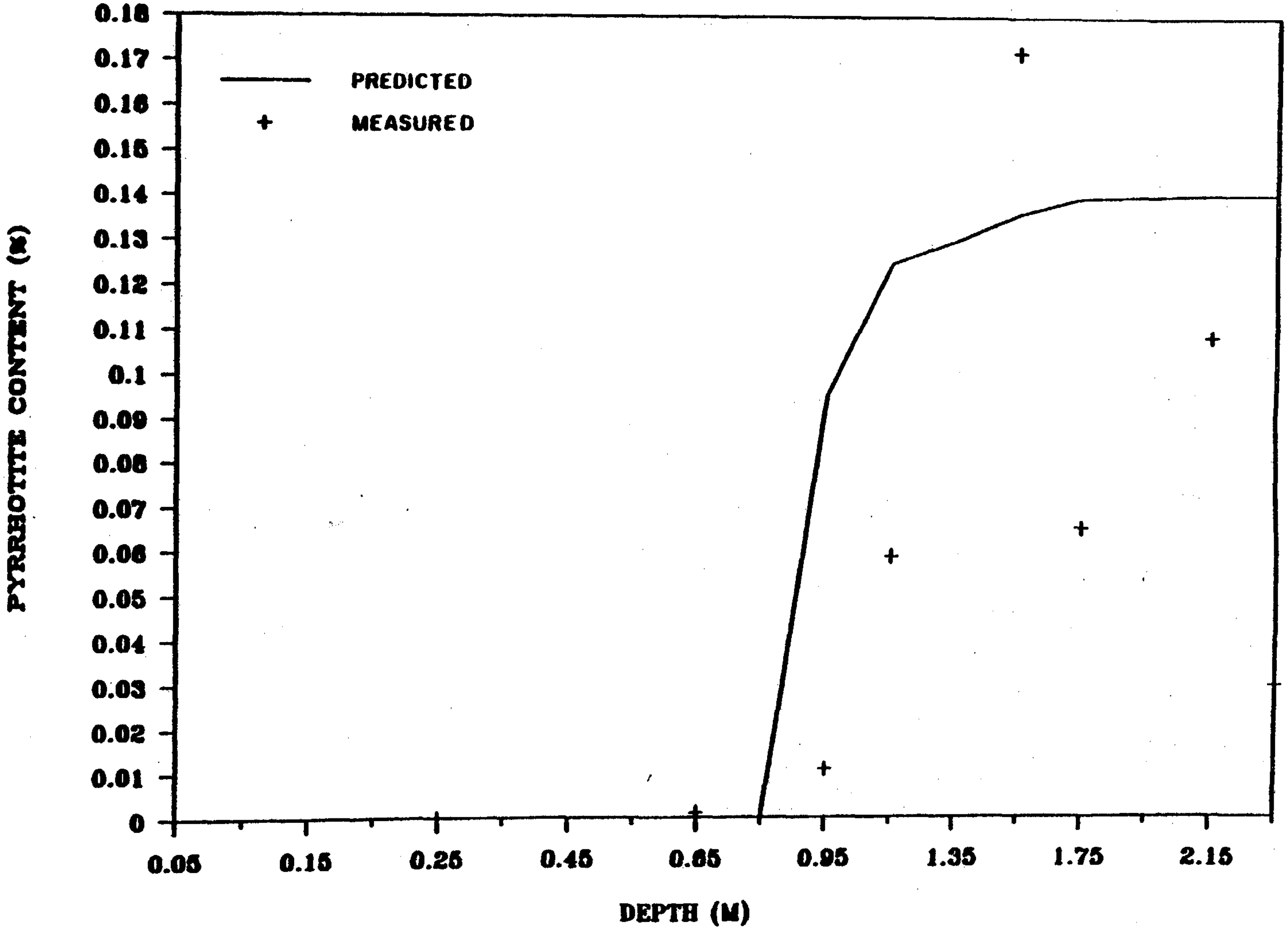


FIGURE 3.3

PREDICTED AND MEASURED PYRRHOTITE
FOR WAITE AMULET
(WA-20)



3.4.3 Aqueous Phase Species

pH

Figure 3.4 presents the predicted and measured pH values. The field data indicates low pH conditions at the surface followed by a pH of approximately 4 at depths greater than 0.2 m. The low pH at the surface may result from runoff as the sulfides at this depth have been depleted, see Figures 3.2 and 3.3 and would not contribute to acidity.

The model underestimates the pH at depths of 0.2 m to 1.0 m. The low pH conditions result from the model predicting the generation of acid from pyrite oxidation. At a depth greater than 1.0 m the model predicts near neutral pH levels, a result of calcite buffering. The field data suggest that the buffering capacity has been depleted. Overall, the model pH predictions are in reasonable agreement with field observations.

3.4.4 Gaseous Phase Species

Oxygen

The measured field data and predicted oxygen profile are presented on Figure 3.5. The measured profile indicates oxygen consumption below 0.10 m but little consumption beyond 0.50 m. The model, however, predicts oxygen consumption over the entire depth profile down to about 1.0 m with the greatest consumption between 0.25 m and 0.95 m.

A higher residual pyrite level in the 0.15 m to 0.6 m range would alter the slope of the predicted curve to better fit the measured profile. It would also, however, alter the pyrrhotite predictions.

4.0 MODEL PREDICTIONS

4.1 Introduction

The primary purpose of the RATAP.BMT1 model is to estimate the upper and lower limits of the rate and quantity of acid generated from the bacteria-assisted oxidation of sulfide minerals present in base metal tailings. The limits are estimated by taking into account the uncertainty in the input parameters in a probabilistic simulation. For demonstration purposes, acid flux calculations are reported in this chapter for base metal tailings characteristic of those found at the Waite Amulet tailings area near Noranda-Rouyn, Quebec.

The definition of acid flux employed in this study is:

$$\text{Acid} = (2\,[SO_4^{2-}] + [HCO_3^-] - 2\,[Ca^{2+}] - [K^+])\,\frac{V_r}{A_x} \qquad (4.1)$$

where

Acid = monthly acid flux ($mol.m^{-2}.mth^{-1}$)

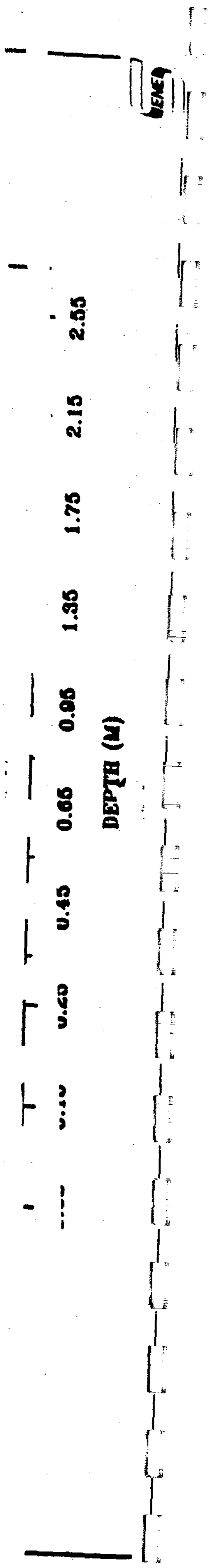
V_r = infiltration rate of precipitation into the tailings ($m^3.mth^{-1}$)

A_x = cross sectional area of the tailings (m^2)

[] = concentration of SO_4^{2-}, HCO_3^-, Ca^{2+} and K^+ ions in the tailings porewater ($mol.m^{-3}$)

This definition accounts for all H^+ produced by sulfide oxidation less that consumed by calcite dissolution. The acid flux is defined in this project in terms of proton (H^+) equivalents. Hence one mole equals one equivalent, the actual units of equation (4.1).

Acid flux is calculated on a monthly basis in the code. The annual flux then is determined as the summation of the twelve (12) monthly acid flux values. Acid flux is also calculated as a cumulative acid flux over time; this equals the sum of the annual fluxes from time zero to the end of the simulation period.



4.2 Input Parameter Distributions

A listing of the input parameters incorporated in the RATAP.BMT1 code and their nominal and probabilistic values are presented in Table 4.1. A total of 255 input parameters are employed in the detailed multi-component model discussed in the appendices.

For the Waite Amulet tailings considered in this study, the parameters are assigned the following types of probability distributions: normal (37); triangular (60); uniform (30); lognormal (3); and constant (125). The number of parameters is based on the tailings profile being divided into twenty-two layers, and would be less if fewer layers were specified. For example, the total number of input parameters for a one layer system only equals 124. Detailed descriptions of the parameters and their distributions are presented in the appropriate appendices.

4.3 Acid Flux

4.3.1 Monthly Acid Flux

The acid flux predicted at a depth of 1.75 m is shown in Figure 4.1 for the month of June. This month was selected as it coincides with the time of the year at which the peak flux is predicted to occur. The flux curves shown on Figure 4.1 are plots of geometric mean values and the upper and lower 95 percentiles (assumed to correspond to the maximum and minimum limits) from 25 trials.

In year 1, the monthly acid flux had a mean value of approximately 2.3 $mol.m^{-2}.mth^{-1}$ and lower and upper limits of about 0.2 and 43 $mol.m^{-2}.mth^{-1}$, respectively. The peak monthly acid flux at the 1.75 m depth occurs in year 2; the geometric mean value equalled about 19 $mol.m^{-2}.mth^{-1}$ and the lower and upper limits approximated 3 and 78 $mol.m^{-2}.mth^{-1}$, respectively. In the longer term, the mean monthly acid flux leveled off at about 1 $mol.m^{-2}.mth^{-1}$ at the 1.75 m depth.

FIGURE 4.1

ACID FLUX FOR JUNE vs. YEAR
AT DEPTH OF 1.75 m

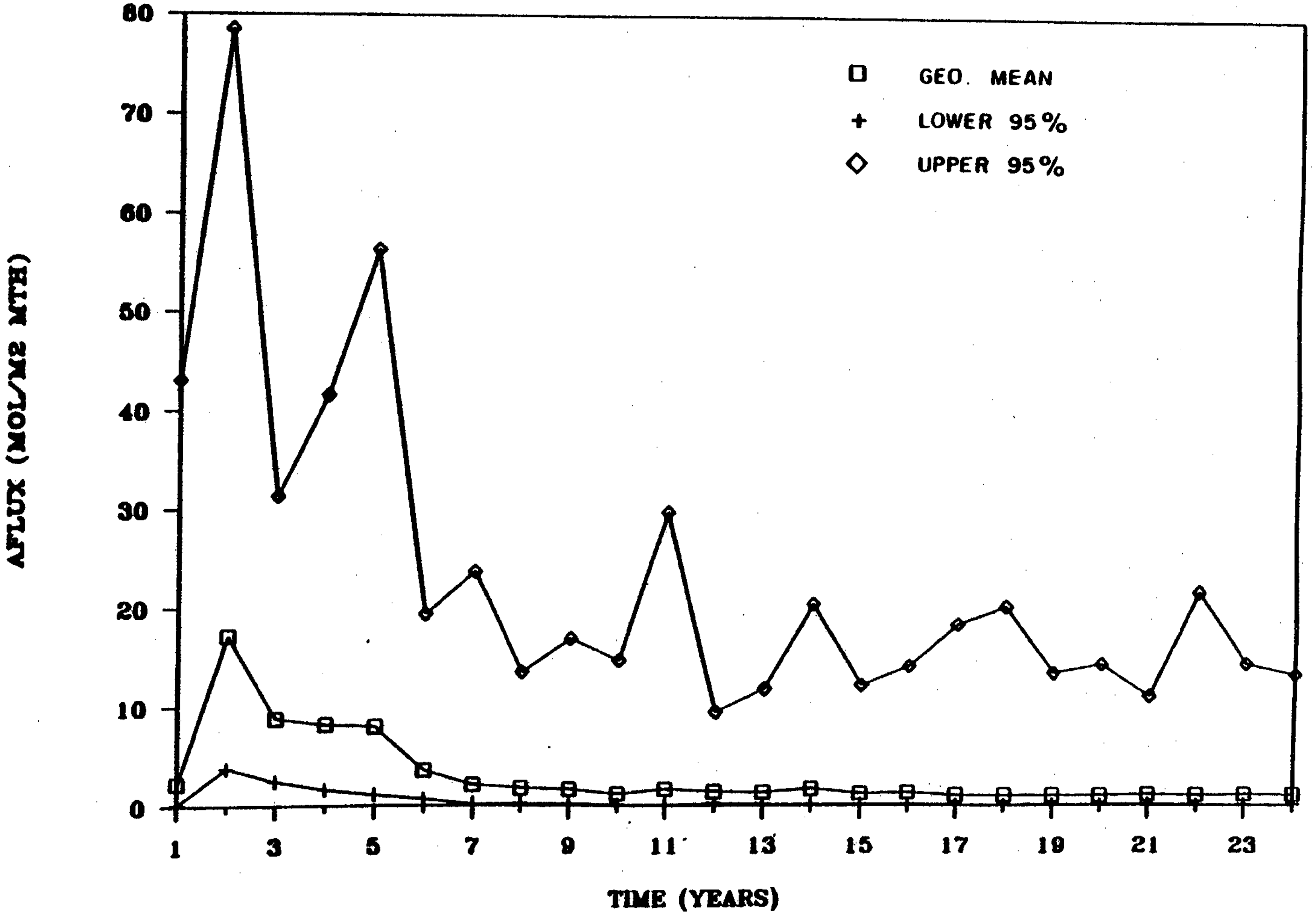


FIGURE 4.2

CUMMULATIVE ACID FLUX
AT DEPTH OF 1.75 m

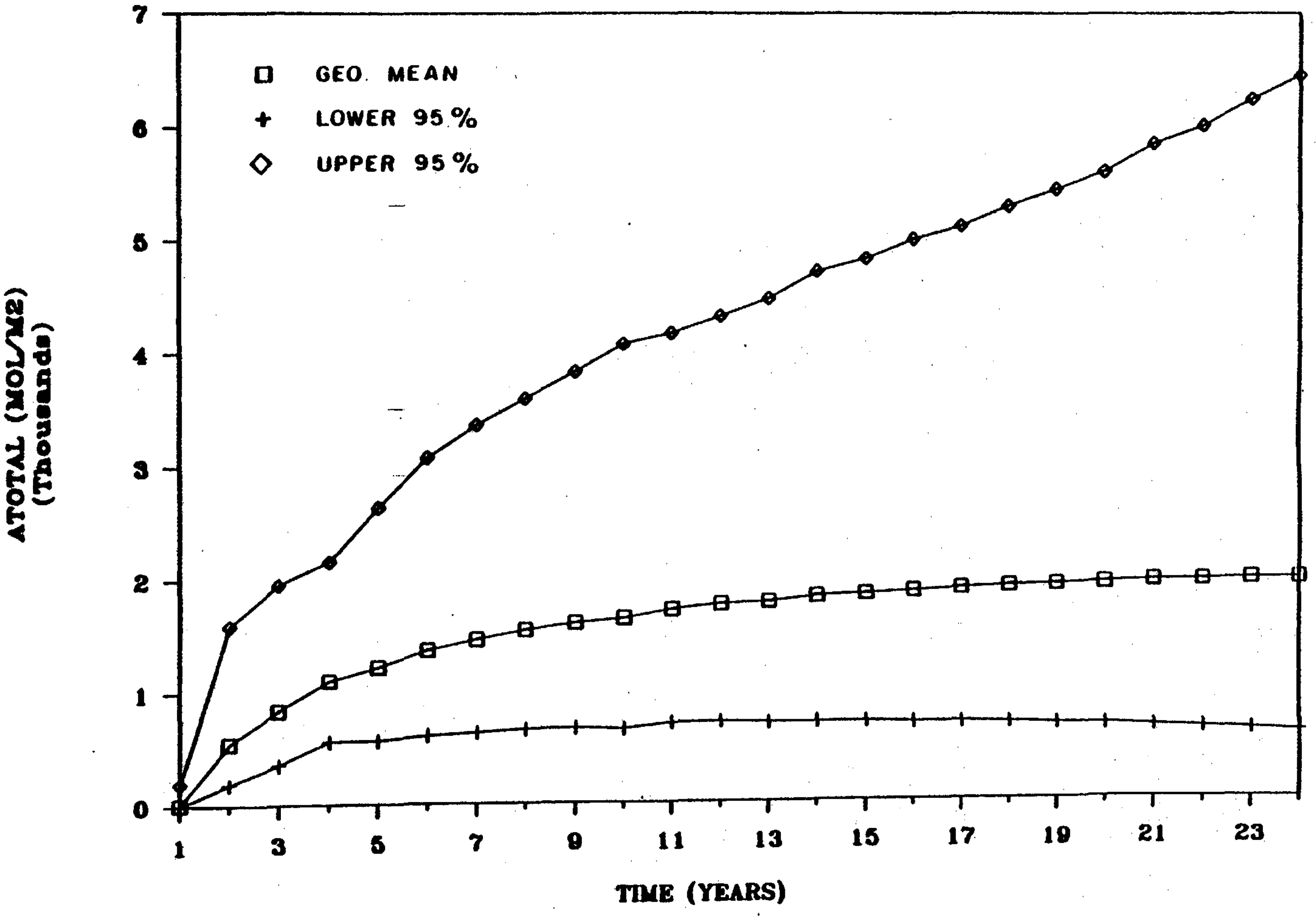


TABLE 4.1

MODEL INPUT PARAMETERS

```
 1 PROBABILISTIC ANALYSIS: WAITEP.DAT
 2 N N
 3 WAITEP.OUT
 4 WAITEP.OUT
 5 255 0    0    0
 6 0913566091  25
 7 288.
 8 PRINT   N 1  N     0.
 9 FLAG1   N 1  N     0.
10 FLAG2   N 1  N     0.
11 FLAG3   N 1  N     0.
12 FLAG4   N 1  N     0.
13 FLAG5   N 1  N     0.
14 FLAG6   N 1  N     0.
15 MNT     N 1  N     6.
16 TSAVE   N 1  N     260.
17 AVGTEM  N 1  N     283.
18 BULKD   N 2  N    1.8E6    1.E5      1.6E6      2.0E6
19 COEFAO  N 1  N     20.
20 COEFPS  N 1  N     0.1
21 COEFDD  N 1  N     2.0
22 COVER   N 1  N     0.
23 D10     N 6  N     0.05    0.08      0.11
24 D10     N 6  N     0.05    0.08      0.11
25 D10     N 6  N     0.05    0.08      0.11
26 D10     N 6  N     0.05    0.08      0.11
27 D10     N 6  N     0.05    0.08      0.11
28 D10     N 6  N     0.05    0.08      0.11
29 D10     N 6  N     0.05    0.08      0.11
30 D10     N 6  N     0.05    0.08      0.11
31 D10     N 6  N     0.05    0.08      0.11
32 D10     N 6  N     0.05    0.08      0.11
33 D10     N 6  N     0.05    0.08      0.11
34 D10     N 6  N     0.05    0.08      0.11
35 D10     N 6  N     0.05    0.08      0.11
36 D10     N 6  N     0.05    0.08      0.11
37 D10     N 6  N     0.05    0.08      0.11
38 D10     N 6  N     0.05    0.08      0.11
39 D10     N 6  N     0.05    0.08      0.11
40 D10     N 6  N     0.05    0.08      0.11
41 D10     N 6  N     0.05    0.08      0.11
42 D10     N 6  N     0.05    0.08      0.11
43 D10     N 6  N     0.05    0.08      0.11
44 D10     N 6  N     0.05    0.08      0.11
45 LA(1)   N 4  N     0.65    0.71
46 LA(2)   N 4  N     0.65    0.71
47 LA(3)   N 4  N     0.65    0.71
48 LA(4)   N 4  N     0.65    0.71
49 LA(5)   N 4  N     0.65    0.71
50 LA(6)   N 4  N     0.65    0.71
51 LA(7)   N 4  N     0.65    0.71
52 LA(8)   N 4  N     0.65    0.71
53 LA(9)   N 4  N     0.65    0.71
54 LA(10)  N 4  N     0.65    0.71
55 LA(11)  N 4  N     0.65    0.71
```

TABLE 4.1

MODEL INPUT PARAMETERS

56	LA(12)	N	4	N	0.65	0.71		
57	LA(13)	N	4	N	0.65	0.71		
58	LA(14)	N	4	N	0.65	0.71		
59	LA(15)	N	4	N	0.65	0.71		
60	LA(16)	N	4	N	0.65	0.71		
61	LA(17)	N	4	N	0.65	0.71		
62	LA(18)	N	4	N	0.65	0.71		
63	LA(19)	N	4	N	0.65	0.71		
64	LA(20)	N	4	N	0.65	0.71		
65	LA(21)	N	4	N	0.65	0.71		
66	LA(22)	N	4	N	0.65	0.71		
67	LI	N	1	N	20.			
68	LSI	N	1	N	19.			
69	NR(1)	N	2	N	0.18	0.2	0.14	0.22
70	NR(2)	N	2	N	0.18	0.2	0.14	0.22
71	NR(3)	N	2	N	0.18	0.2	0.14	0.22
72	NR(4)	N	2	N	0.18	0.2	0.14	0.22
73	NR(5)	N	2	N	0.18	0.2	0.14	0.22
74	NR(6)	N	2	N	0.18	0.2	0.14	0.22
75	NR(7)	N	2	N	0.18	0.2	0.14	0.22
76	NR(8)	N	2	N	0.18	0.2	0.14	0.22
77	NR(9)	N	2	N	0.18	0.2	0.14	0.22
78	NR(10)	N	2	N	0.18	0.2	0.14	0.22
79	NR(11)	N	2	N	0.18	0.2	0.14	0.22
80	NR(12)	N	2	N	0.18	0.2	0.14	0.22
81	NR(13)	N	2	N	0.18	0.2	0.14	0.22
82	NR(14)	N	2	N	0.18	0.2	0.14	0.22
83	NR(15)	N	2	N	0.18	0.2	0.14	0.22
84	NR(16)	N	2	N	0.18	0.2	0.14	0.22
85	NR(17)	N	2	N	0.18	0.2	0.14	0.22
86	NR(18)	N	2	N	0.18	0.2	0.14	0.22
87	NR(19)	N	2	N	0.18	0.2	0.14	0.22
88	NR(20)	N	2	N	0.18	0.2	0.14	0.22
89	NR(21)	N	2	N	0.18	0.2	0.14	0.22
90	NR(22)	N	2	N	0.18	0.2	0.14	0.22
91	NT(1)	N	6	N	0.45	0.5	0.55	
92	NT(2)	N	6	N	0.45	0.5	0.55	
93	NT(3)	N	6	N	0.45	0.5	0.55	
94	NT(4)	N	6	N	0.45	0.5	0.55	
95	NT(5)	N	6	N	0.45	0.5	0.55	
96	NT(6)	N	6	N	0.45	0.5	0.55	
97	NT(7)	N	6	N	0.45	0.5	0.55	
98	NT(8)	N	6	N	0.45	0.5	0.55	
99	NT(9)	N	6	N	0.45	0.5	0.55	
100	NT(10)	N	6	N	0.45	0.5	0.55	
101	NT(11)	N	6	N	0.45	0.5	0.55	
102	NT(12)	N	6	N	0.45	0.5	0.55	
103	NT(13)	N	6	N	0.45	0.5	0.55	
104	NT(14)	N	6	N	0.45	0.5	0.55	
105	NT(15)	N	6	N	0.45	0.5	0.55	
106	NT(16)	N	6	N	0.45	0.5	0.55	
107	NT(17)	N	6	N	0.45	0.5	0.55	
108	NT(18)	N	6	N	0.45	0.5	0.55	
109	NT(19)	N	6	N	0.45	0.5	0.55	
110	NT(20)	N	6	N	0.45	0.5	0.55	

TABLE 4.1

MODEL INPUT PARAMETERS

111	NT(21)	N	6	N	0.45	0.5	0.55
112	NT(22)	N	6	N	0.45	0.5	0.55
113	VRFRAC	N	1	N	0.5		
114	XALOH3	N	1	N	0.0001		
115	XCACO3	N	4	N	0.0	0.001	
116	XCOVER	N	1	N	0.		
117	XFEOH3	N	1	N	0.001		
118	XGYP	N	1	N	0.0005		
119	XSULF	N	4	N	0.03	0.08	
120	XSULF	N	4	N	0.10	0.18	
121	XSULF	N	4	N	0.002	0.004	
122	XSULF	N	4	N	0.003	0.007	
123	XSER	N	4	N	0.03	0.07	
124	YCOVER	N	1	N	0.		
125	ALPH	N	1	N	1.0		
126	ALPHAS	N	1	N	0.8		
127	CP	N	1	N	75.4		
128	CPT	N	1	N	0.84		
129	DH2O	N	1	N	62.		
130	HEAT(1)	N	1	N	1.45E6		
131	HEAT(2)	N	1	N	1.58E6		
132	HEAT(3)	N	1	N	0.903E6		
133	HEAT(4)	N	1	N	0.86E6		
134	KSOIL	N	1	N	1.48E6		
135	BIOEA	N	6	N	10000.	11700.	16300.
136	BIOMAX	N	4	N	11.5	14.5	
137	BIOXP1	N	1	N	1.60E-3		
138	BIOXP2	N	1	N	1.72E-4		
139	BIOXP3	N	1	N	3.20E-4		
140	BIOXP4	N	1	N	2.04E-4		
141	BIOXP5	N	1	N	3.45E-4		
142	BIOXP6	N	1	N	2.02E-3		
143	BIOYXS	N	6	N	2.5	3.2	4.2
144	CHEMEA	N	1	N	0.		
145	CHEMEA	N	1	N	0.		
146	CHEMEA	N	1	N	0.		
147	CHEMEA	N	1	N	0.		
148	CHEMEA	N	1	N	0.		
149	CHEMEA	N	1	N	0.		
150	CHEMEA	N	1	N	4.8E3		
151	CHEMEA	N	1	N	4.9E3		
152	CHEMEA	N	1	N	2.6E3		
153	CHEMEA	N	1	N	2.3E3		
154	CHEMEA	N	1	N	1.33E4		
155	CHEMEA	N	1	N	4.0E3		
156	CHEMKC	N	1	N	0.		
157	CHEMKC	N	1	N	0.		
158	CHEMKC	N	1	N	0.		
159	CHEMKC	N	1	N	0.		
160	CHEMKC	N	1	N	0.		
161	CHEMKC	N	1	N	0.		
162	CHEMKC	N	1	N	1.84		
163	CHEMKC	N	1	N	10.03		
164	CHEMKC	N	1	N	0.136		
165	CHEMKC	N	1	N	0.165		

TABLE 4.1

MODEL INPUT PARAMETERS

166	CHEMKC	N	1	N	3.83E6		
167	CHEMKC	N	1	N	8.24		
168	LIMP	N	1	N	1.29E-3		
169	DX(1)	N	1	N	0.05		
170	DX(2)	N	1	N	0.05		
171	DX(3)	N	1	N	0.05		
172	DX(4)	N	1	N	0.05		
173	DX(5)	N	1	N	0.05		
174	DX(6)	N	1	N	0.1		
175	DX(7)	N	1	N	0.1		
176	DX(8)	N	1	N	0.1		
177	DX(9)	N	1	N	0.1		
178	DX(10)	N	1	N	0.1		
179	DX(11)	N	1	N	0.2		
180	DX(12)	N	1	N	0.2		
181	DX(13)	N	1	N	0.2		
182	DX(14)	N	1	N	0.2		
183	DX(15)	N	1	N	0.2		
184	DX(16)	N	1	N	0.2		
185	DX(17)	N	1	N	0.2		
186	DX(18)	N	1	N	0.2		
187	DX(19)	N	1	N	0.2		
188	DX(20)	N	1	N	0.2		
189	DX(21)	N	1	N	0.2		
190	DX(22)	N	1	N	0.2		
191	HENRY	N	1	N	23.6		
192	WATTAB	N	1	N	2.35		
193	ALPHA	N	1	N	0.9		
194	BETA	N	1	N	1.8		
195	COEFX	N	1	N	2.0		
196	COEFY	N	1	N	-1.0		
197	LIMO2	N	1	N	0.01		
198	RADMAX	N	1	N	1.25E-4		
199	ATAIL	N	1	N	4.1+5		
200	VR(1)	N	6	N	0.001	0.005	0.01
201	VR(2)	N	6	N	0.001	0.005	0.01
202	VR(3)	N	6	N	0.001	0.005	0.01
203	VR(4)	N	6	N	0.018	0.09	0.18
204	VR(5)	N	6	N	0.014	0.07	0.14
205	VR(6)	N	6	N	0.006	0.03	0.06
206	VR(7)	N	6	N	0.004	0.02	0.04
207	VR(8)	N	6	N	0.006	0.03	0.06
208	VR(9)	N	6	N	0.01	0.05	0.1
209	VR(10)	N	6	N	0.01	0.05	0.1
210	VR(11)	N	6	N	0.008	0.04	0.08
211	VR(12)	N	6	N	0.001	0.005	0.01
212	VHARDP	N	1	N	0.1		
213	FEDEN	N	1	N	2.1E6		
214	CALOH	N	1	N	1.07E-5		
215	CFEHS3	N	1	N	1.26E16		
216	CFE2SO4	N	1	N	204.2		
217	KFESO4	N	1	N	3.23E-3		
218	CALOH2	N	1	N	5.0E-10		
219	CALOH3	N	1	N	1.E-15		
220	CALSO4	N	1	N	1047.13		

TABLE 4.1

MODEL INPUT PARAMETERS

221	CCASO4	N	1	N	316.23			
222	CFEOH	N	1	N	6.46E-3			
223	CFEOH2	N	1	N	2.14E-6			
224	CFEOH3	N	1	N	1.E-12			
225	CFESO4	N	1	N	8317.64			
226	CHSO4	N	1	N	1.26E-2			
227	COEFAL	N	6	N	0.01	0.075	0.6	
228	DK1	N	1	N	5.012E-7			
229	DK2	N	1	N	5.012E-11			
230	ACOEF	N	1	N	-5.E-4			
231	KBAS	N	2	N	22.7	1.02	21.7	23.7
232	KCACO3	N	3	N	4.48E-9	1.05	3.89E-9	5.13E-9
233	KCASO4	N	3	N	2.4E-5	1.05	2.14E-5	2.75E-5
234	KCO2	N	1	N	0.053			
235	KFEOOH	N	3	N	39.8	3.16	1.27	1.27E3
236	SATCT	N	4	N	1.E-3	1.0E-2		
237	XKFE3	N	6	N	0.005	0.01	0.05	
238	DCUPRE	N	1	N	1.E6			
239	LKCUCO3N		2	N	-9.63	1.05	-10.63	-8.63
240	LKCUJARN		2	N	-82.6	1.05	-84.7	-80.5
241	LKCUOH2N		2	N	-20.35	1.05	-21.35	-19.35
242	LCCUSO4N		2	N	2.31	1.05	2.11	2.51
243	LKFES	N	2	N	-16.2	1.05	-17.2	-15.2
244	LCH2S	N	2	N	19.92	1.05	19.72	20.12
245	LCHS	N	2	N	12.90	1.05	12.70	13.10
246	LKZNS	N	2	N	-22.5	1.05	-23.5	-21.5
247	ICU	N	1	N	0.			
248	IZN	N	1	N	0.			
249	KANTL	N	1	N	5.13E-9			
250	OPTION	N	1	N	1.			
251	KCUSO4	N	1	N	2.0E-3			
252	LCZNSO4N		2	N	2.37	1.05	2.17	2.57
253	KDZN	N	1	N	1.0			
254	LCZNHS2N		2	N	16.1	1.05	15.9	16.3
255	LCZNHS3N		2	N	14.94	1.05	14.7	15.1
256	LCCUHS3N		2	N	25.9	1.05	25.7	26.1
257	LKCUREDN		2	N	-22.8	1.05	-23.8	-21.8
258	LCCUOH2N		1	N	-12.8			
259	LCCUCO3N		1	N	-28.			
260	LCCUOH3N		1	N	-26.8			
261	LCZNOH3N		1	N	-28.4			
262	LCZNOH2N		1	N	-16.9			

4.3.2 Cumulative Acid Flux

The cumulative acid flux transported through the horizon 1.75 m below the tailings surface is shown on Figure 4.2. The mean, lower and upper limits have again been plotted on this figure.

The curves show a rapid rise in the cumulative flux over the initial three to five years. Thereafter, there is a less dramatic rise. The plot of geometric mean values suggests a very constant rate of accumulation with time, after about year 10. The average annual acid flux between year 10 and 24 equalled about 23.5 $mol.m^{-2}.yr^{-1}$. In contrast, the peak annual acid flux occurred between year 1 and 2 equalled 927 $mol.m^{-2}.yr^{-1}$. Over the twenty-four year simulation period the lower and upper limits in the cumulative acid flux were 177 and 4320 $mol.m^{-2}$, respectively. The predicted mean cumulative flux over the same period was 970 $mol.m^{-2}$.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The Reactive Acid Tailings Assessment Program (RATAP) was developed under a previous contract (SENES and Beak, 1986) for the purpose of assessing the effect of oxidative processes on the rate and quantity of acid generation in pyritic uranium mine tailings. The stated objective of this study was ..."to extend the algorithms and code of the RATAP model to account for the generation of acid due to the oxidation of sulfide minerals, other than pyrite, associated with base metal mine tailings." The term acid generation is defined as the flux of total acidity per unit time (e.g. a month or year) from a unit area of tailings. Total acidity is taken as equivalent to the CO_2 - acidity titration endpoint. Hence, total acidity is a measure of the amount of base which would be required to neutralize free protons, all species of aluminum and iron, and carbonic acid to this endpoint.

The specific processes and mechanisms identified for inclusion in the expanded code included: oxidation of other metal sulfides besides pyrite, specifically pyrrhotite, chalcopyrite and sphalerite; heat generation from sulfide mineral oxidation; chemistry of trace metals, namely copper and zinc; and, precipitation of secondary solids and formation of hardpan. These features have been incorporated into a new version of the code which is referred to as the Reactive Acid Tailings Assessment Program for Base Metal Tailings, Version 1 (RATAP.BMT1).

In developing the original RATAP code, an extensive verification, calibration and validation program was carried out. Considerable use was made of data reported in the published literature and of field data collected at the Nordic uranium tailings area in Elliot Lake, Ontario. In modifying RATAP for base metal tailings applications, each of the eight component modules which comprise the RATAP.BMT1 version was modified, tested and quality assured before being integrated into the overall code to maintain the integrity of the model. Where applicable, the modules were calibrated and validated against the data base employed in the previous study. In addition, field data collected in recent years on the base metal tailings at the Waite Amulet site near Noranda-Rouyn, Quebec were employed in the model calibration and validation.

Sufficient field data at Waite Amulet were available to achieve partial calibration of the model. Predicted and measured values were found to be comparable for the solid phase pyrite and pyrrhotite contents and the gaseous phase oxygen content. The porewater pH predictions were acceptable but did not match the measured data as well as the solid and gaseous phase components. It was not practical to draw firm conclusions about the adequacy of the model predictions, however, as only a limited amount of data has been collected at Waite Amulet on certain key characteristics of the tailings. Specifically, measurements on the solid phase composition of the tailings have been made at only one location and these data showed considerable variation with depth. In addition, the results of measurements which have been made on the chemistry of the porewater in the unsaturated zone were not available at the time of this study. Also, no measurements have been made of temperature profiles in the tailings nor of the water content with depth. It should be born in mind however, that the field studies being carried out at Waite Amulet were not designed to provide the data base required to calibrate and validate RATAP.BMT1. It is understood that future work at the site will allow for collection of data on several of the key elements discussed above.

To summarize, the RATAP model has been successfully adapted for prediction of acid generation from base metal mine tailings. The model accounts for acid generation from the oxidation of pyrite, pyrrhotite, chalcopyrite and sphalerite; other sulfide minerals can be added in the future as required. Certain components of the modified model, RATAP.BMT1, have not been fully tested and must await the collection of additional field data.

Further work is required to verify the applicability of RATAP.BMT1 for predicting acid generation in high sulfide tailings and to demonstrate the appropriateness of the model for assessing the effects of reclamation options. Additional work is also required to increase the number of sulfide minerals

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and trace metal species which can be modelled. Accordingly, the following recommendations are made:

1. Field data are required at a minimum of two sites on the composition with depth of the following key elements:

   - sulfide minerals and secondary solids
   - temperature
   - water content
   - porewater concentrations of acidity, pH, calcium, sulfate, aluminum, iron (II), iron (III), arsenic, copper, lead, nickel and zinc.
   - gaseous oxygen and carbon dioxide
   - hardpan formation and the chemical composition and physical characteristics.

2. Calibration and validation of the model predictions is required on the following:

   - movement of the sulfide mineral fronts, particularly of pyrite and pyrrhotite.
   - porewater acidity and pH with depth, particularly the levels found in the unsaturated zone.
   - tailings temperature profiles, the heat contribution from sulfide mineral oxidation and the heat lost with water vapour transport out of the tailings.
   - trace metal concentrations under various pH conditions.
   - the secondary solids which contribute to hardpan formation and the effects of hardpan on water movement through the tailings.

3. Modification of the model to include additional sulfide minerals and trace metals including arsenic, nickel and lead.

4. Incorporation of pre- and post-processors to make the RATAP.BMT1 model more user friendly.

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CRITICAL REVIEW OF THE REACTIVE ACID TAILINGS ASSESSMENT PROGRAM (RATAP.BMT2)

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TABLE OF CONTENTS

Page Number

EXECUTIVE SUMMARY

Control of acid mine drainage from tailings areas is widely recognized as one of the most serious environmental issues facing many base metal, gold and uranium mine operators today. While collection and treatment of acid mine drainage is commonly practiced at active mine sites, it is generally accepted that continuation of treatment practices for an indefinite period in the post operating phase is neither desirable nor practical. Besides the obvious problems associated with maintaining an effective treatment system after mining activities have ceased, the disposal of chemical treatment plant sludge produced from the neutralization of acid mine drainage is a major operational problem.

Originating from work initiated in the mid 1980's by the Canada Centre for Mineral and Energy Technology, the Reactive Acid Tailings Assessment Program for Base Metal Tailings (RATAP.BMT) was developed as a predictive modelling tool to investigate the factors and processes which control the oxidation of sulfide minerals, to simulate acid generation in mine tailings, to estimate the long-term potential for acid generation in tailings, and to evaluate the effects on acid generation of alternative closeout concepts.

This report describes the extension of the validation of the model by:

1) a discussion of quality assurance procedures followed during each stage of code development and documentation of recent code modifications;

2) a critical review of the concepts behind the program; and

3) a comparative evaluation of computer simulations with a more complete database for the Waite-Amulet zinc/copper mine tailings.

RATAP.BMT addresses questions more numerous and more complex than those addressed by other models. It permits evaluation of the limitations of other modelling work and of many additional questions which are beyond the scope of the other models. However, RATAP.BMT requires a more knowledgeable user and, thus, is more difficult for a novice user to program.

The model considers the following processes:

- sulfide mineral oxidation kinetics as a function of water temperature, oxygen concentration, mass of pyrite, pH, phosphorous concentration, carbon dioxide content, and moisture content.
- oxygen pore-gas diffusivity and its control upon the oxygen flux into the tailings.
- shrinkage of sulfide mineral grains as they oxidize.
- depth-dependent differences in the chemical characteristics of the tailings.
- temperature variation with depth due to oxidation of pyrrhotite, pyrite, chalcopyrite, sphalerite and arsenopyrite.
- moisture variations with depth in the unsaturated zone.
- kinetic reactions between porewater and relevant minerals.
- porewater transport of metals including aluminum, iron, calcium, magnesium, potassium, silica, copper, zinc, and of anions including arsenic, sulfate, and carbonate.

Model validation was based on the comparison of model predictions for selected parameters to data collected on the Waite-Amulet tailings during the Phase 2 and Phase 3 field studies. Part of the data was used to calibrate the site dependent parameter estimates. The second part of the data was used to verify the model both in the temporal and spatial (i.e. with respect to depth) sense. The modelled constituents included temperature, pH, oxygen concentration (variation with depth), and porewater concentration of sulfate, ferrous and ferric iron, dissolved copper, and zinc.

The final test involved running the model both in a deterministic and probabilistic manner. The probabilistic simulations were based on selecting parameter values from established distribution functions. The geometric mean values of the probabilistic outputs were used for comparison to the results of the deterministic runs using nominal parameter values.

1.0 INTRODUCTION

1.1 Background

Control of acid mine drainage from tailings areas is widely recognized as one of the most serious environmental issues facing many base metal, gold and uranium mine operators today. While collection and treatment of acid mine drainage is commonly practiced at active mine sites, it is generally accepted that continuation of treatment practices for an indefinite period in the post operating phase is neither desirable nor practical. Besides the obvious problems associated with maintaining an effective treatment system after mining activities have ceased, the disposal of chemical treatment plant sludge produced from the neutralization of acid mine drainage is a major operational problem.

Recognizing the seriousness of this problem, the Canada Centre for Mineral and Energy Technology, initiated work in the mid 1980's into investigating the factors and processes which control the oxidation of sulfide minerals and on developing a predictive modelling tool to simulate acid generation in mine tailings. The primary objective of this work was to provide a model for predicting the long-term potential of acid generation in tailings and for evaluating the effects on acid generation of alternative closeout concepts.

The first of these studies was completed in 1984 by SENES Consultants Limited on behalf of the National Uranium Tailings Program. This study documented the role that bacteria play in the oxidation of pyrite and other sulfide minerals in uranium mine tailings (SENES, 1984). The mechanisms involved in iron and sulfur oxidation were detailed as were the kinetic relationships reported in the literature for the bacterial oxidation and chemical oxidation of sulfide minerals.

In 1986, SENES Consultants Limited and Beak Consultants Limited developed the Reactive Acid Tailings Program (RATAP) for the National Uranium Tailings Program. The RATAP model was developed to provide an estimate of the upper and lower limits of the rate and quantity of acid generation by the bacteria-assisted oxidation of pyrite present in uranium mine tailings (SENES and Beak, 1986).

SENES and Beak adapted the RATAP model to base metal tailings, as part of a project sponsored by CANMET, in 1988. The model developed, the Reactive Acid Tailings Assessment Program for Base Metal Tailings, Version 1 (RATAP.BMT1), also provided an estimate of the upper and lower limits of acid generation by the bacteria-assisted oxidation of sulfides. The sulfides modelled included pyrite, pyrrhotite, chalcopyrite and sphalerite. In addition, it calculated the aqueous concentrations of zinc and copper.

In 1989, SENES and Beak extended RATAP. BMT1 to allow for arsenic-bearing components in the tailings. Version 2 (RATAP.BMT2) incorporates an algorithm for arsenic geochemistry to accommodate an additional sulfide, arsenopyrite, and to facilitate the calculation of aqueous concentrations of arsenic (SENES and Beak, 1989).

Since its original conception, the model has undergone several conceptual modifications and has been calibrated and validated extensively on pyritic uranium tailings. Partial validation of the modified computer model (i.e. RATAP. BMT2) was also performed in previous work using the Phase 2 field study data on the high sulfide tailings at Waite-Amulet in northeastern Quebec, some relevant data from pyritic uranium tailings investigations in the Elliot Lake area of northern Ontario, and laboratory observations. Due to incomplete data, these validation efforts were only partially successful, since the available database did not allow comparison of predicted and measured values for a full range of parameters. Furthermore, the validity of the geochemical concepts used could not be fully assessed.

1.2 Model Application

RATAP.BMT is both a powerful analytical tool and an effective planning aid. Used analytically, the model predicts concentrations for several solid, aqueous and gaseous phase constituents to enable the assessment of the rate and quantity of acid generation in pyritic tailings. During planning, RATAP.BMT allows an evaluation of the benefits of short and long-term tailings management options and facilitates the development of alternative reclamation or closeout strategies.

As a test of the RATAP model, predictions of acid generation in the Nordic tailings were made for a timeframe spanning the period from 1969 to 2041. Analysis of the data indicated that approximately 90,000 tonnes of acid have been produced at the Nordic site to date. Of this amount, it is estimated that 25% has been neutralized at the lime treatment plant, 45% remains in storage in the tailings porewater and sand aquifer underlying the site, and 30% has been neutralized by the buffering capacity of the tailings and sand aquifer. As of 1988, the rate of acid being generated was approaching the rate of acid release from the system. Although the rate of acid production is declining and currently is at about one-half the rate predicted for the early 1970's, acid generation will continue well into the 21st century because of the large inventory of pyrite remaining to be oxidized.

The RATAP model has also been applied on several of the tailings areas at Elliot Lake to evaluate the potential benefits of closeout options in reducing acid generation. One concept which has been discussed on numerous occasions involves the application of a cover of earthen material or depyritized tailings. For this evaluation, it was assumed that the cover material (soil or depyritized tailings) had the same physical characteristics as tailings. The results demonstrated that cover application will reduce the acid generation rate substantially but does not necessarily impact upon the total quantity of acid generated unless the cover application results in a rise in the water table within the basin.

Application of RATAP to the Elliot Lake situation provided a basis for assessing the need for remedial measures at non-operating properties, for assessing the extent and duration of acid generation and the long-term need for treatment, and most importantly, for comparing the environmental and cost effectiveness of remedial measures and reclamation proposals.

1.3 Study Objectives and Approach

This report describes the extension of the validation of the RATAP.BMT2 computer program by:

1) a discussion of quality assurance procedures followed during each stage of code development and documentation of recent code modifications;

2) a critical review of the concepts behind the program; and

3) a comparative evaluation of computer simulations with a more complete database for the Waite-Amulet zinc/copper mine tailings.

2.0 CRITICAL REVIEW OF THE CONCEPTS

2.1 Acid Mine Drainage Modelling

The development of a model to answer questions concerning acidic drainage from mine tailings is dependent upon the objectives of the investigator. Different questions asked about the same tailings system will necessitate the use of different models. The background of the professional using the models will also influence the selection of a model. These models have the following objectives:

1) to provide a useful predictive basis for making decisions concerning tailings management alternatives; and/or

2) to describe mathematically the most important interactions involving chemical interactions and migrating ground water.

A model is an abstraction of reality that describes, in either qualitative or quantitative terms, a certain set of the complex interrelationships of the system being studied. A quantitative model is described herein as being either empirical or deterministic. An empirical quantitative model involves a statistical relationship between two or more variables. A deterministic quantitative model is based upon physico-chemical principles such as the law of conservation of mass.

In any given situation, the costs of management procedures to ameliorate environmental impacts can be determined with relative ease and accuracy. However, the results or benefits of such procedures can only be predicted with assurance if quantitative models, capable of predicting the response of the tailings to a given management strategy, are available.

The utility of such models for assessing the effects of tailings management alternatives on acidic fluxes is determined by the degree to which the models adequately abstract the coupled nature of hydrogeology and chemistry and are readily understood and applied in a particular use.

A variety of frameworks have been presented in the literature for evaluating the utility of a model, its capabilities and limitations.

Various investigators have presented their approach to the modelling process (e.g., Orlob, 1975). We find it most useful to use the following seven steps:

1) problem definition and objective formulation,
2) system abstraction and discretization (conceptual model, physical and chemical boxes),
3) model construction,
4) mathematical solution,
5) model calibration,
6) model validation, and
7) model prediction.

A model is constructed to fulfill certain objectives. Different objectives necessitate different spatial and temporal scales. For example, one's objective may be to develop a model capable of predicting how long into the future acidic fluxes from a tailings pile will be a problem. Alternatively, one's objectives may be to predict the seasonal change in pH in tailings porewater at a specific depth in the tailings pile. The former objective involves a time scale of years to decades while the latter involves a time scale of weeks or months. The spatial scale of the former objective is the thickness of the tailings mass while the spatial scale of the latter objective is 1 m or less. If one is particularly concerned with predicting the pH variation at the oxidation front, the spatial scale may be 0.01 to 0.1 m.

These examples illustrate particular points about the terminology: spatial scale, temporal scale. These "scales" represent the size of the "time block" or the "distance block" over which significant changes occur. They also become the size of the "time block" or of the "size block" (spatial scale) which is used for organizing the model.

System abstraction and discretization is the physical, biological and chemical representation of the tailings deposit. The system boundaries are selected based on field data which describe the physical, biological and chemical characteristics of the system and from data which describe the flows of mass or energy into and out of the system. Selection of the system boundaries is made to be consistent with the model objectives. A box (e.g., a layer of the unsaturated zone) is considered as one of a spatially distributed set of entities each of which has the capacity to store mass or energy; the total number of boxes describes the physical structure of the entire system.

A box is chosen such that flows of mass or energy occur between interconnected boxes, but such that spatial variations of mass or energy within the box are small. Thus, the tailings mass is divided into volumes (boxes) which are each sufficiently homogeneous such that physical, chemical or biological detail necessary for the realization of a model's objectives is not lost. In the RATAP model, the boxes consist of a number of layers, one lying above the other; for example, for 20 layers in the unsaturated zone and 2 layers in the saturated zone, the total number of boxes is 22.

A box is subdivided into compartments, each describing a different biological or chemical entity deemed to be important to fulfill the model's objective(s). Thus, each compartment describes a different form of mass or energy found within a box (e.g., iron concentration in the porewater, goethite or pyrite content of tailings solids, temperature, and oxygen content of air), and all the compartments within a box describe all of the forms of mass or energy stored within that box. Physical, biological and chemical flows of mass or energy may occur between interconnected compartments.

As Okubo (1971) notes, "the box model treats mixing "averaged" over each box and attempts to see changes only as between boxes. The mixing processes at the interfaces of the boxes are parametrically disguised as exchange - or transfer-rate constants with the dimensions of (t^{-1})." Okubo also notes that other investigators have found the well-mixed assumption unnecessary for successful box model application, and have related the box transfer-rate coefficients to advective and eddy diffusivity processes described in 1-D and 2-D transport models.

Construction of a model involves four basic steps:

1) identifying the physical, biological and chemical processes and the corresponding laws governing the rates of mass flow between compartments and/or boxes (e.g., pyrite oxidation, oxygen diffusion; gypsum precipitation or dissolution);

2) listing the assumptions made, including simplifications of physical laws;

3) constructing systems of mathematical equations which describe the behaviour of the system. The system of equations is constructed by writing a statement of conservation of momentum, energy or mass for each compartment in each box. For example, the rate of change of mass equals the difference between the rate of mass input and the rate of mass output; and

4) evaluating the boundary conditions.

The mathematical solution involves using an analytical solution or numerical solution for the system of equations to obtain the predictions made by the model. If computer techniques are used, the mathematical solution also involves code verification. Code verification is the process used to show that the mathematical equations have been properly coded in the computer language.

Model calibration consists of selecting a set of coefficient values from field measurements and/or literature values such that the model output duplicates a set of *in situ* measurements of some known system. The coefficients are constants describing empirical relations where fundamental laws are unavailable. Their uniqueness is partially a function of the spatial and temporal structure of the model. Selection of values for coefficients for which field measurements have not been made is usually done by varying the coefficient values over the range of reported literature values until satisfactory agreement is reached between model predictions and environmental observations. Coefficient values obtained from field measurements may also be varied if the modeler decides that a measurement does not describe conditions throughout a compartment. Alternatively coefficient values may be determined using an optimization method which minimizes the difference between model predictions and observations.

Model validation is discussed in Section 3.1.

Other models reported in the literature include those of the Rogowski group (e.g., Jaynes *et al.*, 1984a, b) and of the Ritchie group (e.g., Davis and Ritchie, 1986; Davis *et al.*, 1986). The questions addressed by RATAP.BMT have been defined and coded independently of these other modelling efforts. This has resulted in some similarities and some significant differences between the various modelling efforts.

2.1.1 Jaynes *et al.* Modelling Approach

Jaynes *et al.* (1984a, b) evaluated acidity fluxes from spoils associated with coal strip mines. Pyrite dynamics are based upon the total time required to oxidize all pyrite within a box in the discretized vertical profiles (one-dimensional).

"The rate of pyrite oxidation is assumed to be controlled by both first-order reaction kinetics and the combined diffusion rates of the products and reactants to the reaction site within shale blocks. Both oxygen and ferric iron may serve as the oxidant. Ferric iron concentrations are controlled by iron complexation and precipitation reactions that are assumed to be rapid and completely reversible. Ferric iron is assumed to be produced by both direct chemical oxidation of ferrous iron and oxidation of ferrous iron by autotrophic bacteria. Environmental factors which affect the bacterial "activity" are oxygen concentration, temperature, and solution pH. Fluctuations in the bacterial "activity" caused by changes in their environment are considered to be rapid so that their "activity" is always at its maximum. Pyrite oxidation and bacterial "activity" are linked through their modification of a shared environment."

"Oxygen is the ultimate electron acceptor for pyrite oxidation and is considered to be supplied to the profile by gaseous diffusion, from the surface first through the large pore spaces between the shale blocks then into the blocks to reach the reactive pyrite surfaces. Diffusion of oxygen in the blocks is implicit in the model. Sources for hydrogen ion include pyrite oxidation, iron complexation and precipitation reactions. Sinks for hydrogen ion include ferrous iron oxidation, hydrolysis of the rock matrix, and exchange reactions. These last two sink reactions are lumped together as one reaction in the model and given a pH dependence in the form of a simple empirical reaction. Carbonate neutralization reactions are not considered explicitly at this time. Hydrogen ion, ferrous and ferric iron and ferric complexes, sulfate and bisulfate, and solution "acidity" are leached from the spill profile by a constant water flux."

The major differences between the model of Jaynes *et al.* (1984) work and RATAP.BMT include the following concepts considered by RATAP:

- acid flux based on particle size distribution;
- mechanistic (rather than empirical) modelling approach;
- carbonate mineral interactions;
- mass balance on the various mineral phases;
- explicit inclusion of all relevant porewater cations and anions and use of the electroneutrality equation to calculate pH, rather than use of an empirical relationship of Jaynes *et al.* for calculating pH; and
- uncertainty analyses.

Jaynes *et al.* (1984) found that the oxidation of pyrite is primarily controlled by the oxygen diffusion rate. There is no evidence of kinetic control for any substantial period.

According to the RATAP model, the acidic flux depends on both the kinetics and oxygen transport. As time progresses, a quasi-steady state in oxidation is reached and the thickness of the oxidizing zone remains essentially constant. As the sulfide minerals are exhausted from the zones near the surface, diffusion control becomes more important and the RATAP concept becomes essentially identical with those employed by Jaynes *et al.* (1984).

2.1.2 Ritchie *et al.* Modelling Approach

The work of Ritchie's group is a landmark in the sulfidic mine waste literature which parallels the development of RATAP.

Their main objective was to calculate the acidic flux from tailings. They assume that the "oxidation rate is limited by the rate that oxygen is supplied to oxidation sites within the particles comprising the wastes. Oxygen supply is assumed to be controlled by diffusion through the pore space of the wastes followed by diffusion into a moving reaction front within the particles. An approximation is made which incorporates the effect of reaction of pyrite into the boundary conditions. A further approximation involving a pseudo steady-state simplification is made that allows an analytical solution to be formulated." The results predicted by this analytical solution are compared with the calculations of an earlier simpler model (Harries & Ritchie, 1983). The chemistry of the porewater is ignored.

In further work, two additional refinements were considered. "In the first, the limiting approximations were examined by developing a numerical solution to the set of equations for oxidation in pyrite mine wastes under natural conditions. The numerical solution allows one to examine oxidation at the moving front within the blocks comprising the wastes. Properties predicted by the numerical solution were compared with results predicted by an approximate analytical solution."

In the second refinement, "the assumption of just one initial size for pyritic blocks was relaxed to take proper account of the range of particle sizes in the wastes. Comparison of the simpler model with the more realistic model (i.e., incorporating the sulfide mineral) shows that for practical purposes the simpler model is good enough to assess the magnitude and longevity of the environmental impact of pollutant generation in the wastes. It is, however, essential to include the particle size distribution to obtain accurate estimates of the heat source distribution profile and to a lesser extent the oxygen concentration profile, two parameters that can be measured and used to assess the applicability of the model to the real field situation."

In an extension of this work (Bennett *et al.*, 1989) the convection and diffusion of oxygen into heaps was examined. "Both downward oxygen transport through the surface and horizontal movement in through the side were modelled. Measured values of pyrite oxidation were used to evaluate kinetics. The results show that for time scales smaller than about two years, diffusion is always an important oxygen supply process. For air permeabilities less than about 10^{-10} m^2 thermal convection is never a significant air transport mechanism at these early times but it is significant at permeabilities exceeding 10^{-10} m^2. For time scales longer than 2 years after establishing the heap, and at permeabilities less than about 10^{-10} m^2, thermal convection can become significant depending on the magnitude of other parameters such as heap size and pyrite content."

Similar to the findings of RATAP, oxygen diffusion is a dominant process controlling pyrite oxidation. However, their formalism does not allow one to assess the relative importance of kinetics versus diffusion upon controlling oxygen fluxes into the heap as readily as RATAP.

An overview of the different components addressed by each of these models is summarized in Table 2.1. In general, the models from the left column to the right most column represent a gradation from those which were developed to answer simple questions to those which were constructed to address more complex questions.

In terms of deciding whether a more complex model is required, the work of Ritchie's group indicates that for some questions, more complicated treatments (e.g., considering the particle size distribution of sulfide mineral blocks) do not give significantly different answers than simpler treatments (e.g., uniform sized pyrite minerals). However, a systematic evaluation of all possible simplifications is required before one can decide that a particular degree of detail is not required in a model.

To assist the MENDS committee in their evaluation of models, a systematic listing of simplifications for RATAP could be made. Then a comparison of RATAP's calculations with and without these simplifications could be made to determine whether particular modifications/simplifications are required for the model.

Welcome Screen Search Report List

Table 2.1

COMPARISON OF CAPABILITIES OF SEVERAL MODELS

Component	Jaynes *et al.*	Harries & Ritchie	Nicholson *et al.*, 1986	RATAP.BMT2
Sulfide Mineralization	Pyrite in shale blocks	Sulfide in blocks of rock	Pyrite particles	Pyrite, pyrrhotite, chalcopyrite, sphalerite and arsenopyrite particles
Sulfide Particle Size Distribution	No	No/Yes	No	Yes
Sulfide Mineral Oxidation Kinetics	Biological, chemical	Implicit as boundary condition	First order coefficient	Biological, chemical
Diffusion Coefficient/ Oxygen Transport	Constant inter-particle and through porous media	Constant inter-particle and through water in porous rock	Calculated from moisture content	Calculated from moisture content
Pore Water Chemistry	Yes	No	No	Yes
Neutralization	Semi-empirical	-	-	Thermodynamic/ kinetic
Mass Balance on Sulfide	Yes	Yes	Yes	Yes
Mass Balance Other Minerals	No	No	No	Yes
Effectiveness of Management Options	-	-	-	Yes
Uncertainty Analysis	No	No	No	Yes

Using the work of Ritchie's group and the RATAP.BMT as a base, the following summary can be made.

The work of Ritchie's group present an oxygen transport-control approach to model construction and testing. It involves defining the problem, assessing important mechanisms, and then making the appropriate modelling assumptions upon which the code formalism and model predictions are based. As even more questions are raised about the modelling assumptions, more complex models must be formulated to address these questions concerning the appropriateness of the original model. In the case of the more complex questions, Ritchie's work indicates that the original models were essentially "good enough" for the relatively simple questions being asked, but that the models required significant modification when the questions being asked, changed.

In reflection of questions addressed by the RATAP.BMT code, it addresses a larger number of questions and questions which are more complex than those addressed either by the work of Ritchie's group or by Jaynes' work. It permits evaluation of the limitations of the modelling work of these two respective investigators. RATAP.BMT permits evaluation of many additional questions which are beyond the scope of the questions evaluated by these investigators. But RATAP.BMT requires a more informed user and is harder for a novice user to obtain an understanding of the main processes controlling acidification reactions and the resultant transport of metals and anions.

2.1.3 The RATAP.BMT2 Modelling Approach

RATAP.BMT and RATAP.BMT2 were formulated to answer the following questions:

1. How much time is required to oxidize all pyrite in a tailings area?

2. How long will acid generation be a problem for a tailings area?

Or, more specifically:

i) How much time is required to oxidize most of the sulfide minerals in the unsaturated zone? (This is similar to question 1 above.)

ii) How much time is required before the acid generation flux decreases by one order of magnitude or two orders of magnitude to cause a substantially different geochemical regime than at present? For this interpretation, the same variables used for question 1 would be required.

iii) How much time is required before the acid flux reaches a specific level (e.g., x mol acid.m^{-2}.y^{-1}) which the environment can accept? (This question is addressed below under question 3.)

3. What is the acid flux from a tailings area?

4. What is the flux of acidity and toxic heavy metals from a tailings area?

5. What is the uncertainty in estimates of fluxes of acidity and metals from a tailings area?

The model considers the following processes:

- sulfide mineral oxidation kinetics as a function of water temperature, oxygen concentration, mass of pyrite, pH, phosphorous concentration, carbon dioxide content, and moisture content.
- oxygen pore-gas diffusivity and its control upon the oxygen flux into the tailings.
- shrinkage of sulfide mineral grains as they oxidize.
- depth-dependent differences in the chemical characteristics of the tailings.
- temperature variations with depth due to oxidation of pyrrhotite, pyrite, chalcopyrite, sphalerite and arsenopyrite.
- moisture variations with depth in the unsaturated zone.
- kinetic reactions between porewater and relevant minerals.
- porewater transport of metals including aluminum, iron, calcium, magnesium, potassium, silica, copper, zinc, and of anions including arsenic, sulfate, and carbonate.

The concepts adopted for modelling a tailings area are illustrated on Figure 2.1. The tailings soil profile is subdivided into the unsaturated zone, capillary fringe and saturated zone. Conditions conducive to the oxidation of sulfide minerals are limited to the unsaturated zone and top layer of the capillary fringe due to the barrier posed by water to oxygen transport. Hence, the characteristics of the tailings mass in the top horizon may be subdivided into twenty layers with each layer having its own distinct physical and chemical properties. In contrast, the saturated zone, which is a reducing environment, is modelled as either a one or two layer system depending on the flowpath assumed for the tailings porewater.

Precipitation entering the tailings is modelled to flow downward through the unsaturated zone and capillary fringe. On entering the saturated zone, a portion of the flow may be modelled as moving horizontally through the tailings mass and emerge as seepage passing through or beneath the perimeter dams while the remaining portion moves further downward into a subsurface aquifer beneath the tailings.

The rate and quantity of acid generated from the biochemical oxidation of sulfide minerals is dependent on a host of factors which have been extensively reported in the literature and were reviewed in an earlier report by SENES (1984). The RATAP.BMT2 code accounts for many of these factors and is based upon principles of mass balance, geochemical kinetics or equilibria, where appropriate, and solution transport to estimate the pH and the acidity of tailings porewater. The geochemical and biochemical formulations currently used in RATAP.BMT2 include three types of modelling expressions: a) dynamic expressions; b) equilibrium expressions; and c) empirical expressions.

Dynamic expressions are used for modelling time dependent processes. These include sulfide oxidation kinetics, mass transport (oxygen, water, chemical constituents) and energy (enthalpy) transport. The dynamic processes are evaluated for each tailings layer. Although the calculation procedure allows steady state approximation each month, the time dependence of these processes is an important feature of the model.

Equilibrium concepts are used in RATAP.BMT2 for modelling solid dissolution, aqueous speciation, ionic balance (neutralization/buffering), ion exchange, and adsorption processes. It is assumed that these reactions, although dynamic in nature, are sufficiently fast, so that the time scale may be neglected (i.e. processes are essentially instantaneous).

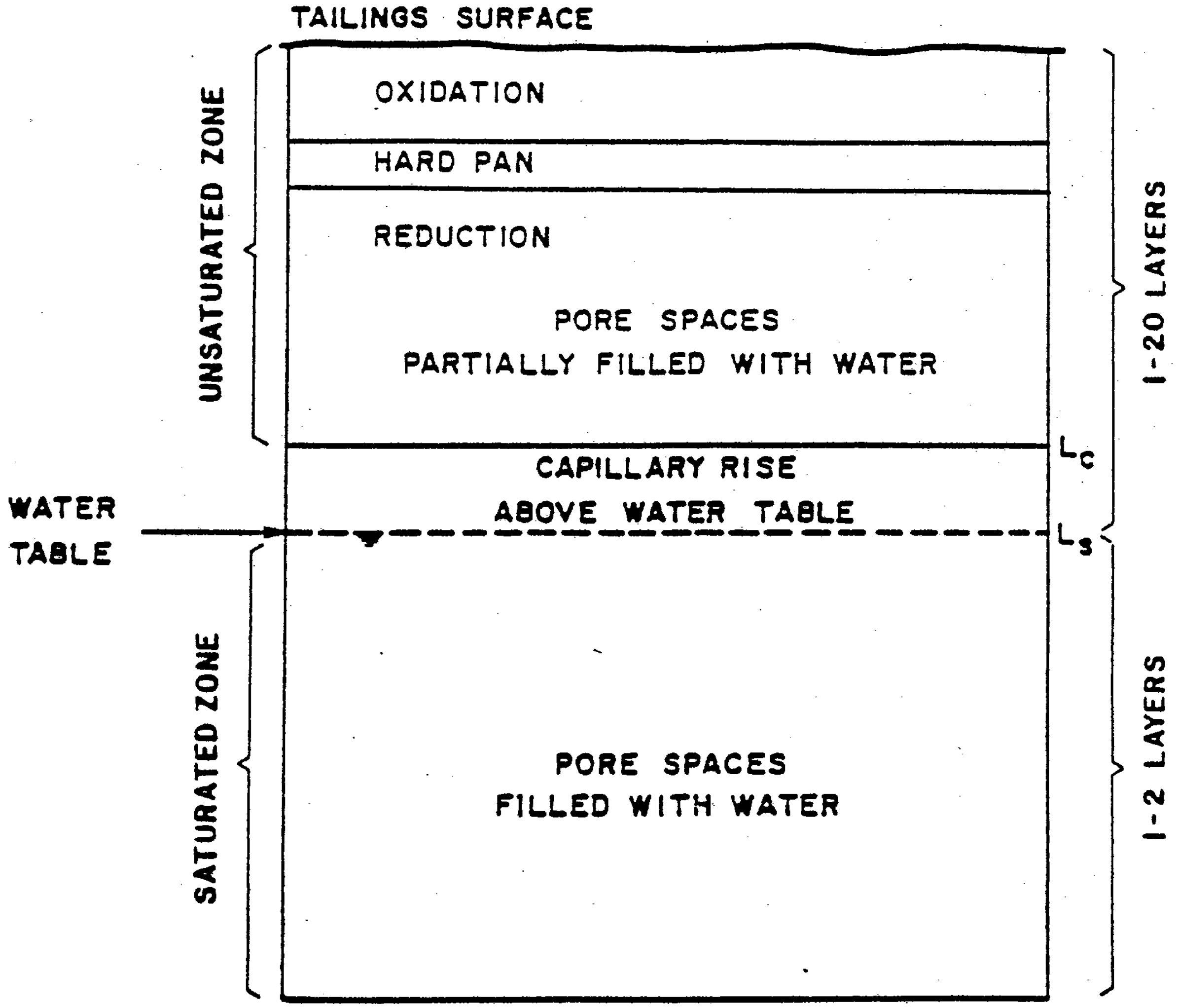
Empirical expressions are used to model periodic (seasonal) variations of temperature, and atmospheric precipitation. These natural processes are modelled by empirical expressions, which have no apparent physical significance (other than built-in periodicity).

In this section of the report, the concepts and theories incorporated into the RATAP.BMT2 code are critically reviewed to assess whether they are appropriate for the potential applications for

Welcome Screen | Search | Report List

FIGURE 2.1

CONCEPT ADOPTED
FOR MODELLING OF TAILINGS



which RATAP.BMT2 may be used, whether they need to be revised in light of current knowledge or whether they need to be expanded to include other factors or processes not included in the current version. Finally, the user-friendliness of the model and its potential use by the mining community are discussed.

2.2 Conceptual Considerations

2.2.1 Hydrogeology

Flow through a tailings pile is modelled in a very simplistic and straight forward manner. Precipitation landing on the tailings watershed is partitioned into a component which flows across and around the tailings area as surface flow and a residual component which penetrates the tailings and moves downward to the saturated zone. Tailings porewater entering the saturated zone is further partitioned into a component which moves horizontally through the tailings to emerge as seepage at the perimeter dams and a component which moves vertically downwind to join a deep subsurface aquifer.

To run the model, the user must specify the monthly infiltration rate, the fractional split in the flow between the horizontal and vertical flowpaths as well as the depth to the water table (i.e. phreatic surface). The user is then required to have a prior understanding of the hydrologic and hydrogeologic characteristics of the tailings area and the effects that closeout or reclamation options would have on these characteristics. An obvious question which may be posed here is: should the RATAP.BMT2 code include detailed hydrologic and hydrogeologic models? If so, what form should they take?

Given the structure of the RATAP.BMT2 model, we believe it would be unwise to incorporate detailed surface and ground water flow models into the code for several reasons. Firstly, analysis of flow conditions in a tailings area can be carried out independently, for the most part, of the evaluation of acid generation. Hence the analysis of depth to the water table, flowpaths and flow rates can be undertaken for any number of conceivable closeout options prior to selecting those options which offer most promise for full analysis. Once the hydrogeology of a tailings area is understood, the results can be adequately simplified for input into RATAP.BMT2.

Secondly, the expertise required to understand and run a hydrogeological model is quite different from that required to understand and run a biogeochemical model such as RATAP.BMT2. Consequently it will generally be necessary to involve at least two team members with appropriate expertise in the investigation.

Thirdly, the RATAP.BMT2 model treats a tailings area as a multi-layer system in contrast to the continuous three dimensional hydrogeologic models. The dimensions of the layers are fixed at the start of each run using RATAP.BMT2 to permit the mass inventory of sulfide minerals and chemical precipitates to be tracked with time. Also, the water table is set at a constant depth over the area being modelled. In reality, the depth to the water table will vary considerably across a tailings area as will the physical and chemical characteristics of the tailings. In applying the RATAP or RATAP.BMT2 models, it will often be desirable to subdivide a tailings area into several segments each of which has its own characteristics. Acid generation in each sub-area can then be assessed independently and aggregated to determine the overall total acid production for the entire area with time. This approach has been successfully applied to the Nordic tailings area in Elliot Lake, Ontario using the RATAP model.

2.2.2 Steady State Versus Non-Steady State

An implicit concept in the development of the RATAP models has been the assumption of steady state. This assumption was uniformly applied for each process. There were both theoretical and computational reasons underlying this concept. First, the key transport processes (for example, the diffusion of oxygen in the gaseous pore space) were shown to be significantly faster than the monthly time frame. On the other hand, the kinetic geochemical processes (pyrite oxidation) were significantly slower. Consequently, the system would either remain in the vicinity of or rapidly approach a steady state condition. It should be emphasized that the steady state approximations were performed on a monthly basis. The net effect of this monthly approach to steady state was a response profile that resembled a dynamic response.

A major advantage of the steady state approach is computational. The differential equations for a time-dependent system become algebraic relationships using steady state assumptions. These sets of algebraic equations are readily solved by standard, matrix based algorithms. On the other hand, the non-linear differential equations require numerical integration, which greatly diminishes the speed of the program.

The differences between the steady state approach and the unsteady state solution may be illustrated by the following simple example. Let us consider the following differential equation:

$$\frac{dy}{dt} = R(t) - \left(\frac{1}{\tau}\right) y \qquad (2.2.2\text{-}1)$$

where:

y = dependent variable
t = time
τ = first order time constant
$R(t)$ = time dependent rate

Discretizing the equation in monthly time steps results in the analytical solution illustrated in Table 2.2a. These calculations illustrate that both the overall trend and the mean values of the dependent variable are similar when calculated by the two methods. However, these calculations reflect a highly simplified situation and the validity of the steady state assumptions requires more extensive testing.

2.2.3 Constant Versus Variable Layer Depth

The dynamic events in RATAP were modelled by numerical methods based on finite differences and a "box" approach. The finite difference method (with forward differencing) was used to solve second order differential equations involving gaseous oxygen and energy (heat) transport through the tailings. Solute and liquid transport modelling was based on a numerical technique known as Thomann's controlled volume approach. Although this technique was originally used for modelling estuarine environments, it has been proven to be useful for many other situations. The tailings are treated as a series of segments extending from the surface to the hydraulically saturated zone. Conditions and porewater quality within each zone are assumed to be homogeneous and well-mixed. These assumptions within a segment do not preclude variability from one segment to another.

The application of the controlled volume approach to a modelled constituent in the tailings pore space results in the following differential equations:

TABLE 2.2a

COMPARISON OF STEADY STATE AND UNSTEADY STATE SOLUTIONS

Month	R(t)	Steady State Value	Unsteady State Value
1	1.59	1.59	1.44
2	5.00	5.00	3.69
3	7.07	7.07	5.83
4	8.66	8.66	7.62
5	9.66	9.66	8.91
6	10.00	10.00	9.60
7	9.66	9.66	9.64
8	8.66	8.66	9.02
9	7.07	7.07	7.79
10	5.00	5.00	6.03
11	1.59	1.59	3.22
12	0.00	0.00	1.18
Annual Mean		7.16	6.16

$$\frac{dC_i}{dt} = \frac{\Sigma\alpha_i R_i}{\epsilon_i} + \left(\frac{F_{i-1}}{\epsilon_i V_i}\right)C_{i-1} - \left(\frac{F_i}{\epsilon_i V_i}\right)C_i + \left(\frac{D_{e,i}}{\epsilon_i \bar{Z}^2_{i-1}}\right)(C_{i-1} - C_i)$$

$$+ \left(\frac{D_{e,i}}{\epsilon_i \bar{Z}^2_{i+1}}\right)(C_{i+1} - C_i) \qquad \text{if } C_i < C_{eq}$$

$$W_i = \Sigma\alpha_i R_i + \left(\frac{F_{i-1}}{V_i}\right)C_{i-1} - \left(\frac{F_i}{V_i}\right)C_{eq} + \left(\frac{D_{e,i}}{\bar{Z}^2_{i-1}}\right)(C_{i-1} - C_{eq})$$

$$+ \left(\frac{D_{e,i}}{\bar{Z}^2_{i+1}}\right)(C_{i+1} - C_i) \qquad \text{if } C_i = C_{eq} \qquad (2.2.3\text{-}1)$$

where:

C_i = concentration of constituent "i" in the pore pace
C_{eq} = equilibrium concentration of constituent "i" in the pore space
V_i = volume of tailings segment "i"
F_i = convective flow from tailings segment "i"
R_i = reaction rate/unit surface area in segment "i"
$D_{e,i}$ = effective diffusion coefficient in segment "i"
$\bar{Z}_{i-1}$ = distances between the midpoint of segment "i" and the midpoint of adjacent segment "i-1"
W_i = rate of deposition of precipitating constituent per unit segment volume
α_i = reactive surface area per segment volume
ϵ_i = porosity (gas filled or liquid filled) of segment "i"

Equation (2.2.3-1) contains advection, diffusion, and reaction terms. Usually, it is further simplified by considering the individual terms. For example, the advective terms are negligible

(F_i=0) in the case of gaseous oxygen transport, while the diffusive terms are neglected (D_e=0) in the case of liquid phase transport of dissolved ionic species.

The use of the controlled volume approach under steady state conditions has several advantages. The dimensions of the segment need not be uniform and this approach is very useful when variable sized segments are needed. In addition, the steady-state response matrix can be obtained with relative ease and the effect of changes in parameters can be easily studied. The current version of the RATAP model is one dimensional. However, the periodic steady state approach allows expansion to multi-dimensional configuration.

An important aspect of the numerical solution is computational stability. Divergence, often called numerical diffusion, results when step sizes are selected improperly.

The computational stability is more likely to be affected by step size in the case of dynamic (time dependent) calculations. Thomann (1972) has shown that the following inequality constraint is applicable:

$$1 + \frac{u}{Z_i} \Delta t \, (\beta - \tau) - \frac{2 \, D_e \, \Delta t}{Z_i^2} > 0 \qquad (2.2.3\text{-}2)$$

where:

$$\beta = \frac{Z_i}{Z_{i-1} + Z_i} \qquad \tau = \frac{Z_{i-1}}{Z_i + Z_{i-1}} \qquad (2.2.3\text{-}3)$$

Although the use of unequal tailings depths does not necessarily result in computational chaos, since sufficiently small time steps (Δt) will assure stability, it should be noted that for equal tailings depths, the inequality expression reduces to the following:

$$\frac{2 \, D_e \, \Delta t}{Z^2} < 1 \qquad (2.2.3\text{-}4)$$

The above inequality is always met when advective flow dominates (D_e = 0) and can be achieved for any other situation. In addition, the controlled volume based computational procedure can be compared with finite difference methods if equal tailings depth is used. For these reasons, there is an advantage for using equal tailings depths in case of dynamic adaptations of the current RATAP code.

The choice of using unequal versus equal depth sizes is somewhat subjective. The use of small step sizes in the unsaturated zone details the chemical events and provides a sharper focus on the oxidizing front (i.e. oxygen profile). However, uneven step size may lead to computational instability by the inadvertent use of large time steps with small depth steps.

In Table 2.2b, model predictions using constant and variable layer depths are compared. The comparison is performed at a total depth of 1.5 m in the tailings. Although most predictions are comparable, significant differences exist. The differences are most likely due to the unequal residence times arising from the variable depth segments. This can give rise to a "chromatographic effect" of having a high concentration front moving through the system. Recalling that the model calculates the spatial average in a segment, it may be argued that constant segment size is preferable. In the final analysis, the size of the segments should be a compromise between the degree of resolution of the tailings chemistry and computational stability.

2.3 Model Algorithm Development

2.3.1 Temperature

The function of this module is the estimation of temperature with depth in reactive tailings. The first version of the algorithm was part of the RATAP.BMT code. This original version did not work satisfactorily. The TEMP module was completely rewritten and was implemented in RATAP.BMT2 code issued in June 1989. The ensuing section describes a revised, improved version of the RATAP.BMT2 temperature estimation program.

Tailings Temperature Algorithm Development

The calculation of tailings temperature is based on an enthalpy balance. This balance can be expressed by the following partial differential equation:

TABLE 2.2b

COMPARISON OF CONSTANT AND VARIABLE LAYER DEPTHS ON MODEL PREDICTIONS (DEPTH = 1.5 m)

	Month = 1		Month = 22		Month = 120	
Constituent	Con	Var	Con	Var	Con	Var
Copper (mg/L)	0.07	0.11	0.01	0.39	0.46	2.1
Aluminum, total (mg/L)	0.11	0.11	0.11	0.11	0.11	23.2
Iron (III), total, (mg/L)	0	0	0.31	0.7	0.13	1.9

Con = Constant Layer Depths
Var = Variable Layer Depths

$$\rho C_p \frac{\delta T}{\delta t} = Q + k \frac{\delta^2 T}{\delta Z^2} + F_w C_w \frac{\delta T}{\delta Z} + \Delta H_{vap} \quad Ew \qquad (2.3.1\text{-}1)$$

where

ρ = density of the tailings ($kg.m^{-3}$)

C_p = heat capacity of the tailings solids ($J.kg^{-1}$)

Q = internal enthalpy generation ($J.m^{-3}.s^{-1}$)

k = thermal conductivity ($J.m^{-1}.s^{-1}K^{-1}$)

F_w = water flux ($mol.m^{-2}s^{-1}$)

C_w = heat capacity of water ($J.mol^{-1}$)

ΔH_{vap} = enthalpy of evaporation ($J.mol^{-1}$)

E_w = evaporative water loss ($mol.m^{-3}$)

T = temperature (K)

Z = depth into tailings from surface (m)

The first term on the right hand side represents internal heat (enthalpy) generation, while the subsequent terms express conductive, convective and latent (evaporative) enthalpy changes, respectively. As in the case of chemical and biological processes in the tailings, a monthly approach to steady state (i.e. $^{\delta T}/\delta t = 0$) is assumed. A numerical solution for steady state conditions is given as follows:

$$Q + \frac{k\,(T_{n-1} - T_n)}{(\delta Z)^2} - \frac{k\,(T_n - T_{n+1})}{(\delta Z)^2} + \frac{F_w C_w (T_{n-1} - T_n)}{\delta Z} + \Delta H_{vap} E_w = 0 \qquad (2.3.1\text{-}2)$$

The subscripts n-1, n, and n+1 represent the successive layers and increase with depth. δZ is the distance between the layers in question. It is assumed that the temperature profile of the tailings in the absence of pyrite or other sulfidic mineral oxidation is known, thus equation (2.3.1-2) need not be solved explicitly. A difference operator "Δ" is introduced so that ΔT represents a differential temperature rise in the tailings if active sulfidic ore oxidation takes place. Equation (2.3.1-2) may be easily rewritten in terms of this temperature difference:

$$Q_{Rx} + \frac{k\,(\Delta T_{n-1} - \Delta T_n)}{(\delta Z)^2} - \frac{k\,(\Delta T_n - \Delta T_{n+1})}{(\delta Z)^2} + \frac{F_w C_w (\Delta T_{n-1} - \Delta T_n)}{\delta Z} = 0 \qquad (2.3.1\text{-}3)$$

Equation (2.3.1-3) is subject to the boundary condition:

$$\Delta T_1 = 0$$

where

Q_{Rx} = enthalpy generation rate due to sulfide mineral oxidation ($J.m^{-3}.s^{-1}$)

The above boundary condition is based on the assumption that the surface temperature, which is controlled by wind, radiation and other factors is not affected by sulfide mineral oxidation.

Since evaporative (i.e. latent) heat losses largely depend on surface temperature, the difference in evaporative losses was neglected.

Solution of the set of algebraic equations (one equation for each layer) was implemented in the RATAP.BMT2 program by making the thickness of zones small and assuming initially that:

$$\Delta T_{n+1} = \Delta T_{n-1} \text{ for } n \neq 1 \tag{2.3.1-4}$$

The difference, ΔT_{n+1}, was re-evaluated as the calculations progressed to the layer below the current one. Using the above equality, equation (2.3.1-3) was rewritten to yield:

$$\Delta T_n = \frac{Q_{Rx}(\delta Z)^2 + F_w C_w (\Delta T_{n-1})(\delta Z) + 2k(\Delta T_{n-1})}{2k + F_w C_w (\delta Z)} \tag{2.3.1-5}$$

The calculation commenced with the second layer ($\Delta T_1 = 0$) using sulfide oxidation rates from one month previous (Q_{Rx}) for each mineral. The actual temperature was then obtained by the following:

$$T_n = T_{n,sb} + \Delta T_n \tag{2.3.1-6}$$

where

$T_{n,sb}$ = background tailings temperature in layer "n" (K)

Once the temperature is obtained, the reaction rates (Q_{Rx}) were re-evaluated in the kinetics module and the procedure was repeated until temperature convergence was obtained.

Several unforeseen problems were encountered during the running of the temperature module: the most serious problem was the slow convergence, often requiring 20 or more iterations. Temperature estimates for a particular location often fluctuated ± 10°C between each iteration. In addition, slight underprediction of temperatures from theoretical values for "steady state", long term situations was noted. These problems were largely overcome by a more efficient algorithm as described below.

Revised Temperature Algorithm for RATAP.BMT2

To develop a more efficient algorithm, equation (2.3.1-3) was rearranged as follows:

$$-\frac{k}{(\delta Z)^2}\Delta T_{n-1} + \left(\frac{2k}{(\delta Z)^2} + F_w C_w\right)\Delta T_n - \left(\frac{k}{(\delta Z)^2} + F_w C_w\right)\Delta T_{n+1} = Q_{RX} \qquad (2.3.1\text{-}7)$$

Let:

$$\frac{k}{(\delta Z)^2} = a_{n-1}$$

$$\frac{2k}{(\delta Z)^2} + F_w C_w = b_n$$

$$\frac{k}{(\delta Z)^2} + F_w C_w = c_{n+1}$$

The non-zero components (a_n, b_n, c_n) are stored as vectors and the entire temperature profile can be expressed as a tridiagonal matrix:

$$\begin{bmatrix} b_1 & c_1 & 0 & \cdots\cdots & & & \\ a_2 & b_2 & c_2 & \cdots\cdots & & & \\ & & & \cdots\cdots & & & \\ & & & \cdots\cdots & a_{n-1} & b_{n-1} & c_{n-1} \\ & & & \cdots\cdots & 0 & a_n & b_n \end{bmatrix} * \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \\ \cdots \\ \Delta T_{n-1} \\ \Delta T_n \end{bmatrix} = \begin{bmatrix} Q_{Rx(1)} \\ Q_{Rx(2)} \\ \cdots \\ Q_{Rx(n-1)} \\ Q_{Rx(n)} \end{bmatrix}$$

A very efficient algorithm has been developed for the tridiagonal matrix (TRIDAG) which will always succeed (Press *et al.*, 1988) for the following inequality:

$$|a|_n > |b|_n + |c|_n \qquad (2.3.1\text{-}8)$$

The TRIDAG matrix solution was very successful in accelerating the convergence and resulted in "smooth" temperature profiles. Typical results are shown in Table 2.3 to Table 2.4. For comparison, the temperature profiles generated by the original RATAP.BMT2 code are shown in Table 2.5 to Table 2.6. An obvious and previously unrecognized finding is the high sensitivity of the temperature prediction to the conductivity of the tailings (KSOIL).

This sensitivity is particularly remarkable for KSOIL<10^6 ($J.m^{-1}.mth^{-1}.K^{-1}$). Typical thermal conductivities may range from 1.5×10^5 to 1.5×10^6 $J.m^{-1}.mth^{-1}.K^{-1}$, hence, site dependent calibration will be important. It may be noted, that for the same KSOIL value, the TRIDAG matrix solution results in higher temperature predictions than the original RATAP.BMT2 method.

2.3.2 Sulfide Oxidation Mechanisms

The bacterial oxidation of sulfide minerals has been attributed to two mechanisms, namely, direct and indirect oxidative mechanisms. These mechanisms are by no means mutually exclusive. Their relative significance has been the subject of considerable discussion and conjecture. The direct mechanism involves an enzyme-mediated attack of the iron moiety, the sulfur moiety, or both if they occur in the same mineral to procure sulfate and/or ferric ion (Silver, 1987). In the case of chalcopyrite, for example, the stoichiometry of the reaction in acidic solutions is as follows:

Table 2.3

Temperature Profile with TRIDAG Matrix Solution. KSOIL = 10^5 J.m^{-1}.mth^{-1}. K^{-1}

						Month						
Layer	1	2	3	4	5	6	7	8	9	10	11	12
1	264.88	266.75	272.58	281.41	291.24	298.91	302.57	301.07	294.90	285.76	276.22	268.58
2	271.09	276.30	279.11	285.15	296.10	303.64	307.93	305.51	299.04	289.11	282.50	274.71
3	275.10	280.57	281.38	285.81	297.02	304.83	309.87	306.94	301.65	290.88	287.53	287.87
4	277.61	282.85	282.11	285.61	297.15	304.64	310.62	307.15	303.65	292.03	291.92	281.81
5	279.30	284.25	282.33	285.24	297.14	303.86	310.89	306.81	305.37	292.84	296.05	283.94
6	280.54	285.15	282.35	284.86	297.20	302.80	310.94	306.15	306.99	293.44	300.09	285.51
7	281.51	285.73	282.28	284.52	297.41	301.60	310.89	305.31	308.61	293.86	304.16	286.67
8	282.28	286.07	282.16	284.23	297.84	300.34	310.82	304.35	310.33	294.14	308.35	287.51
9	282.90	286.23	282.03	283.99	298.53	299.08	310.78	303.33	312.24	294.30	312.74	288.11
10	283.38	286.26	281.88	283.79	299.53	297.83	310.81	302.26	314.39	294.37	317.43	288.52
11	283.74	286.18	281.71	283.60	298.78	296.58	309.62	301.15	314.13	294.33	318.72	288.76
12	283.99	286.02	281.54	283.42	297.63	295.26	307.93	299.91	313.04	294.15	317.69	288.86
13	284.17	285.79	281.36	283.24	296.42	293.82	305.49	298.50	311.28	293.80	315.84	288.82
14	284.26	285.47	281.16	283.04	295.11	292.37	303.00	297.06	309.33	293.38	313.67	288.68
15	284.27	285.05	280.94	282.79	293.67	290.90	300.46	295.59	307.14	292.88	311.15	288.43
16	284.19	284.52	280.68	282.46	292.05	289.40	297.84	294.08	304.70	292.30	308.26	288.09
17	284.04	283.89	280.39	282.02	290.19	287.85	295.15	292.52	301.98	291.64	304.96	287.65
18	283.81	283.16	280.05	281.43	288.04	286.25	292.38	290.91	298.93	290.87	301.23	287.13
19	283.50	282.33	279.67	280.65	285.52	284.58	289.49	289.24	295.51	289.96	297.01	286.53
20	283.11	281.39	279.24	279.62	282.57	282.82	286.49	287.49	291.63	288.90	292.25	285.84

Table 2.4

Temperature Profile with TRIDAG Matrix Solution. KSOIL = 10^6 J.m^{-1}.mth^{-1}. K^{-1}

							Month					
Layer	1	2	3	4	5	6	7	8	9	10	11	12
1	264.51	265.89	271.82	280.77	290.41	298.02	301.63	300.28	294.30	285.35	275.77	268.15
2	266.39	267.40	272.21	280.29	289.56	296.95	300.88	300.12	294.71	286.83	277.88	270.33
3	268.03	268.50	272.33	279.58	288.48	295.60	299.92	299.59	294.94	287.91	279.63	272.21
4	269.49	269.45	272.41	278.90	287.38	294.21	298.89	298.89	295.04	288.73	281.13	273.86
5	270.83	270.34	272.55	278.31	286.33	292.84	297.85	298.09	295.04	289.36	282.44	275.34
6	272.07	271.20	272.75	277.83	285.37	291.54	296.81	297.25	294.95	289.84	283.57	276.68
7	273.23	272.03	273.00	277.45	284.50	290.31	295.81	296.37	294.78	290.18	284.57	277.88
8	274.32	272.84	273.31	277.16	283.74	289.17	294.86	295.48	294.56	290.40	285.44	278.96
9	275.34	273.61	273.66	276.96	283.09	288.12	293.96	294.59	294.29	290.53	286.20	279.92
10	276.30	274.36	274.04	276.84	282.40	287.15	292.85	293.71	293.86	290.57	286.71	280.79
11	277.18	275.07	274.45	276.78	281.79	286.26	291.74	292.84	293.31	290.53	287.08	281.55
12	278.00	275.76	274.88	276.78	281.27	285.46	290.68	291.99	292.72	290.41	287.35	282.22
13	278.75	276.42	275.33	276.84	280.82	284.70	289.64	291.15	292.11	290.24	287.53	282.80
14	279.44	277.04	275.78	276.93	280.43	284.02	288.66	290.34	291.49	290.02	287.64	283.30
15	280.07	277.63	276.23	277.07	280.11	283.41	287.74	289.57	290.87	289.76	287.68	283.74
16	280.64	278.18	276.68	277.23	279.84	282.86	286.88	288.83	290.24	289.47	287.67	284.10
17	281.15	278.69	277.12	277.42	279.62	282.37	286.08	288.12	289.62	289.16	287.60	284.40
18	281.60	279.17	277.56	277.62	279.44	281.95	285.32	287.45	289.01	288.82	287.49	284.64
19	282.00	279.60	277.97	277.84	279.30	281.57	284.62	286.82	288.41	288.46	287.33	284.83
20	282.35	280.00	278.37	278.06	279.18	281.24	283.96	286.22	287.82	288.09	287.13	284.97

Table 2.5

Temperature Profile with Original RATAP.BMT2 Code, KSOIL = 10^5 J.m^{-1}.mth^{-1}. K^{-1}

							Month					
Layer	1	2	3	4	5	6	7	8	9	10	11	12
1	264.47	265.80	271.74	280.69	290.31	297.92	301.53	300.19	294.24	285.28	275.72	268.10
2	266.92	268.80	273.61	281.52	290.55	298.04	301.30	301.03	294.74	287.46	278.28	270.87
3	268.97	280.57	274.31	281.24	289.95	297.17	300.46	300.90	294.93	288.84	280.24	273.06
4	270.69	271.83	274.62	280.71	289.07	296.03	299.43	300.40	294.95	289.85	281.81	274.91
5	272.19	272.92	274.88	280.21	288.13	294.83	298.32	299.74	294.86	290.60	283.13	276.53
6	273.54	273.95	275.16	279.80	287.22	293.64	297.18	299.00	294.66	291.17	284.24	277.99
7	274.79	274.93	275.49	279.47	286.38	292.52	296.05	298.21	294.38	291.59	285.19	279.29
8	275.96	275.89	275.87	279.24	285.62	291.45	294.94	297.39	294.04	291.88	285.99	280.47
9	277.05	276.80	276.28	279.10	285.59	290.49	295.38	296.57	294.33	292.06	287.41	281.51
10	278.08	277.68	276.72	279.02	285.09	289.63	294.69	295.79	294.27	292.22	288.22	282.49
11	279.03	278.51	277.19	279.02	284.61	288.83	293.88	295.02	293.94	292.25	288.76	283.34
12	279.91	279.30	277.68	279.07	284.22	288.29	293.00	294.27	293.55	292.24	289.23	284.11
13	280.73	280.07	278.18	279.18	283.90	287.64	292.23	293.51	293.05	292.14	289.55	284.76
14	281.48	280.80	278.69	279.33	283.66	287.06	291.48	292.79	292.57	291.99	289.80	285.34
15	282.18	281.50	279.21	279.53	283.47	286.56	290.79	292.09	292.07	291.80	289.98	285.84
16	282.81	282.17	279.72	279.75	283.35	286.12	290.16	291.44	291.57	291.58	290.11	286.28
17	283.39	282.79	280.22	280.00	283.28	285.75	289.63	290.85	291.09	291.34	290.19	289.69
18	283.91	283.38	280.72	280.27	283.25	285.44	289.12	290.28	290.60	291.08	290.22	287.01
19	284.37	283.94	281.20	280.56	283.27	285.18	288.66	289.74	290.13	290.80	290.24	287.30
20	284.79	284.45	281.67	280.85	283.32	284.97	288.25	289.24	289.68	290.52	290.21	287.52

Table 2.6

Temperature Profile with Original RATAP.BMT2 Code. KSOIL = 10^6 J.m^{-1}.mth^{-1}. K^{-1}

							Month					
Layer	1	2	3	4	5	6	7	8	9	10	11	12
1	264.47	265.80	271.74	280.69	290.31	297.92	301.53	300.19	294.24	285.28	275.72	268.10
2	265.99	266.74	271.75	279.86	288.90	296.36	300.23	299.63	294.46	286.44	277.40	269.92
3	267.45	267.60	271.76	279.05	287.54	294.81	298.90	298.93	294.53	287.36	278.88	271.59
4	268.84	268.45	271.84	278.35	286.29	293.32	297.58	298.16	294.49	288.11	280.20	273.14
5	270.16	269.31	272.00	277.78	285.15	291.92	296.30	297.34	294.35	288.72	281.37	294.57
6	271.42	270.18	272.23	277.32	284.14	290.62	295.06	296.50	294.13	289.19	282.40	275.89
7	272.62	271.06	272.53	276.98	283.24	289.41	293.87	295.65	293.83	289.55	283.31	277.10
8	273.76	271.92	272.88	276.73	282.56	288.31	292.90	294.80	293.56	289.80	284.09	278.21
9	274.84	272.78	273.28	276.56	281.89	287.31	291.85	293.96	293.19	289.97	284.80	279.25
10	275.85	273.62	273.72	276.50	281.31	286.40	290.85	293.13	292.77	290.05	285.37	280.16
11	276.79	274.44	274.18	276.49	280.83	285.59	289.92	292.32	292.32	290.07	285.86	280.99
12	277.67	275.22	274.67	276.54	280.43	284.87	289.04	291.54	291.84	290.02	286.26	281.73
13	278.49	275.98	275.17	276.65	280.12	284.21	288.22	290.78	291.34	289.91	286.58	282.38
14	279.24	276.71	275.68	276.80	279.87	283.63	287.47	290.05	290.84	289.76	286.82	282.96
15	279.94	277.41	276.19	276.99	279.68	283.13	286.78	289.35	290.33	289.58	287.01	283.47
16	280.57	278.07	276.70	277.21	279.56	282.69	286.14	288.70	289.82	289.36	287.13	283.90
17	281.14	278.69	277.20	277.46	279.48	282.31	285.57	288.08	289.32	289.11	287.21	284.28
18	281.66	279.27	277.69	277.72	279.45	282.00	285.05	287.50	288.83	288.85	287.24	284.60
19	282.13	279.82	278.16	278.01	279.46	281.73	284.58	286.95	288.36	288.57	287.23	284.86
20	282.55	280.32	278.63	278.30	279.50	281.51	284.16	286.45	287.90	288.28	287.19	285.08

$$2FeCuS_2 + 8.5\ O_2 + 2\ H^+ \dashrightarrow 2\ Fe^{3+} + 2\ Cu^{2+} + 4\ SO_4^{2-} + H_2O \qquad (2.3.2\text{-}1)$$

Both the oxidation of sulfide sulfur and the iron (II) moiety provide metabolic energy for the bacteria. Equation (2.3.2-1) implies net hydronium ion consumption. At pH values above 2.5, this is not observed experimentally. In fact, hydronium ions are re-generated by the hydrolysis and precipitation of dissolved iron (III) compounds:

$$\begin{aligned} &Fe^{3+} + H_2O \dashrightarrow Fe(OH)^{2+} + H^+ && (2.3.2\text{-}2)\\ &Fe^{3+} + 2H_2O \dashrightarrow Fe(OH)^{+}_{2} + 2H^+ &&\\ &Fe^{3+} + 3H_2O \dashrightarrow Fe(OH)^{0}_{3}\ (aq) + 3H^+ &&\\ &Fe^{3+} + 3H_2O \dashrightarrow Fe(OH)_3\ (s) + 3H^+ && \end{aligned}$$

The indirect mechanism entails oxidation by the ferric ion in solution. The reaction products in this case are often the sulfates of the sulfide mineral and elemental sulfur. For example, pyrite (FeS_2) may be oxidized by the ferric ion in the following manner:

$$FeS_2 + Fe_2(SO_4)_3 \dashrightarrow 3FeSO_4 + 2\ S^0 \qquad (2.3.2\text{-}3)$$

Equation (2.3.2-3) represents the partial oxidation of pyrite. Under certain conditions, elemental sulfur does not form in appreciable quantities and the reactions proceed to completeness (Lowson, 1982):

$$FeS_2 + 8\ H_2O + 14\ Fe^{3+} \dashrightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16H^+ \qquad (2.3.2\text{-}4)$$

The reaction given by Equation (2.3.2-4) does not involve oxygen. Iron (III) is a very aggressive oxidizing agent for many sulfides. The rate of the redox can exceed the oxygen dependent reaction rate. Oxygen is needed, however, in the biological re-oxidation of the ferrous ion:

$$2\ Fe^{2+} + 2\ H^+ + 1/2\ O_2 \dashrightarrow 2\ Fe^{3+} + H_2O \qquad (2.3.2\text{-}5)$$

It is the re-oxidation of the ferrous ion which provides the oxidative power to maintain continual pyrite oxidation by indirect means. Equation (2.3.2-5) is often regarded as the rate limiting process.

Bacteria are also capable of oxidizing elemental sulfur to sulfate. Several bacterial species are capable of oxidizing elemental sulfur, but *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* are the most active under acidic conditions (Arkesteyn, 1979):

$$2\,S^{o} + 3\,O_2 + 2\,H_2O \longrightarrow 4\,H^{+} + 2\,SO_4^{2-} \qquad (2.3.2\text{-}6)$$

Since elemental sulfur and metal sulfide possess exceptionally low solubilities in water, surface contact is required for bacterial action. The oxidative enzymes are located in the cytoplasmic membrane on the surface of the organisms. Attachment to the mineral is often accomplished through organelles known as pili. Intimate contact of the bacteria with mineral surfaces has been shown to occur with pyrite, chalcopyrite, galena and elemental sulfur.

Several authors have attempted to find relationships between the oxidation rates and physico-chemical properties of the mineral in question. Torma and Sakaguchi (1978) reported that the rate is dependent on the solubility constant of the mineral; higher solubility results in higher oxidation rates. This suggests that the reaction rate is dependent on the availability of sulfide or hydrogen sulfide in the aqueous phase:

$$\begin{aligned} &ZnS \longrightarrow Zn^{2+} + S^{2-} \qquad (2.3.2\text{-}7)\\ &S^{2-} + 2\,H^{+} \longrightarrow H_2S\ (aq) \end{aligned}$$

In the past, indirect oxidation was regarded as the principal means of mineral oxidation. However, significant oxidation rates of synthetic base metal sulfides without significant quantities of iron point to direct biological oxidation as the dominant mechanism. Studies with various inhibitors have lent further support to the importance of direct bacterial participation. For example, N-ethyl maleimiole (NEM) is known to inhibit the biological oxidation of sulfide sulfur, while sodium aride inhibits enzymatic iron (II) oxidation. Observations of reaction rates obtained by the selective use of these inhibitors, either individually or in combination, have shown that the abiological and enzymatic oxidation rates of sulfur and iron are additive.

Evidence for significant indirect oxidation has been given by Arkesteyn (1979). He has demonstrated that pyrite is oxidized indirectly via bacterial oxidation of dissolved ferrous ion to the ferric state. Bacteria and the ore were separated by a dialysis membrane. The ferric ion produced by bacterial activity diffused through the membrane and reacted with the pyrite. The overall rate of pyrite oxidation was less than in the case of direct contact with the mineral. However, in both cases, the reaction rate was greatly reduced as the pH increased to 5.0.

Unlike direct oxidation, indirect mechanisms may result in the oxidation of arsenides, silicates, selenides, and other non-sulfide minerals. Although chemical oxidation can be significant, the reaction rates are greatly increased if bacteria are present. Lacey and Lawson (1970) have estimated that the rates may be some 500,000 times greater in the presence of bacteria. Although this degree of enhancement has been observed under controlled laboratory conditions only, the importance of biological activity on mineral dissolution in natural environments has been firmly established. Five sulfides have been selected for incorporation in the model: pyrite, pyrrhotite, chalcopyrite, sphalerite and arsenopyrite.

2.3.3 Sulfide Oxidation Kinetics

Numerous investigations into the mechanisms and kinetics of bacteria-assisted sulfide oxidation have been carried out (MacDonald and Clark, 1970; Dugan and Randles, 1971; Torma *et al.*, 1972; Wong *et al.*, 1974; Hoffmann *et al.*, 1981; Tributsch and Bennett, 1981; Brown and Forshaug, 1983; Jaynes *et al.*, 1984a,b). For a heterogeneous reaction involving reactive solids such as pyrite, the specific reaction rate is normally defined (Aris, 1969) as:

$$R = \frac{-1}{A} \frac{dN_s}{dt} \qquad (2.3.3\text{-}1)$$

where

R = the specific reaction rate ($\text{mol.m}^{-2}.\text{mth}^{-1}$)

A = the tailings particle surface area (m^2)

t = time (mth)

N_s = amount of sulfide (mol)

Assuming spherical symmetry, the decrease of particle size with time becomes:

$$\frac{dr}{dt} = \frac{R}{P} \qquad (2.3.3\text{-}2)$$

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where

r = particle radius (m)
R = sulfide oxidation flux ($mol.m^{-2}.mth^{-1}$)
P = molar density of the sulfide mineral ($mol.m^{-3}$)

Rearranging Equation (2.3.3-2) and solving for the sulfide content in the solid phase results in:

$$\left(\frac{N_{s,t}}{N_{s,t_o}}\right)^{1/3} = 1 - \frac{R}{P\, r_o}\, t \qquad (2.3.3\text{-}3)$$

where

N_{s,t_o} = the initial amount of sulfide at time "t_o" (mol)

$N_{s,t}$ = amount of sulfide at time "t" (mol)
r_o = initial radius of the sulfide particle (m)

Those factors which have an important influence on the rate of sulfide oxidation described by the above equations are oxygen transport and sulfide surface area (particle size).

Equation (2.3.3-3) is applicable for uniformly sized particles of known initial radius. For calculating the sulfide oxidation rate in tailings, a Paretto-type particle size frequency function is useful:

$$F(r) = A\left(\frac{r}{r_m}\right)^{\alpha} + B\left(\frac{r}{r_m}\right)^{\beta} \qquad (2.3.3\text{-}4)$$

where
$F(r)$ = cumulative particle size distribution function (mass fraction of particles having a radius less than "r")
r_m = maximum radius

Using Equation (2.3.3-4) together with Equations (2.3.3-1) and (2.3.3-2), the molar mass of

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pyrite at any time "t" may be estimated by the following polynomial expression:

$$\frac{N_{s,t}}{N_{s,o}} = 1 + Q_1\left(\frac{\Sigma kt}{r_m}\right)^{\alpha} + Q_2\left(\frac{\Sigma kt}{r_m}\right)^{\beta} + Q_3\left(\frac{\Sigma kt}{r_m}\right) + Q_4\left(\frac{\Sigma kt}{r_m}\right)^{2} + Q_5\left(\frac{\Sigma kt}{r_m}\right)^{3} \qquad (2.3.3\text{-}5)$$

where

$k = \frac{R}{P\,r_o}$ (see Equation (2.3.3-3))

The constants $a_1 \ldots a_5$ can be readily calculated from the parameters of the size distribution function. It is noteworthy that Equation (2.3.3-5) is analogous to Equation (2.3.3-3) for conditions involving variable particle size. Equation (2.3.3-5) may be easily modified for variable environmental conditions which, in turn, affects the reaction rate. In case of a variable environment, the rate constant k_t for a given time period is evaluated recursively and the term "$k_o t$" in equation 2.3.3-5 is replaced by:

$$k_o t = \sum_{n=0}^{N} k_t \, \Delta t \qquad (2.3.3\text{-}6)$$

Δt = time period (month)

The term, k_t, is usually evaluated at monthly intervals.

2.3.4 Solute Transport

Several models have been developed which predict the transfer of aqueous species in the unsaturated zone, e.g. Femwater/Femwaste (Yeh and Ward, 1979). These are based either upon a steady state or non-steady state approach.

Generally a zonal approach is used. The space is partitioned into various zones, and the law of mass balance for a dissolving substance becomes:

$$V_t \frac{dC}{dt} = q\,C_{in} - qC + r\,V_t \qquad (2.3.4\text{-}1)$$

where

V_t = porewater volume per unit area of tailings ($m^3_{water} \cdot m^{-2}_{tails}$)
C = concentration in porewater ($mol.m^{-3}$)
q = infiltration rate ($m.mth^{-1}$)
C_{in} = concentration in infiltrating rain water ($mol.m^{-3}$)
r = dissolution rate ($mol.m^{-3}.mth^{-1}$)

If the volume of water, infiltrating concentration, or dissolution rate changes substantially from timestep to timestep, then non-steady state conditions are evaluated. For this work, an approach to steady state conditions is assumed, resulting in an equation as follows:

$$C = \frac{q\,C_{in} + r\,V}{q} \qquad (2.3.4\text{-}2)$$

Equation (2.3.4-2) is known as a "mixing cell" model, since concentrations and conditions within a layer are regarded to be uniform. An alternative approach using no assumptions of uniformity gives rise to much more complex expressions. Such a model was used in UTAP (SENES, 1987). However, it may be shown that the mixing cell and the "plug flow" models give essentially identical results when a sufficient number of layers (usually more than 12) is employed.

The calculation of aqueous transportation depends upon the presence or absence of equilibrium between the solid phases and solution. Equation (2.3.4-1) assumes that equilibrium does not exist between solid phase and solution. For conditions when equilibrium does exist, the concentration of the constituent in the layer and leaving the given layer becomes:

$$C = C_{eq} \qquad (2.3.4\text{-}3)$$

where

C_{eq} = the calculated equilibrium concentration ($mol.m^{-3}$).

The mass balance above the cell affects the mass of solid phase present. It is:

$$\frac{dM}{dt} = q\,C_{in} + r\,V_t - q\,C_{eq} \qquad (2.3.4\text{-}4)$$

where

M = the mass of solid per unit volume of tailings (mol.m^{-3})

For certain ions such as aluminum and iron (III), C_{eq} is a function of pH when the solid phases basaluminite and iron hydroxide occur in the tailings. This necessitates a mathematical solution of the mass balance for certain ions (e.g. K^+, Fe^{2+}), a mathematical solution of the electroneutrality equation to define C_{eq}, and solids mass balance calculations. Thus, portions of the mathematical solution for the mass balance, solids mass balance and the electroneutrality equation must be conducted simultaneously or iteratively.

2.3.5 Aqueous Speciation

The objective of the aqueous speciation module is to calculate the pH of the solution for a given composition. This calculation is based upon the electroneutrality equation which is derived from the principle of charge balance. This principle basically states that a solution must be electrically neutral and hence that the sum of positive charges in solution must equal the sum of negative charges in solution.

For ions present in leachate from the base metal tailings, the following is the electroneutrality equation:

$$\begin{aligned}
[H^+] &+ 2[Ca^{2+}] + 3[Fe^{3+}] + 2[FeOH^{2+}] + [Fe(OH)_2^{+}] + [FeSO_4^{+}] + 2[Fe^{2+}] \\
&+ 3[Al^{3+}] + 2[AlOH^{2+}] + [Al(OH)_2^{+}] + [AlSO_4^{+}] + [K^+] \\
&= [HCO_3^-] + 2[CO_3^{2-}] + 2[SO_4^{2-}] + [Fe(OH)_4^{-}] + [Al(OH)_4^{-}] + [NO_3^{-}]
\end{aligned}$$

(2.3.5-1)

In the above equation, copper, zinc and arsenic are not included since they are assumed to be trace metals and hence have a negligible impact on the charge balance.

In Equation (2.3.5-1), the brackets [ ] represent the concentrations of these ions in solution. By balancing the concentrations of all other ions in solution, the H^+ concentration and hence the pH can be calculated directly.

However, the problem is complicated by the different procedures required to estimate the concentration of the other cations and anions. First, various ions are themselves a function of the pH. Iron (III) and aluminum hydrolyze to form various hydrolytic complexes. For example, the reaction:

$$Al^{3+} + H_2O = AlOH^{2+} + H^+ \qquad (2.3.5\text{-}2)$$

describes the hydrolysis of Al^{3+} to form $AlOH^{2+}$ and H^+. Second, various ions may be estimated from solution mass balance principles (e.g. potassium) while others (e.g. Al^{3+}, Fe^{3+}, Ca^{2+}) may be estimated from equilibrium principles. Ions are estimated from equilibrium principles if a solid phase is present, which contains the same chemical species at the identical oxidation state (valence number). If the solid phase completely dissolves, the solution mass balance is used to estimate the ion concentration. The equilibrium solution concentrations are a function of pH for various ions (e.g. aluminum and iron). For example, the solubility of iron is a function of pH according to the following precipitation reaction:

$$Fe^{3+} + 3H_2O = Fe(OH)_3(s) + 3H^+ \qquad (2.3.5\text{-}3)$$

To estimate pH, the overall electroneutrality equation must be phrased as a function of pH and appropriate total solution concentrations or solid phases, and then solved mathematically for pH. This requires that an iterative solution be used to solve the basic equations.

2.3.6 Oxygen Transport

Oxygen may be transported into porous media such as tailings by advection and/or diffusion. In the saturated zone of tailings, the diffusive transport of oxygen through the air phase is the dominant transfer mechanism. In the capillary fringe and saturated zones of the tailings, the dominant transfer mechanism is the advection of oxygen dissolved in the infiltrating porewater.

Oxygen consumption internally in the tailings is caused mainly by sulfide mineral oxidation (i.e. by oxidative dissolution of pyrite, pyrrhotite, etc.). Small net amounts of sulfide mineral dissolution occurs in the water-filled portion of the tailings by Fe^{3+} attack upon the minerals and the reduction of Fe^{3+} to Fe^{2+}.

To account for these processes, the following assumptions are presently made in the RATAP.BMT2 model:

1) The dominant variation in oxygen concentration occurs vertically from the air-tailings boundary downward. Any horizontal variability in oxygen concentration around the dams of the tailings pile are negligible.

2) Sulfide mineral oxidation occurs completely in zones where oxygen is present, resulting in Fe^{3+} and SO_4^{2-} as end products (i.e. Fe^{2+} and sulfide in the sulfide minerals are fully oxidized to their highest oxidation state, Fe^{3+} and SO_4^{2-}). Thus, oxidation occurs in tailings layers containing gas-filled spaces and in the upper boundary layer of the water-filled zone where dissolved oxygen is present.

3) Some additional sulfide mineral dissolution occurs in the anoxic zone of the water-filled layers due to the flux of Fe^{3+} into the layers from above. This has an effect upon the solution electroneutrality balance but not upon the oxygen balance.

4) The rate of vertical transport of oxygen is much faster than the rate of sulfide mineral oxidation. Accordingly, over the time frame of variation calculated by the model (one-month), steady state conditions exist. This results in the following equations:

   a) for the gas-filled region where all air diffusion controls transport:

$$D_e \frac{d^2C}{dx^2} - R = 0 \qquad (2.3.6\text{-}1)$$

b) for the water-filled boundary layer below the gas-filled region where advection controls transport:

$$V \frac{dC_w}{dx} - \frac{R}{n_w} = 0 \qquad (2.3.6\text{-}2)$$

where:

D_e = gas diffusion coefficient of oxygen ($m^2 . mth^{-1}$)
C = gas concentration of oxygen ($mol.m^{-3}$)
C_w = aqueous concentration of oxygen ($mol.m^{-3}$)
x = distance in the vertical direction (m)
R = oxygen consumption rate ($mol.m^{-3}.mth^{-1}$)
n_w = volumetric soil water content ($m^3{}_{water}.m^{-3}{}_{tailings}$)

Welcome Screen | Search | Report List

3.0 VALIDATION OF THE MODELLING APPROACH

3.1 Approach to Model Validation

Model validation consists of using the calibrated model to predict one or more sets of system conditions independent of the first set. If the validation is acceptable, then the model may be used, with confidence, to make predictions for purposes described in the model objectives. If the validation is not acceptable, then the model should not be used to make predictions where one requires much confidence in the predictions. If the validation is not acceptable, it may be necessary to modify the model with respect to its assumptions, or mathematical basis. Further, if the model is to be used for research purposes (to determine the most important factors in the model) or for extrapolation purposes, it must be done with care as one's confidence in the results may be fair to poor.

For model validation, several tests are possible. The first (least severe and insufficient) test is to compare the model structure (compartments and intercompartment mass flows) with the real world to determine that functional responses are reasonable and that all major factors are included. A second test involves comparing model predictions and environmental observations for one tailings pile for one time period (e.g., for a month or year) equal to or longer than the time scale of the model's objectives. A third (more severe) test involves two possibilities: (i) a comparison between model predictions and environmental observations for several tailings piles and/or (ii) a comparison between model predictions and observations from one tailings system for a time period equal to several time scales. A fourth test involves comparison between model predictions and observations for several time scales on one tailings system and for one time scale on several tailings systems. The standard used to determine the adequacy of agreement between model predictions and observations may be either qualitative (e.g., judgment of reasonableness) or quantitative (e.g., use of an appropriate statistics and lack of fit tests). To the present time, most model validation efforts have been qualitative.

Model validation was based on the comparison of model predictions for selected parameters to data collected on the Waite-Amulet tailings during the Phase 2 and Phase 3 field studies (Siwik, 1986; Siwik *et al.*, 1987; Blowes and Jambor, 1989). The database was compiled, reviewed and tested for spatial homogeneity and temporal variability. Part of the data was used to calibrate the site dependent parameter estimates. The second part of the data was used to verify the model both in the temporal and spatial (i.e. with respect to depth) sense. Several constituents were modelled, however, only the results of porewater pH and ferrous iron predictions are included in the comparisons presented in this report. The predictability of each parameter was assessed by qualitative comparison of the simulations and field observations.

The final test involved running the model both in a deterministic and probabilistic manner. The probabilistic simulations were based on selecting parameter values from established distribution functions. The geometric mean values of the probabilistic outputs were used for comparison to the results of the deterministic runs using nominal parameter values.

3.2 Review of Previous Validation Efforts

In developing the original RATAP code, an extensive verification, calibration and validation program was carried out. Considerable use was made of data reported in the published literature and of field data collected at the Nordic uranium tailings area in Elliot Lake, Ontario. In modifying RATAP for base metal tailings applications, each of the eight component modules which comprise the RATAP.BMT1 version was modified, tested and quality assured before being integrated into the overall code to maintain the integrity of the model. Where applicable, the modules were calibrated and validated against the data base employed in the previous study. In addition, field data collected in recent years on the base metal tailings at the Waite Amulet site near Noranda-Rouyn, Quebec were employed in the model calibration and validation.

Sufficient field data at Waite Amulet were available to achieve partial calibration of the model. Predicted and measured values were found to be comparable for the solid phase pyrite and pyrrhotite contents and the gaseous phase oxygen content. The porewater pH predictions were acceptable but did not match the measured data as well as the solid and gaseous phase components. It was not practical to draw firm conclusions about the adequacy of the model predictions, however, as only a limited amount of data has been collected at Waite Amulet on certain key characteristics of the tailings. Specifically, measurements on the solid phase composition of the tailings have been made at only one location and these data showed considerable variation with depth. In addition, the results of measurements which have been made on the chemistry of the porewater in the unsaturated zone were not available at the time of this study. Also, no measurements have been made of temperature profiles in the tailings nor of the water content with depth.

To summarize, the RATAP model was successfully adapted for prediction of acid generation from base metal mine tailings. The model accounted for acid generation from the oxidation of pyrite, pyrrhotite, chalcopyrite, sphalerite and arsenopyrite; other sulfide minerals could be added in the future as required.

3.3 Extension of Validation with Waite Amulet Data

3.3.1 Characterization of the Initial Condition of the Tailings

An important aspect of the study of the geochemistry of inactive tailings impoundments is the assessment of the initial nature of the tailings solids and porewaters as they were deposited. This initial condition, which provides the basis for all future geochemical changes in the tailings, cannot be directly assessed because the mill at the Waite Amulet site closed in 1962. The initial condition of the tailings can be inferred, however, from knowledge of the milling process and from examination of tailings solids and tailings porewaters that have not been affected by sulfide oxidation.

Tailings water samples obtained from piezometers located deep in the tailings are likely to contain concentrations of dissolved constituents similar to those of the mill process waters discharged with the tailings. Porewater chemical analyses from two deep piezometers, (Siwik *et al.*, 1987) indicated that the water near the base of the impoundment is neutral in pH, and contains high concentrations of Na, Ca, SO_4 and lower concentrations of dissolved metals including Fe, Pb, Zn and Cu. This is similar to the composition expected for the mill process water (Blowes and Jambor, 1989).

An initial examination of the mineralogy in the unsaturated zone indicated that below the water table where there was minimum alteration, there was 60% pyrite and 14% pyrrhotite (Siwik *et al.*, 1988). CO_2 analysis and mineralogical studies indicated that at least trace amounts of carbonate minerals, principally calcite, are present throughout the unaltered tailings (Blowes and Jambor, 1989). Tables 3.3.-1 and 3.3-2 list some of the physical properties of Waite Amulet tailings.

TABLE 3.3-1

PHYSICAL PROPERTIES OF WAITE AMULET TAILINGS

Grain size (mm)	0.2[1]
Initial oxygen activity at the tailings surface (atm)	0.21[1]
Initial concentration of arsenopyrite (mass fraction)	0.005[2]
Initial concentration of basaluminate (mass fraction)	0.0001[2]
Initial concentration of calcite (mass fraction)	0.0003[2]
Initial concentration of chalcopyrite (mass fraction)	0.003[2]
Initial concentration of ferric hydroxide (mass fraction)	0.001[2]
Initial concentration of gypsum (mass fraction)	0.0005[2]
Initial concentration of sphalerite (mass fraction)	0.005[2]
Initial concentration of sericite (mass fraction)	0.05[2]
Initial concentration of pyrite (mass fraction)	0.6[3]
Initial concentration of pyrrhotite (mass fraction)	0.14[3]

Note

1 Blowes and Jambor, 1989.
2 SENES and Beak, 1989.
3 Petruk and Pinard, 1986.

Welcome Screen Search Report List

TABLE 3.2-2

TAILINGS PROPERTIES AT WAITE AMULET BOREHOLES
(Blowes and Jambor, 1989)

	WA17	WA22
Depth to Water Table (m)	2.75	6
Depth to Clay (m)	11	11

3.3.2 The Sampling Program

Of the eight oxygen-concentration profiles measured at the Waite Amulet site, Blowes and Jambor (1989) considered five (WA2, WA8, WA20, WA21, WA24) unacceptable for comparison with O_2 profiles predicted using the model of Davis and Ritchie (1986). Measured on the benches of the impoundment, profiles WA20 and WA21 were subjected to compaction during dam construction. Because profiles WA2 and WA8 were saturated to within 20 cm of the tailings surface, they contained fewer than 2 data points. A clay layer at profiles WA8 and WA24, 20-40 cm thick, was placed over the tailings during the vegetation program. Of the remaining three sites (WA11, WA17 and WA22), two were chosen for validation.

WA17

At this location, two sections, totalling 300 cm, were cored. From the initial 100 cm section, 80 cm of core were recovered and divided into 5 equal sections, each assumed to be 20 cm. From this section, porewater samples are collected from 0 to 40 cm and 80 to 100 cm intervals. No water could be expressed from the core sections from 40 to 80 cm. A second core was taken from 100 to 300 cm, from which 200 cm were recovered and divided into 10 equal sections. Pore water samples were expressed from all sections of this core.

WA22

Site WA22 is located on the southern edge of the tailings where the water table is at a greater depth than at most of the other sites. A total of 600 cm of core, in three sections, was taken at this location. "The first section was cored from 0 to 100 cm, with a full 100 cm recovery. Samples were obtained from all sections squeezed except the section from 80 to 100 cm. The second core was taken between 100 and 300 cm, with full recovery, and divided into 10 equal sections. Samples were expressed from all core sections except for the two sections between 180 and 220 cm. The final core was taken from 300 cm to 600 cm, with full recovery. The last 300 cm was divided into 12 sections, each 25 cm long. Samples were obtained from each of the sections squeezed from the final core" (Blowes and Cherry, 1987).

3.3.3 Model Validation

Model validation using the Waite Amulet tailings as the test case involved running RATAP.BMT to predict pH and ferrous iron concentrations at two locations. All input parameter values were held constant between the two locations with the exception of the depth to the water table which was set equal to 2.75 metres for WA 17 and 6 metres for location WA 22. While it was recognized that there were differences in the tailings characteristics between the two locations, there was insufficient basis for changing any of the parameter values. RATAP.BMT runs were performed for one deterministic run at each location and 25 probabilistic runs at each location. The results of these runs are discussed below.

WA22

The data from this borehole was used to calibrate the model. Field data shows that "the pH in the top 1 m of core rises sharply from 3.42 in the uppermost section (Figures 3.1 and 3.2) to about 5.0 at 80 cm, then rises more slowly to a relatively constant value of about 6.4" (Blowes and Cherry, 1987). Predicted pH values agree well with measured values as indicated on Figure 3.1 for the deterministic model run and Figure 3.2 for the probabilistic model run. Both the deterministic and probabilistic model runs show more abrupt pH change with depth than is suggested by the field data.

There is good agreement between predicted and measured ferrous iron values as evidenced from the plots on Figures 3.3 and 3.4. The sharp reduction in the ferrous iron concentration between 2 and 3 metres below the tailings surface mimics the sharp rise in pH from about 4.5 to 6.5 - 7.0. This pH change contributes to the precipitation of dissolved ferrous iron as ferrous hydroxide.

The plot of the probabilistic model run includes error bars which span one standard deviation about the mean values. These error bars were calculated from the results of 25 probabilistic runs and represent the uncertainty in the predicted values due to uncertainty in the model input values, specified as distributions rather than constants. The large uncertainties predicted at a depth of 2 to 3 metres in the tailings pile are not unexpected but rather reflect the range in values which could be measured at this depth depending on the particular values selected for the input parameters.

WA 17

"The sampling program was conducted in the late fall of 1987, during a period of mixed snowfall and rainfall. The samples from WA17 were collected shortly after snowmelt had occurred, while samples from most other locations were collected through the unmelted snow cover" (Blowes and Cherry, 1987). The unusual pH values in the near surface area suggest that the water expressed from the uppermost core may reflect recently infiltrated rain or snow melt water. Below the top 100 cm the pH rises to a level between 5.0 and 6.0 (Figures 3.5 and 3.6), similar to other sites at Waite Amulet (Figure 3.1). There is reasonable agreement between predicted and measured pH values, although the lower predicted values in this case suggest that more buffering capacity may have been available at this location than was assumed. The starting mineralogical composition at WA 17 was assumed to be identical to WA 22 since location specific data were not available. A better fit of observed and predicted values could have been obtained by adjusting some of the input parameter values.

The ferrous iron concentrations plotted on Figures 3.7 and 3.8 show that the predicted values agree well with the measured values. It is noted that the measured values at WA 17 were significantly higher than measured at WA 22, and the predicted values (deterministic and probabilistic) follow the same trend.

Welcome Screen Search Report List

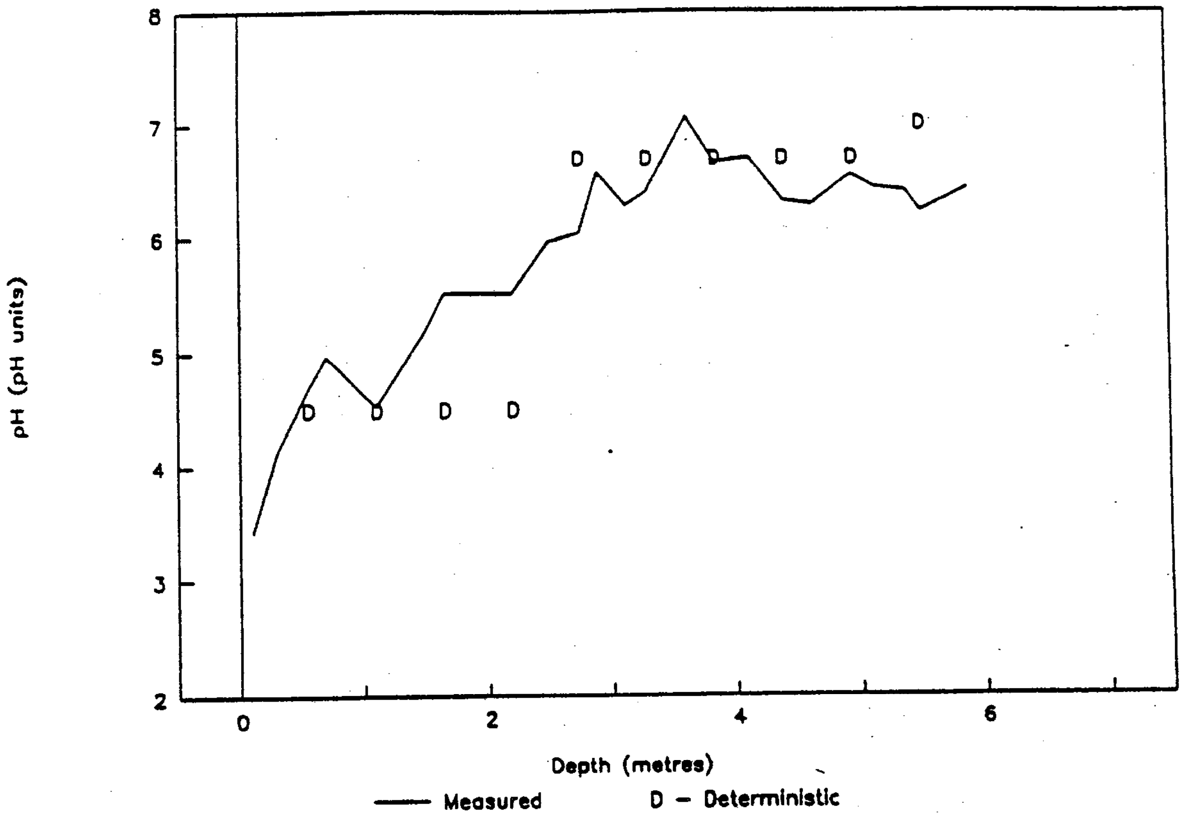

Figure 3.1 WA 22 - pH versus Depth - Deterministic Run

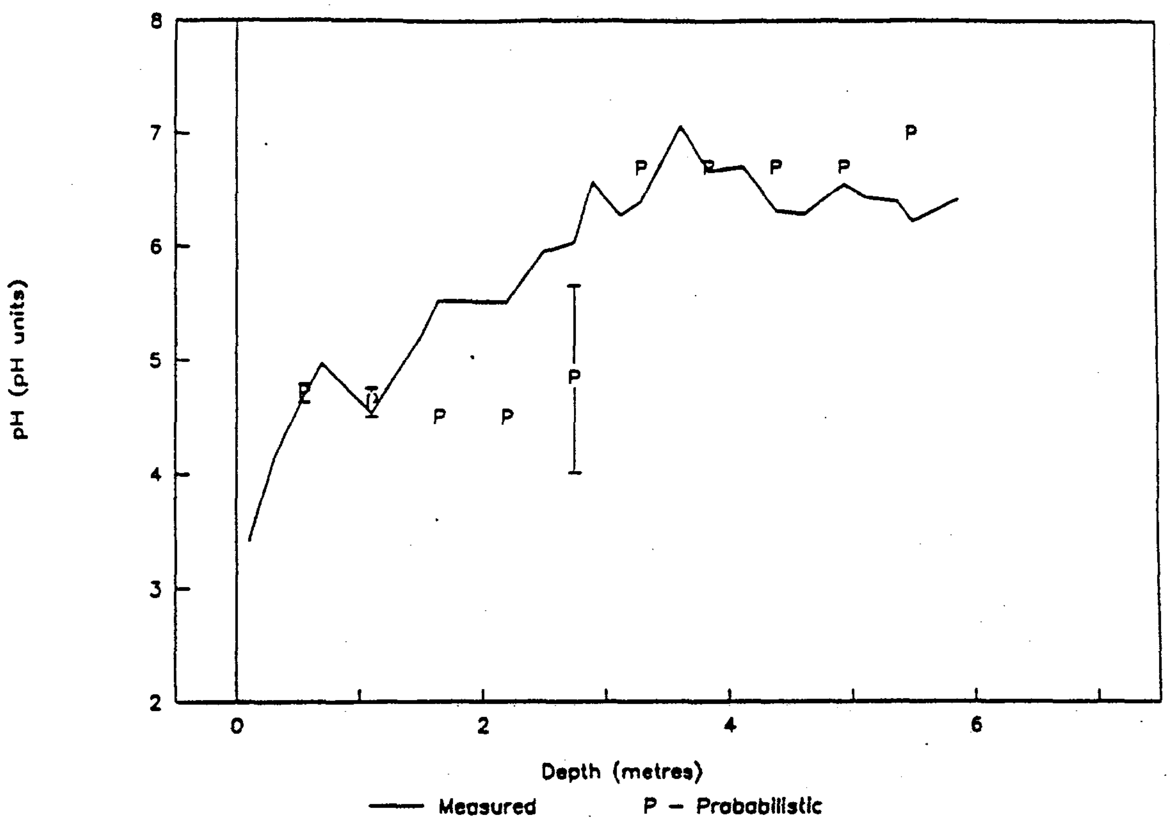

Figure 3.2 WA 22 - pH versus Depth - Probabilistic Run

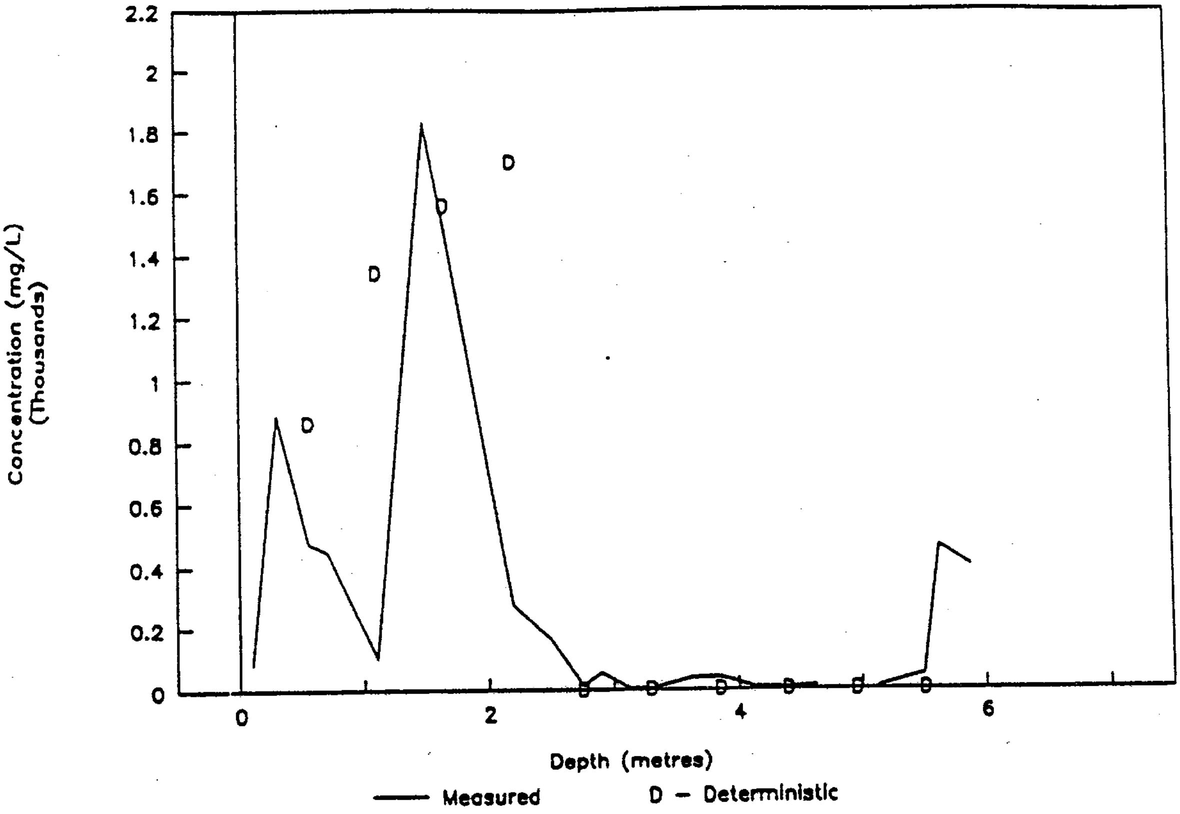

Figure 3.3 WA 22 - Ferrous Iron Concentration versus Depth - Deterministic Run

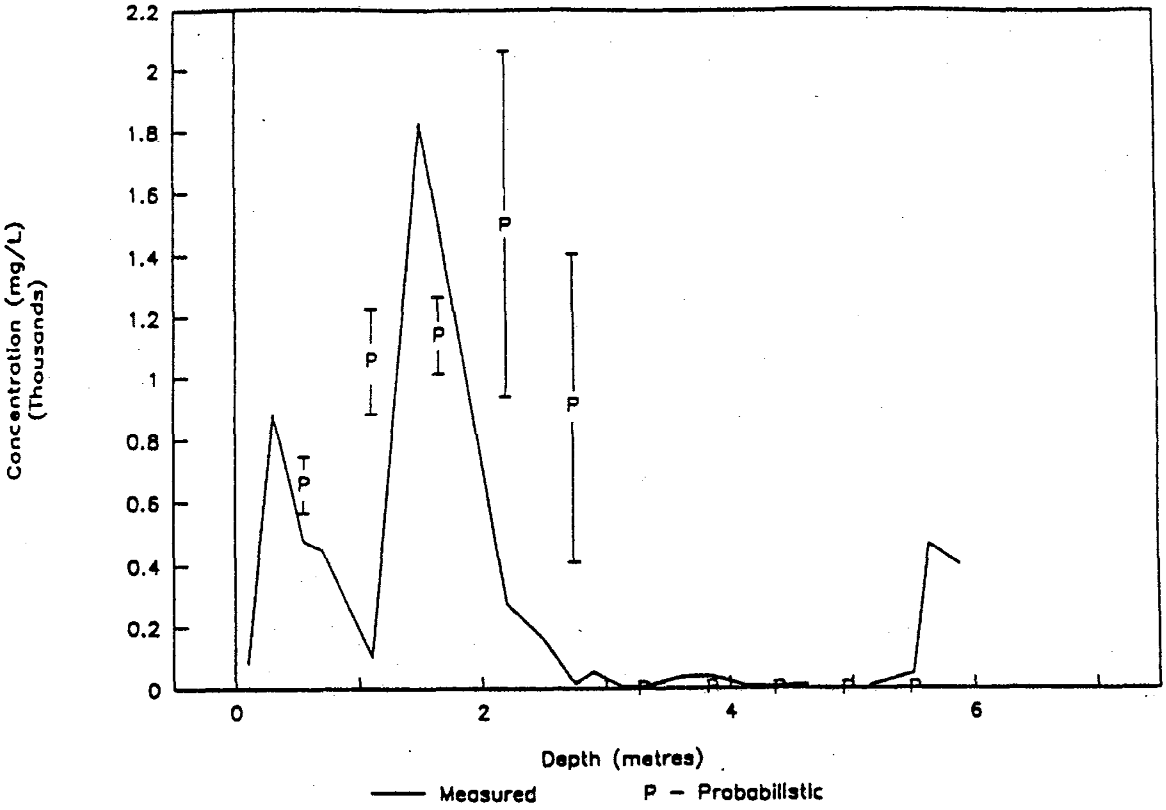

Figure 3.4 WA 22 - Ferrous Iron Concentration versus Depth - Probabilistic Run

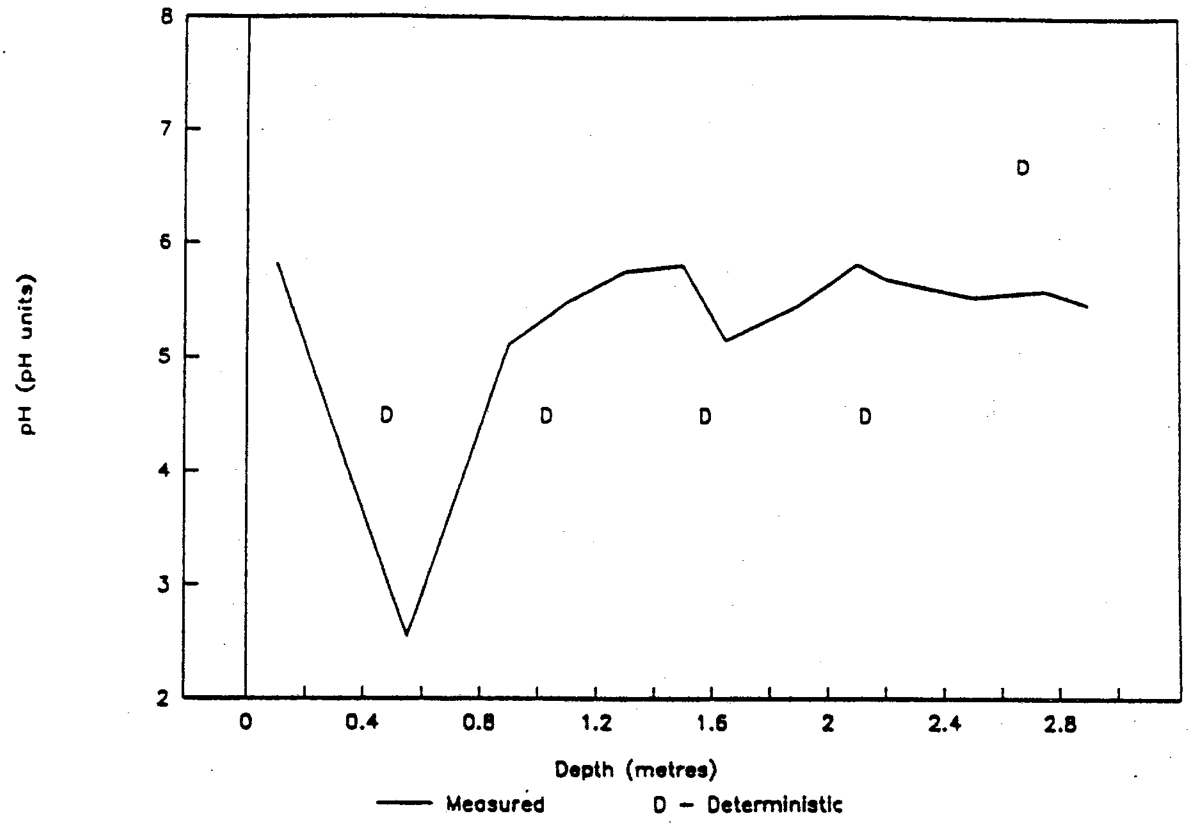

Figure 3.5 WA 17 - pH versus Depth - Deterministic Run

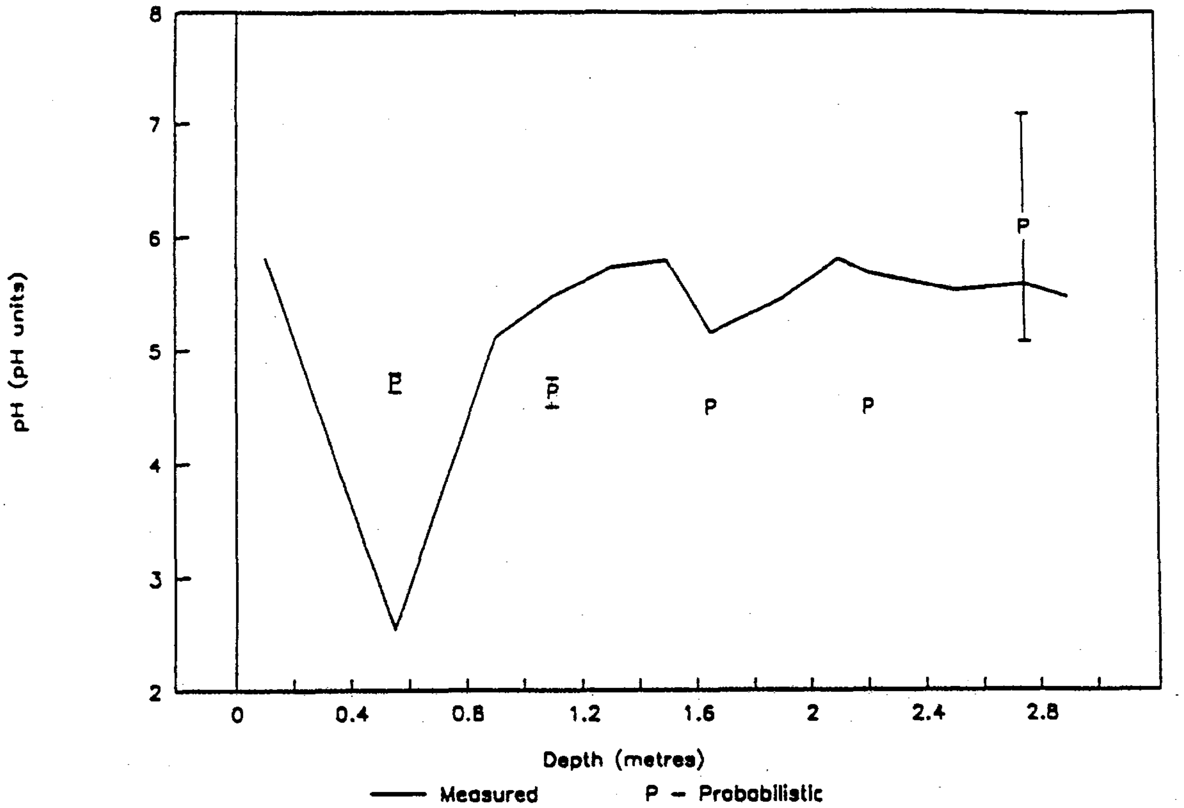

Figure 3.6 WA 17 - pH versus Depth - Probabilistic Run

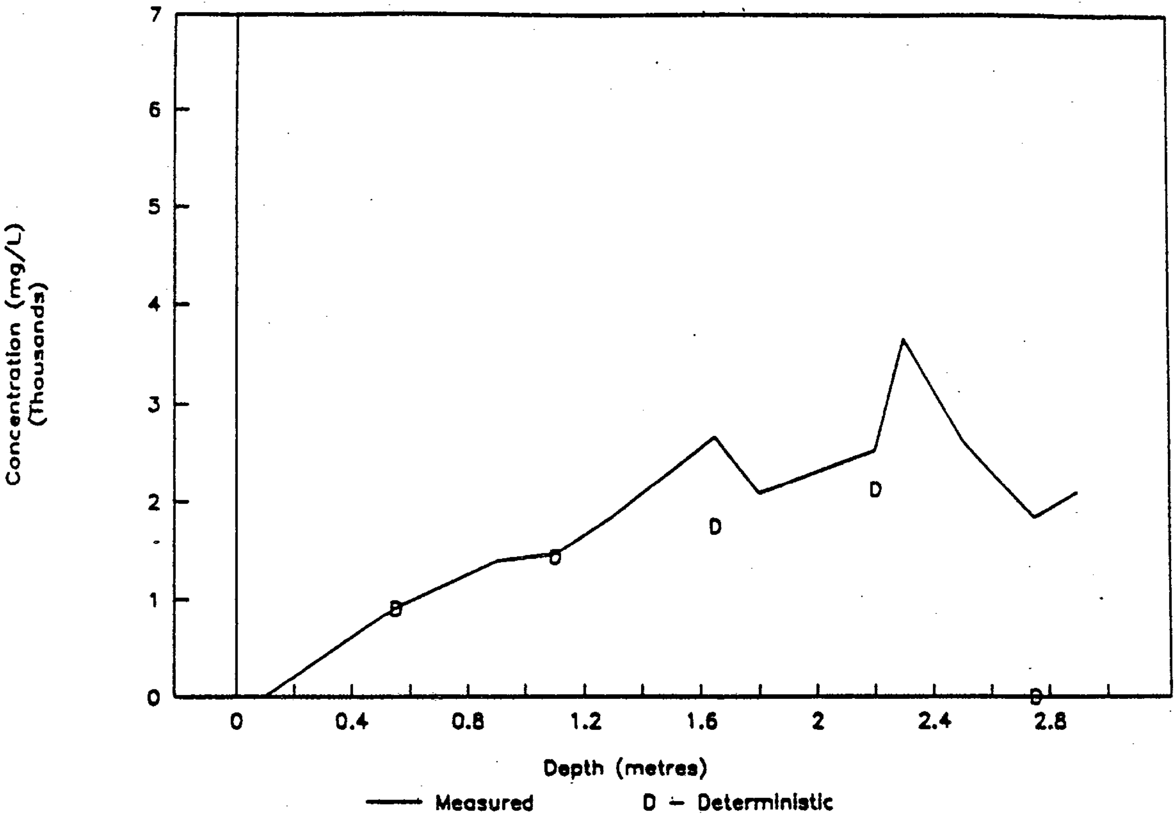

Figure 3.7 WA 17 - Ferrous Iron Concentration versus Depth - Deterministic Run

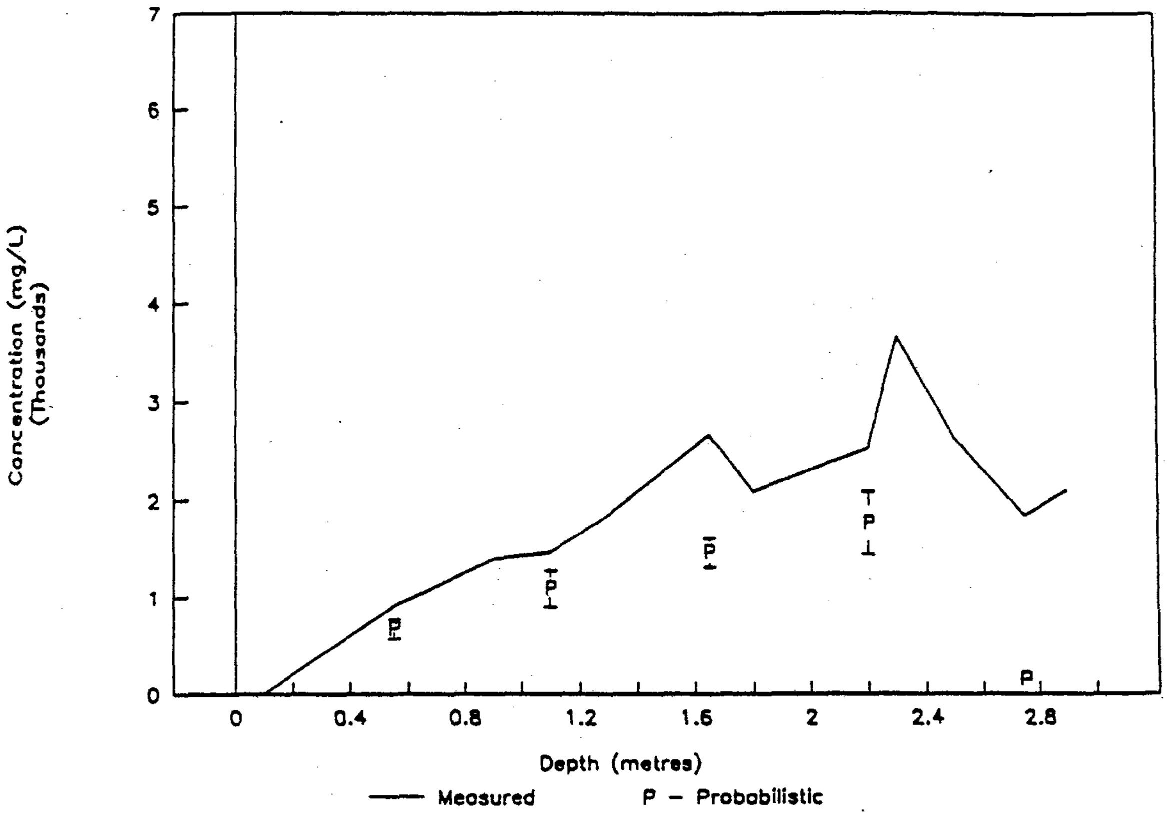

Figure 3.8 WA 17 - Ferrous Iron Concentration versus Depth - Probabilistic Run

4.0 CONCLUSIONS

1. RATAP.BMT addresses questions more numerous and more complex than those addressed by other acid generation models.

2. RATAP.BMT permits an evaluation of the limitations of other acid generation models.

3. RATAP.BMT permits evaluation of many additional questions which are beyond the scope of the questions evaluated by other acid generation models.

4. RATAP.BMT model structure is built around established physical and chemical principles. Empirical relationships are kept to a minimum.

5. RATAP.BMT requires a more knowledgeable user and, thus, is more difficult for a novice user to program.

6. Partial model validation was successfully performed using data collected on the Waite Amulet tailings. Further validation work is required and should preferably be undertaken on several tailings areas.

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