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INVESTIGATION ON THE PLACEMENT OF LIME NEUTRALIZATION SLUDGE ON ACID GENERATING WASTE ROCK

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This project was prepared by NB Coal Limited for
CANMET Energy Mines and Resources Canada, Canada Centre for Mineral and Energy Technology

November 1996

INVESTIGATION ON THE PLACEMENT OF LIME NEUTRALIZATION SLUDGE ON ACID GENERATING WASTE ROCK

FINAL REPORT

November, 1996

Prepared for:
CANMET Contract
23440-4-1196
Serial No. 41196-01SQ
Energy Mines and Resources Canada
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INVESTIGATION ON THE PLACEMENT OF LIME NEUTRALIZATION SLUDGE ON ACID GENERATING WASTE ROCK

0.0 EXECUTIVE SUMMARY

Capping the acid generating rock at a mine site with lime neutralization sludge could provide several benefits to the final reclamation of the mine site including:

- utilization of the residual lime which is contained in the sludge to neutralize the acidic water,
- provide a low cost final disposal area for the sludge on the surface of the waste rock and within the void space of the reclaimed mined out area, and;
- potentially reduce the ingress of oxygen into the overburden by applying an impermeable seal.

Further investigations were considered, however, to provide information on whether:

- the metal hydroxides in the aged neutralization sludge would redissolve; and,
- whether the sludge had any sealing potential to reduce the ingress of oxygen.

The investigations completed included:

- chemical, morphological and geotechnical evaluations of the sludge,
- on-site barrel reactors and weathering cells which monitored leachate quality; and,
- a field test which evaluated the geotechnical laboratory results on several sludge applications of different ages on the waste rock.

The investigations completed have provided information on:

- the ability of the sludge to minimize the generation of acid by the waste rock when the alkaline sludge is present in significant amounts;
- the insolubility of the metal hydroxide in the lime neutralization sludge acid generating waste rock when the alkaline sludge was present in significant amounts.
- the geotechnical parameters pertinent to describing the handling characteristics of the sludge;
- suggestions and benefits to retaining the sludge near the surface, and;
- the sealing potential of the sludge to reduce or minimize the ingress of oxygen when applied either as a cap to the surface of the waste rock or "injected" into the waste rock.

The projects were conducted by contractors under the management of NB Coal.

1.0 OBJECTIVES

Capping the acid generating rock with lime neutralization sludge could provide several benefits to the costly neutralization operation of the abandoned mine site including:

- utilization of the residual lime which is contained in the alkaline sludge to neutralize the acidic water,
- provide a low cost final disposal area for the alkaline sludge on the surface of the waste rock and within the void space of the reclaimed mined out area,
- potentially reduce the ingress of oxygen into the overburden by applying an impermeable seal.

Further investigations were considered, however, to provide information on whether:

- the metal hydroxides in the aged neutralization sludge would redissolve; and,

- whether the alkaline sludge had any sealing potential to reduce the ingress of oxygen.

2.0 INTRODUCTION

The liability of acid generating mine sites in Canada has been estimated to be in excess of $6 billion over the last 20 years Mine Environment Neutral Drainage (MEND 1994 Annual Report). Currently, many acid generating operations are opting for the "perpetual pump and treat" method for meeting government regulated effluent discharge requirements. Major drawbacks to this option include the long term liability, both environmentally and personal, associated with the storage of the thixotrophic sludge generated from neutralizing the acidic mine water, the stability of the sludge (Renton et.al, 1993), the expense of constructing sludge sedimentation ponds to collect the sludge in the neutralized mine water and the vast amount of land which is rendered economically useless by the construction of these huge storage/containment areas. Thus, the perpetual neutralization of acidic mine water has created another potential perpetual liability (MEND 1994 Annual Report).

Vachon (1987), Ackman (1982), USEPA (1983), Higgs (1991), Martel (1991), Brown et.al (1995) and others have considered sludge disposal options including injection in abandoned underground mining operations or refuse piles, thickening, mechanical drying, freeze drying, using sludge as a soil ameliorant, and stabilizing the sludge with an amendment.

2.1 SITE HISTORY

At the NB Coal Fire Road mine site, coal was strip mined from 10 to 25 meters of pyrite bearing sandstone/sandstone conglomerate. The 120 ha. site was mined between 1982 and 1986 and has been generating acid since 1984. In 1986, the mining operation was abandoned in an effort to reduce the rate of acid generation from the waste rock. The final cut was filled in with the mined waste rock and the entire site was graded to approximately the original topography. The waste rockfill area is approximately 3,450 m. long and averages 350 m. wide. Its surface extends from el. +130 m. to el. +150 m. The total volume of rockfill is approximately 15 million m^3, of which approximately 11 million m^3 is above the ground water level (Gemtec, 1995). A cross section through the disturbed waste rock is presented in Appendix O.

Approximately 2.4 million cubic meters of mine water have been neutralized annually with hydrated lime since 1986. The lime neutralization sludge resulting from the neutralization process (approximately 260,000 cubic meters) has been stored in fifteen ponds located adjacent to and on the reclaimed mine site.

In 1990, consideration was given to placing the neutralization sludge on the waste rock but concerns were raised by Monenco (1990), Vachon (1987), Watzlaf and Casson (1990), and others on the potential redissolution of the metal hydroxides precipitated in the sludge when the sludge came in contact with an acidic environment. The sludge disposal on waste rock concept was rejuvenated again in 1992 when investigations by Dearborn indicated that the metal redissolution from the sludge was negligible after aggressive laboratory leach tests of the sludge were performed (Dearborn, 1992), but the concerns of metal redissolution were not completely alleviated (MEND Report 3.32.1).

In the spring of 1992, aged sludge was removed from a sedimentation pond with an excavator and loaders. Because of the thixotropic nature of the sludge, this relocation method was not considered for future sludge remobilization operations.

In the fall of 1992 and 1993, dredging of operations were conducted to:

- establish the viability of relocating the sludge on the waste rock;
- to monitor the initial effect of the sludge on the mine water, and;
- to monitor the effect of the dredging operation on the water balance in the reclaimed mine site.

The 1992/3 investigation indicated the importance of carefully evaluating the sludge pumping capability of the dredge so as to not disrupt the water balance in the mine site and to also retain a higher concentration of solids on the surface of the waste rock. The water balance in the waste rock could be maintained during dredging operations by careful monitoring of the mine water elevation and increasing treatment flow rates when necessary.

Dredging operations continued during the early summer of 1994 and fall of 1994 and 1995 to monitor the conditions at which sludge can be placed on the surface of the waste rock.

The quality of the mine water is monitored daily at the lime neutralization facility. The quality of the ground water in and adjacent to the mine site is monitored annually at a series of ground water monitoring wells. Although a short term (several weeks) reduction of the acidity of the mine water was recorded after the 1992/3 dredging operations, (the acidity fluctuated from 1300 mg/l to 500 mg/l and then back up to 1300 mg/l as $CaCO_3$ to a pH of 8.3), the overall quality of the mine water did not appear to be affected by the sludge applications. Subsequent dredging operations have produced similar acidity decreases in the mine water. Since 1992, the acidity of the mine water has decreased to an annual average of between 800 and 900 mg/l and the pH of the mine water has risen from the 2.7 - 2.8 range up to the 3.2 - 3.3 range. These changes have not been identified in the ground water samples.

3.0 EVALUATION OF THE SLUDGE AND WASTE ROCK

To characterize the sludge incorporated in the investigation, sludge samples were evaluated for chemical composition, net neutralization potential, morphological character and their geotechnical parameters.

The waste rock was evaluated for its acid generating potential.

3.1 CHEMICAL EVALUATION OF THE SLUDGE
(Edited from Grace Dearborn Inc., March 1995)

Representative samples of the sludge were obtained from NB Coal's Fire Road mine site. Two samples of sludge were collected in September 1994 from sedimentation ponds 88-1 (sludge less than 1 year old) and 89-2 (sludge more than 2 years old). Additional samples of sludge were collected from sedimentation ponds 90-2 (sludge less than one year old) and 89-2 (sludge more than 2 years old) in November 1994 to make a mixture comprised of 50% "fresh" and 50% aged. Watzlaf and Casson (1990) and Brown et.al (1995) found that the largest increase in sludge stability occurred during the first month.

All samples were analyzed in triplicate (due to the heterogeneous nature of the materials) and characterized by determining the acid generating/neutralization potential. The total amount of potential acidity/alkalinity within each sample was calculated from the sulfur content and quantity of standard acid consumed. The sludge samples were further characterized by x-ray diffraction and metal analysis.

3.1.1 NET NEUTRALIZATION POTENTIAL OF THE SLUDGE
(Edited from Grace Dearborn Inc., June, 1996)

All sludge samples were submitted to the New Brunswick Research and Productivity Council (RPC) in Fredericton for determination of net neutralization potential. From the sulfur content and acid consumption rate, the theoretical calcium sulfate ($CaSO_4$) and calcium oxide (CaO) contents of each sludge type were calculated.

The theoretical calcium sulfate calculation assumes that all sulfur measured in the sludge is present as calcium sulfate. Each set of triplicate results have been averaged in Appendix A, Table A-1.

All samples were found to exhibit a significant and consistent fraction of available alkalinity. However, it is expected that the acid consumed in the test for the determination of neutralization potential will be somewhat higher than the amount actually consumed by the lime due to the presence of metal hydroxides ($Fe(OH)_3$, $Al(OH)_3$, etc.) contained in the sludge. These hydroxides may be partially dissolved by the acid used in the analysis. As a result, the calculated free available lime content of the sludge is expected to be somewhat higher than the amount actually available for neutralization of AMD.

3.1.2 X-RAY DIFFRACTION OF THE SLUDGE
(Edited from Grace Dearborn Inc., June 1996)

A sample of the mixed Fire Road sludge was further characterized by x-ray diffraction techniques to determine the species present (Duncan and Bruynesteyn, 1979). The trace for the sample and the principles behind XRD are included in Appendix B. The sample analyzed was found to contain the following primary species:

♦ Gypsum	$CaSO_4 2 H_2O$
♦ Portlandite	$Ca(OH)_2$
♦ Quartz	SiO_2
♦ Ferric Hydroxide	$Fe(OH)_3$
♦ Iron Pyrite	FeS_2

It should be noted that the results provided by XRD are qualitative only and do not provide any quantitative information. However, it is expected that the pyrite would be a minor component of the solids produced.

3.1.3 METAL ANALYSIS OF THE SLUDGE
(Edited from Grace Dearborn Inc., June 1996)

An additional sample of mixed Fire Road sludge was further characterized by digesting the sample in nitric acid and performing an analysis of soluble metals by ICAP using ASTM Designation 04190-82. The samples were analyzed for aluminum, calcium, cadmium, copper, iron, magnesium, manganese, nickel, lead and zinc. The results are presented in Appendix C, Table C-1. Based on this analysis, the total calcium content of the sludge was approximately 9%, the aluminum concentration was approximately 11% and the iron concentration was approximately 6%.

3.2 EVALUATION OF THE WASTE ROCK
(edited from Grace Dearborn Inc., March 1995)

The waste rock for this program was prepared and collected in September 1994 from the Fire Road mine. Samples of waste rock were collected at 10 separate locations with an excavator and loader. The sample locations were chosen under the direction of NB Coal Limited personnel. The waste rock samples were placed on a liner and mixed with a front-end loader to achieve a composite sample consisting of approximately 30 tonnes of material ranging in size from one millimeter sand particles to boulders exceeding two meters in diameter. This material was subsequently crushed by a local contractor to a top size of five centimeters, returned to the lined area at the Fire Road site and covered.

3.2.1 NET ACID GENERATING POTENTIAL OF THE WASTE ROCK (edited from Grade Dearborn Inc., June, 1996)

Waste rock samples (approximately 500 g. each) were submitted to RPC for determination of net acid generating potential. The procedure used the Leco Furnace Procedure (Sobek et.al., 1978) for sulfur determination. This determination assumed that all of the sulfur would be present in the sulfide form and therefore eventually generate sulfuric acid on extended contact with oxygen and moisture (see sample calculation in Appendix A).

Based on the sulfur content and acid consumption rate, the theoretical acid generating potential was calculated. The characteristics of the nine samples have been averaged and presented in Appendix A, Table A-2. The results indicate that after allowing for any inherent neutralizing potential (as determined by the consumption of standard acid), all samples were found to be net acid producers with an average equivalent sulfuric acid generation potential of approximately 20 lbs/ton.

3.2.3 SLUDGE AND WASTE ROCK NEUTRALIZATION POTENTIAL COMPARISON (edited from Grace Dearborn Inc., June, 1996)

The waste rock samples were all found to be potentially acid generating while the sludge was a net acid consumer. Based on the results presented in Appendix A, Tables A-1 and A-2 and assuming the rates of alkalinity and acidity release would be the same, it was calculated that the theoretical ratio of sludge to waste rock required to achieve neutralization would be on the order of 1:3.

The details of the neutralization potential determination procedures and sample calculations have been provided in Appendix A.

3.3 MORPHOLOGICAL EVALUATION OF THE SLUDGE (edited from Gemtec Ltd., 1995)

Because of the unusual characteristics of the sludge, as compared with conventional soils, a SEM investigation of the sludge particles was carried out. The details of the investigation, including micrographics at magnifications up to 3300X and mineralogical analysis are presented in Appendix D.

The SEM investigations showed that the sludge particles were porous and that the sludge structure was extremely porous. These observations were supported by the results of the geotechnical evaluation which reported extremely high water contents and low material strength as discussed in section 3.4.

The results of grain size analysis of the sludge material are shown on the attached grading charts also in Appendix D. These charts indicate that the content of particles smaller than 0.08mm size (silt) was 100% only for the non-dried material. Under any drying conditions, the silt content increased to 25 to 40%, regardless of the drying temperature and/or the extent of freeze-dried conditions. This indicated that any type of drying caused some of the particles to flocculate.

3.4 GEOTECHNICAL EVALUATION OF THE SLUDGE (edited from Gemtec Ltd., 1995)

The sludge structure was quite different from conventional mineral soil structures. Soil structures consist typically of solid particles in contact with each other resulting in porosities in the range 0.20 to 0.45 and water contents in the range 20 to 45% (by dry weight).

The sludge materials investigated were very fine-grained, containing only silt and clay size particles. These particles were porous so it became necessary to distinguish between intraparticle (within particle) and interparticle (between particle) voids. The interparticle water mass/ volume was derived by air drying a sludge sample and calculating the amount of water which had evaporated. The intraparticle water mass/volume was calculated after oven drying an air dried sample. The consistency of the sludge could be described by measuring the interparticle water content of the sludge as a mass ratio of the mass of the interparticle water content divided by the total mass of the sludge solids and the intraparticle water. If the sample contained more interparticle water by mass than the mass of sludge and intraparticle water, the interparticle water content would be greater than 100%.

The water content of the sludge after deposition and coagulation in a holding pond was typically in the range 500 to 800% (by dry weight) which corresponded to about 91 - 94% interparticle porosity, (i.e. only 6 to 9% of the structure represented porous sludge particles. For this to be possible, there must have existed interparticle forces that held the highly flocculated structure together.

Geotechnical laboratory testing concentrated on specific gravities, moisture contents, compaction tests and permeability tests. These tests were carried out on samples from the original material in the sludge ponds collected in September 1994 as well as on the dredge effluent and the sludge material congealed in the deposition area beyond the end of the dredge pipe discharge during the October and November 1994 dredging campaign.

3.4.1 SPECIFIC GRAVITY
(edited from Gemtec Ltd., 1995)

The determination of the specific gravity of the sludge material proved to be non-standard procedure. Many of the sludge particles were porous as shown in the scanning electron micrographs in Appendix D. It was therefore necessary to distinguish between intraparticle and interparticle voids (i.e. between voids within the particles and voids between them). It also became necessary to distinguish between dry particles, saturated particles and dry but saturated aggregates of particles. Further details of this terminology is given in Appendix E.

The specific gravity of 1.96 had been calculated for surface dry but intraparticle saturated sludge (Appendix E).

3.4.2 WATER CONTENT
(edited from Gemtec Ltd., 1995)

For conventional mineral soils, the conversion of water contents from percentage by dry weight to percentage by total weight or total volume was a simple matter. However, when the particles making up the structure were themselves porous, the conversion became much more complicated, particularly when taking into consideration that after the sludge was oven dried, the intraparticle water evaporated, whereas in the field, particles which were dry to the touch (dry on the interparticle level) were saturated on the intraparticle level.

The details and examples in Appendix E were presented to explain the aspects of water contents and dry densities in structures which consisted of porous particles bonded together in a highly porous manner.

The water (moisture) contents tabulated in the Summary of Index Properties (Appendix D) were water contents by dry weight after oven-drying, (i.e. they included the intraparticle water content).

3.4.3 HYDRAULIC CONDUCTIVITY (PERMEABILITY) OF COMPACTED SLUDGE
(edited from Gemtec Ltd., 1995)

Hydraulic conductivity (permeability) tests were conducted on compacted samples only. The material was dried from its natural moisture content in the field. It was then compacted in a 100 mm diameter split mold and mounted on a triaxial cell base. One sample (P5) was subjected to several cycles of freezing and thawing in the triaxial cell base covered with a rubber membrane. Two samples (P6 and P7) were prepared from the dry material sampled from the older dredge deposit areas.

The test results for hydraulic conductivity are shown in Appendix F, Figures 1a and 1b. It was noted that neither the freezing and thawing in the laboratory nor the freezing and drying in the field had any significant influence on the test results. Up to a compaction moisture content (interparticle moisture content) of about 100%, the coefficient of permeability (k) was about 3 x 10^{-4} cm/sec. The permeability decreased sharply with increasing compaction moisture content of around 250% to about 5 x 10^{-7} cm/sec

If an optimum combination of compaction moisture content and permeability was selected, Gemtec Ltd. (1995) recommended a compaction moisture content of 150%, which yielded a permeability of about 1 x 10^{-5} cm/sec. (and a dry density about 500 kg/m^3). However, even though the material was relatively easy to compact in the laboratory at this water content, compaction in the field would still present problems. The practically saturated sludge at this water content would be quite soft and relatively difficult to handle as compared with mineral soils.

3.4.4 COMPACTION CHARACTERISTICS (edited from Gemtec Ltd., 1995)

The results of the compaction tests on the sludge material are shown in Appendix F, Figure 2. The dry densities included the weight of the intraparticle void water and the water contents were calculated on the basis of dry weight plus the weight on the intraparticle water (detailed derivations of the nomenclature relationships are presented in Appendix E).

The compaction curves showed that many of the samples were compacted at a degree of saturation equal or close to 100%. Although no definite maximum dry density was determined, the curve indicated that it was around 850 kg/m^3 at a compaction moisture content approaching zero.

The material became quite difficult to compact at moisture contents lower than 100% (too powdery) or higher than 250% (too mushy). On the basis of the results shown in Appendix F, Figure 2, and observations during the testing, it was recommended that a suitable moisture content for compaction would be approximately 150% which would yield a dry density of about 500 kg/m^3. At this compaction moisture content, the permeability would be as high as 10^{-4} cm/sec. At a moisture content of 200%, the permeability would be 10^{-5} cm/sec. At a moisture content of 250%, the permeability would be 10^{-6} cm/sec. However, as the moisture content increased, it became more difficult and impracticable to compact the sludge material.

There was no clear trend to differentiate between various compaction energies.

3.4.5 PENETRATION OF SLURRY INTO ROCK FILL
(edited from Gemtec Ltd., 1995)

The behavior of the slurry pumped from the dredge to the waste rock fill in 1994 prompted a series of tests in which a slurry was introduced at the top of a fine rock fill and the container shown in Appendix F, Figure 3. The purpose of these tests was to determine in a model if the slurry did penetrate the rock fill and by how much.

Four penetration tests were carried out. The rock fill was weighted dry before the tests and wet after the tests. The weight after the test would be that of the dry rock fill plus intergranular water plus intergranular slurry. The weight of the intergranular water was assumed to be the same as that of the water holding capacity of the rock fill, which was checked separately and found to be 4.6% by dry weight.

Details of the penetration test are given in Appendix F. The cells were 14 cm. in diameter and filled with 30 cm. of rock fill.

The tests showed that the slurry did penetrate the rock fill although perhaps less so than expected. For example, a slurry of water content around 2000%, which was very close to a liquid, did not (in the case of test #4) penetrate more than 3.5 cm. in the rock fill sample under a differential head of about 40 cm. The same limited penetration could be expected in the field in similarly sized rock fill.

The permeability of the fine rock fill (34% gravel size, 30% sand size, 4% silt size) was determined to be about 2.2 x 10^{-1} cm/sec. The permeability of the same rock fill mixture with a small amount of slurry was about 1.4 x 10^{-2} cm/sec., i.e about 16 times lower even though the ratio (saturated surface dry mass of sludge solids)/(dry mass of rock fill) was only 0.013 (1.3%).

To put this into prospective, a 1 m^3 of dry rock fill, which would weigh about 1620 kg., would contain 0.013 x 1620 = 21 kg of saturated surface dry sludge particles. The volume of these particles would be 21/1.96 = 10.7L (L = litres, specific gravity of saturated surface dry sludge was calculated to be 1.96 in Appendix E). The volume of the sludge with a water content of 560% (w_{vir} = 91.6%) would be 10.7/(1 - 0.916) = 127 L. The void volume of the rock fill would be about 0.40 x 1000 = 400 L, i.e. the degree of saturation of the rock fill voids with respect to the content of sludge would be 127/400 = 0.32.

3.4.6 FREEZE AND THAW TESTS FOR CRACKING
(edited from Gemtec Ltd., 1995)

Some freeze-and-thaw tests were carried out on slurry prepared to a moisture content of about 800%. Photos from one series of tests are shown in Appendix F, Figure 4. Other tests were carried out on compacted material (i.e. on sludge compacted at about 150% moisture content and the 300 x 300 mm containers.

The conclusion from all these tests was that the sludge in all cases cracked in the familiar hexagonal pattern on drying. The cracking on drying at room temperature was more severe in the case of the wetter material but even for the drier compacted material, a crack pattern was evident on drying.

The cracked sludge was then flooded after freezing and drying in an attempt to check if the cracking process was reversible; that is, if the sludge on flooding would swell so that the cracks would close. This was found not to be the case for any of the dried or freeze-dried sludges.

The freeze-dried material displayed certain characteristics that are difficult to quantify or even describe in conventional geotechnical terms. First, although the sludge appeared to be dry, it became mushy and started to behave as if it was wet as soon as compaction was attempted. Secondly, compaction of this material was extremely difficult, and when external pressure was applied (before the permeability tests) the compression of the sample was much greater than that for samples which had not been subjected to freezing.

4.0 EVALUATION OF LEACHATE QUALITY
(edited from Grace Dearborn Inc., June, 1996)

A 12 month investigation was conducted to evaluate the impact of the residual lime and the effect of potential metal hydroxide redissolution when the sludge was in contact with the waste rock. The investigation compared the quality of the leachate produced when the sludge was applied to waste rock in both bench and field scale applications.

Twelve field reactors incorporating four test conditions (including a control) were set up in triplicate. Each reactor contained approximately 200 Kg of waste rock. The amended reactors contained between 10 and 30 Kg sludge. These reactors provided results which more closely simulated the environment for field application of the materials. The leachate produced following precipitation events was collected from each reactor at five intervals and subsequently analyzed for key parameters.

Nine weathering cells (three test conditions including a control) were set up in triplicate. Each cell contained approximately 2 Kg of as received waste rock. The amended cells contained either 1 or 2 Kg of as received mixed sludge. Each bi-weekly weathering cycle consisted of initial dewatering followed by 13 days of air drying with the addition of water on the fourteenth day. The leachate collected during each cycle was decanted and analyzed for key parameters for each of the weathering cells. The evaluation also included a determination of the acid/base balance and the magnitude of pyrite oxidation which occurred. This would indicate whether acid generation still occurs in the presence of this alkaline sludge. The weathering cell concept has been discussed previously by Bradham and Caruccio (1990) and Caruccio et.al; 1993.

4.1.1 BARREL REACTORS CONSTRUCTION

The field scale reactor barrels and associated fittings were constructed by NB Coal personnel at the Fire Road Mine site in November, 1994. Twelve 200 L. plastic barrels (approximately one meter high and 0.5_meters in diameter) were placed on wooden pallets adjacent to the existing treatment pond and filled with waste rock and sludge.

Details on the construction of the reactors and a diagram illustrating the set up is presented in Appendix G.

4.1.2 INITIATION OF REACTOR FIELD STUDY

The waste rock for the test was obtained in September 1994 from Fire Road as described in Section 3.2 and the sludge was obtained in September and November 1994 as described in Section 3.1.

Three different sludge consistencies were placed on the reactor barrels. The applications varied in sludge age and water content.

Barrels	Sludge Characteristics
1 - 3	Control (no sludge)
4 - 6	15.24 cm. (6 inches) sludge (less than one year old); 40 vol. % saturated solids after freeze/thawing sample.
7 - 9	15.24 cm. (6 inches) sludge (deposited between 1989 and present); 78 vol. % saturated solids after freeze/thawing sample.
10 - 12	5 cm. (2 inches) sludge; 27 vol. % saturated solids after freeze/thawing sample.

Approximately 50 cm. of waste rock with a top size of 5 cm. was added to each reactor barrel. Demineralized water with a pH of 6.4 was added to each barrel in volumes sufficient enough to completely saturate the waste rock (approximately 20 L.) and tested for pH the following day for determination of acidification of the leach water. Once the leach water was acidified from rinsing the acid from the waste rock, sludge was added to each barrel. Since the barrels were open at the top, they received water with each precipitation event. The sludge also air dried between precipitation events which increased its stability (Brown et.al; 1995)

Whalen (1992) calculated a minimum of freeze/thaw zone for the Fire Road area of 61 cm. (24 inches). Because of the exposed location of the reactor barrels, the entire contents froze solid between mid-December 1994 and April 1995. The behavior of the sludge in the barrels therefore represented the behavior of sludge in the upper 0.6 m. of the mine site which would freeze solid in the winter.

Photographs of the barrel reactors are presented in Appendix H.

The field reactors were constructed in an effort to provide a field comparison of the results obtained from the laboratory weathering cells. The sludge to waste rock ratios used in the field reactors were significantly lower than the 0.5:1 and 1:1 test conditions used in the weathering cells but closer to the 1:3 theoretical ratio of sludge to waste rock which would be required to neutralize acid generation (Grace Dearborn Inc., March, 1995). The initially proposed weathering cell test conditions were considered accelerated when compared to conditions observed in the field.

4.1.3 ANALYTICAL RESULTS OF BARREL REACTORS (edited from Grace Dearborn Inc., June, 1996)

Five sets of samples were collected from the reactor barrels and subsequently analyzed for pH, conductivity, sulfate concentration, acidity and thiobaccillus ferroxidans. The results are presented in Appendix I, Table I-1. Detailed results from soluble metals found in the field reactor leachate collected are presented in Appendix I, Table I-2. Microbiological data for Adenosine Triphosphate (ATP) and Thiobacillus ferroxidan counts are included in Appendix I, Table I-3.

The following is a detailed discussion of the results of each parameter.

pH: The amended reactors containing have typically exhibited slightly higher pH values (3.7 - 5.0) than those measured in the unamended waste rock reactors (3.1 - 4.3). It is also interesting to note that the reactor set containing fresh sludge used for plugging (5 cm applications) generally exhibit the highest pH values of the amended reactors. This may indicate that sludge may be impeding the ingress of oxygen and water in the waste rock, thus reducing the generation of acidity. A detraction to this conclusion is that these reactors still had sludge on the surface so very little sludge would actually be involved in plugging. Also, the plugging may be occurring in the saturated zone where the rate of acid generation is significantly reduced anyway but the constant contact time of the sludge with the water may allow for more alkalinity to be leached from the sludge.

Conductivity: Based on the data collected, it is evident that the conductivity of amended groups II and III (700 - 2500 umhos/cm) are higher than those measured in the control samples (600 - 1400 umhos/cm). As to be identified with the weathering cell samples, this is believed to be due to the redissolution of the inherent calcium sulfate present initially in the sludge. In addition, due to the small amount of sludge added in amended group IV, there is a very small amount of calcium sulfate dissolution (300 - 1200 umhos/cm).

Sulfate Concentration: The trend in leachate sulfate concentration is consistent with the earlier reported conductivity levels. Clearly, amended groups II and III are showing slightly higher concentrations (600 - 2400 mg/L) than those exhibited by the control reactors (300 - 1300 mg/L). The trend in sulfate concentration from amended group IV is consistent with the earlier reported conductivity levels (250 - 900 mg/L).

Acidity: Leachate acidities range widely within all samples and hence, no discernable impact of sludge addition can be made. This is most likely due to the wide variations in the acid generating potentials of the waste rock samples in the individual reactors. However, the acidities are slightly higher for the control reactor leachates (200 - 1100 mg/L as $CaCO_3$) compared to those found in the amended reactor leachates (50 - 800 mg/L as $CaCO_3$).

Soluble Metals: Results for the soluble metal concentrations found in the leachate collected from the reactors are presented in Appendix I, Table I-2. For the amended reactors, the samples collected generally exhibit metal concentrations which are lower than those taken from the control samples, indicating that metals contained in the sludge are not dissolving in the acidic pH ranges observed. In addition, calcium concentrations are generally higher in the more amended reactors due to the redissolution of the inherent calcium sulfate contained in the sludge. This was not evident in the reactors with the minimal 5 cm sludge application.

Microbiological Counts: Results for *Thiobacillus ferroxidans* and ATP counts found in the leachate collected from the reactors are presented in Appendix I, Table I-3. Based on the variability in the microbiological data collected, the only conclusion which may be drawn is that approximately the same level of microbiological activity exists in the amended reactors in comparison with the control reactors which at least indicates that the presence of sludge does not increase the growth of *Thiobacillus ferroxidans*.

4.2 WEATHERING CELLS

The weathering cells were set up as a controlled bench scale investigation whereby oxidation, hydrolysis and temperature controls were initially employed to accelerate the effect of the sludge on the waste rock.

4.2.1 PROCEDURE

(edited from Grace Dearborn Inc., March & September, 1995)

Three test conditions, including a control, were set up in triplicate in 4.7L air tight plastic containers. Nine samples (each approximately 2.5 Kg.) of waste rock were separated for use in the weathering cells. Mixed sludge (1:1 <1 year old/>2 years old) was used as an amendment as follows:

(1) Control - Waste rock only.
(2) Mixture 1 - 0.5:1 mass ratio of sludge to waste rock.
(3) Mixture 2 - 1:1 mass ratio of sludge to waste rock.

Details of cell construction are in Appendix J.

Cycling of wet and dry air to accelerate the weathering process by oxidation and hydrolysis commenced in January 1995 after the interparticle water in the sludge was removed by freezing and thawing of the weathering cells. Based on the start-up date and a program duration of 1 year, the investigation was completed by February 1996.

Leachate samples from each cell were initially analyzed weekly for pH, sulfate concentration, conductivity and acidity. Solid samples were analyzed for paste pH only.

Several cycles were completed before it became apparent that the cells were not drying out between cycles. After discussions initiated by NB Coal Limited, the following modifications were incorporated into the procedure to accelerate the rate of acid generation in the cells.

Modification 1 The original test protocol was modified at week 14 to ensure that the contents of each weathering cell were washed thoroughly, such that the layer of calcium sulfate surrounding the pyrite particles in the weathering cells were removed. This allowed further oxidation of the pyrite within each cell and provided the conditions for accelerated weathering to occur. This modification involved adding a larger quantity of water to the entire contents of each weathering cell, rather than removing a smaller portion of the cell for subsequent water addition.

Modification 2 In order to allow the complete evaporation of any residual moisture, the covers were removed from the cells. The weathering cells were then sampled at two week intervals since week 18. This allowed for more weathering to occur between cycles. This modification eliminated the potential benefits to be derived from the original proposed accelerated weathering concept which used circulated dry air through the cells.

The original procedure is attached in Appendix J.

The step-by-step procedure for the production and collection of leachate was amended as follows to accommodate the 2 week cycle:

1. Add enough distilled water (approximately 500 mL.) to each cell until a paste consistency is achieved and measure the paste pH. Raise the volume of water added to each cell to a total of 1 L. and mix thoroughly. Allow the cell contents to settle until a clear supernatant is obtained. Remove the supernatant from each cell and record the volume removed. Measure the pH, conductivity and sulfate concentration of the leachate. Finally, determine the acidity of the leachate from each of the nine samples by titrating with caustic to a final pH of 9.

2. Remove the lids on each cell for 13 days to allow the evaporation of residual moisture.

3. On the last day of the cycle, added distilled water to each cell and repeat the procedure as outlined in steps 1 and 2.

4.2.2 ANALYTICAL RESULTS OF WEATHERING CELLS (edited from Grace Dearborn Inc., June 1996)

Leachate samples were collected and analyzed in detail for soluble metals, *Thiobacillus ferroxidans* counts (Lizama and Suzuki, 1988) and ATP counts at five intervals as specified in Table 4-1. Leachate samples were also collected from each cell for weekly or bi-weekly analysis of pH (GDI procedure #209.1.80), sulfate concentration (GDI Test Procedure #2873), conductivity and acidity (ASTM Designation D1067-88), while solid samples were analyzed for paste pH (Sobek et.al., 1978) only.

The solids used in this bench scale test were initially characterized as described in section 3.1 and 3.2. The sludge was analyzed for net neutralization potential, major species by XRD and by nitric acid digestion of metal concentrations. The waste rock was also analyzed for its acid generating potential. The net neutralization potential of the amended weathering cells and the net acid generating potential of the control samples were also measured at the conclusion of the weathering cell investigation to quantity the effect of the sludge on the rate of acid generation in the cells.

Table 4-1
Weathering Cell Sampling Schedule

	PARAMETER	FREQUENCY
LEACHATE	Acidity	Weekly/ Bi-weekly
	Conductivity	Weekly/Bi-weekly
	pH	Weekly/Bi-weekly
	Sulfate Concentration	Weekly/Bi-weekly
	Al/As/Ca/Cd/Cr/Cu/Fe/Mn/Ni/Pb/Zn	Weeks 1,2,10,26,52
	Thiobacillus ferroxidans & ATP	Weeks 2,7,26,39,52
SOLIDS	Paste pH	Weekly/Bi-weekly
	Acid Generating/Neutralization Potential	Weeks 0,52
	Metals Analysis after Nitric Acid Digestion	Week 0
	XRD for Calcium Speciation (sludge)	Week 0

4.2.2.1 WEATHERING CELLS LEACHATE EVALUATION

The results of the leachate evaluation are discussed below. Complete details with tables and graphs are included in Appendix K.

Acidity: The leachate sample acidities were determined using a standard ASTM technique by titrating the sample to an endpoint pH of approximately 9 using standard caustic. The control cell leachate samples have consistently displayed significantly higher acidity levels than those displayed by the amended cell samples. Therefore, sludge addition may be neutralizing the acidity generated by the waste rock or at least slowing down the acid generating process by reducing exposure to oxygen. However, the acidity of control cell leachate samples have continuously dropped over the course of the test program, which indicates that a portion of pyrite has been oxidized thus reducing the subsequent amount of acid generation.

Conductivity:

The amended cell samples have exhibited significantly higher conductivity levels than the control cell leachates for the duration of the test program. However, these conductivities have been dropping over the duration of the test program. The conductivity levels in 1:1 amended cells are slightly higher than the 0.5:1 amended cells. The elevated conductivity levels in the amended cell leachates is believed to be due to the solubility of the gypsum (calcium sulfate) in the sludge. The 1:1 amended cells have a slightly higher conductivity which is consistent with the fact that twice the amount of sludge has been added. In addition, the drop in amended cell leachate conductivities may indicate that most of the calcium sulfate has been dissolved and subsequently removed in the leachate collected from the amended cells.

Leachate pH:

All amended cell leachate samples have remained slightly alkaline (7 - 8), while control cell leachate samples have remained acidic (3 - 4). The consistently high pH values observed within the amended cell samples indicate that alkaline conditions are prevalent. The consistently low pH values observed within the control cell samples indicate that pyrite oxidation and subsequent acid generation are occurring. The 1:1 sludge amended cells have exhibited slightly higher pH levels than the 0.5:1 sludge amended cells. This is consistent with the fact that the increased sludge mass would provide more alkalinity and material to treat the acidic leachate produced by the oxidation of the pyritic component of the waste rock.

Sulfate Concentration:

The leachate sample sulfate concentrations were determine using Grace Dearborn Test Procedure 2873. The amended cell leachate samples have consistently displayed higher sulfate concentrations than those displayed by the control cell samples. In addition, all weathering cell leachate SO_4 concentrations have been dropping indicating that the calcium sulfate initially present in the sludge is being dissolved.

Soluble Metals:

The amended cell leachate samples have consistently exhibited significantly lower levels of soluble metals, with the exception of calcium, in comparison with control cell leachate samples. The higher calcium concentrations, however, were expected due to the dissolution of $CaSO_4$ and excess hydrated lime initially present in the sludge. Calcium concentrations continued to decrease over time within the control cells as the natural alkalinity of the waste rock is consumed.

The low concentrations of soluble metals reported from the amended cell leachate samples may indicate the following:

I. Sludge addition in 0.5:1 or 1:1 ratios may be neutralizing the acidity generated by the waste rock; or at least slowing/reducing the acid generating process within the cells in the period represented by the leaching of these cells.

II. Metals contained in the sludge are not dissolving in the alkaline conditions of the cells as there is no evidence of metals being leached from the sludge.

Soluble metals including aluminum, maganese, nickel and zinc are present in higher concentrations within the control cell samples based on their high solubilities at low pH values. However, soluble iron concentrations have remained low (0.4 mg/L to 1.3 mg/L) in the control cell leachate samples. These iron concentrations are significantly lower than the concentration reported in the mine water samples from the site. The low soluble iron concentration and the pH in the control cell samples indicate that all of the iron is being oxidized to the ferric form, precipitated as ferric hydroxide (due to its limited solubility) and subsequently removed by filtration prior to ICAP scan.

Thiobacillus Ferroxidans and ATP Counts

All amended cell leachate samples have exhibited significantly lower *Thiobacillus ferroxidans* counts (between 1 and 1000) than those observed within control cell leachate samples (between 10 and 10,000) for most of the test program. However, all samples (including the controls) exhibited low *Thiobaccillus ferroxidans* counts (≤ 1) by the conclusion of the program.

For most of the test program, ATP counts remained the same in all cell samples.

The drop in control cell sample *Thiobacillus ferroxidans* counts during the latter part of the test program may be due to the depletion of nutrients or lack of pyrite available to the bacteria.

The amended cells appear to either provide an environment which is inhibitory to the growth of *Thiobacillus ferroxidans* or the results were also affected by the depletion of nutrients or lack of pyrite available to the bacteria.

4.2.2.2 WEATHERING CELLS SOLIDS EVALUATION (edited from Grace Dearborn Inc., June, 1996)

The results of the progressive solids evaluations are discussed below. Results of the initial evaluations of the sludge (week 0) are discussed in Section 3.1. Complete details are included in Appendix K.

Paste pH: All amended cell samples have remained slightly alkaline (between 7 and 8). Control cell samples have remained acidic (between 3 and 4) indicating that pyrite oxidation and acid generation are occurring in this bench scale investigation.

4.2.2.3 WEATHERING CELLS ACID/BASE BALANCE (edited from Grace Dearborn Inc., June, 1996)

In addition to the weekly monitoring of overall weathering cell characteristics and the periodic analysis of leachate samples for soluble metals and microbiological counts, the project included both an initial and final evaluation of cell contents to determine the acid/base balance. These tests involved the determination of both total and pyritic sulfur contents as well as the neutralization potential (acid consumption) of all samples. The primary objective of this investigation was to determine whether the sludge impedes the pyrite oxidation process or the sludge acts as a neutralizing agent after the acidity has been generated.

In total, 12 samples of initial cell materials (9 waste rock and 3 mixed sludge samples) were obtained for initial analysis and characterization. These results are presented in their entirety in Table P-1 of Appendix P. For purposes of data correlation and interpretation, the average results of the three sludge samples will be used, while the results of each individual waste rock sample taken from each cell will be used.

In order to address the objectives while recognizing that both the sludge and the waste rock are highly variable in terms of chemical composition, all weathering cell sampling was conducted in triplicate. In total, therefore, 27 solid samples were extracted from the weathering cells for final analysis and characterization in triplicate. These results are presented in their entirety in Table P-2 of Appendix P. For purposes of data correlation and interpretation, the average of each triplicate set of data collected from each weathering cell will be used.

Table P-3 presents a summary of the initial weathering cell conditions as well as the initial total and pyritic sulfur concentrations in each case. It should be noted that for this characterization, the unmixed waste rock and sludge were actually analyzed and the figures presented for the amended cells are based on weighted averages. The masses in the cell description column and discussed in Table P-3 are based on the wet weight ratio. The remaining columns present the mass on a dry weight basis.

Table P-4 presents a comparison of the initial and final sulfur compositions of each cell. The pyritic sulfur content was calculated by subtracting the sulfate sulfur concentration from the total sulfur concentration. Calcium sulfate and H_2SO_4 are the main contributors to the sulfate sulfur concentration. The final pyritic sulfur cell content indicates that a significant portion of the pyritic sulfur in each cell has been converted to sulfate sulfur based on the difference between the initial and final pyritic sulfur contents. This is an indication that pyrite oxidation has occurred in all cells.

A comparison of the initial and final acid/base balances based on the determination of pyritic sulfur contents (theoretical acid generating potential) and the acid consumption (theoretical neutralization potential) of each cell is presented in Table P-5.

The neutralization potential (NP) of the initial and final cell contents was measured using the B.C. Research Initial Test Procedure which involves titrating the pre-ground slurried sample with standardized H_2SO_4 to an endpoint pH of 3.5 ± 0.1 for 4 hours. However, the results obtained for the control cell samples indicate that the final NP is greater than the initial NP which would suggest that the theoretical neutralization potentials may be suspect based on the following facts:

1) Soluble calcium (160 mg/L initially) was found in the leachate collected from the control cells at week 1 of the test program which would suggest that some alkalinity was initially present as calcium carbonate in the waste rock even though the initial neutralization potential was found to be essentially zero. This discrepancy is probably attributable to the highly heterogeneous nature of the waste rock and the associated difficulty in obtaining a representative sample.

2) The increased NP of the final control cell contents may be an indication that some of the precipitated ferrous or ferric hydroxides formed during the weathering program may have been dissolved by the acid used in the test procedure (particularly ferrous hydroxide). This conclusion is further supported by the fact that a decrease in soluble calcium (160 mg/L to 8 mg/L) in the leachate collected was observed over the duration of the program (i.e: no significant calcium carbonate present at the conclusion).

3) For the amended cells, the small difference between the initial and final neutralization potentials can also be attributed to the same mechanism of calcium carbonate (or calcium hydroxide) consumption and ferrous or ferric hydroxide precipitation since ferric hydroxide solubility is reduced at pH's above approximately 2.8.

In addition, Table P-5 presents the estimated fraction of pyrite oxidation which occurred during the one year test period. Based on these findings, several observations can be made as follows:

- A significant fraction of the pyrite was oxidized in all samples. As such, it can be surmised that the sludge, even though inhibiting to the growth of *Thiobacillus ferroxidans* bacteria, did not totally impede the production of acid.

- The same relative degree of pyrite oxidation was found in all amended cells, which indicate that the sludge provided alkalinity for the in-situ neutralization of the amended cell leachates for the duration of the test program.

- After one year of leaching, all amended cells have retained their excess alkalinity. This is also confirmed by the presence of soluble calcium (between 360 mg/L and 590 mg/L) found in the leachate at the completion of the test program.

- After one year of leaching, the 1:1 amended cells have retained more excess alkalinity than the 0.5:1 cells which is consistent with the fact that twice the amount of sludge is present in the 1:1 amended cells. This is also confirmed by the presence of the same level of soluble calcium concentrations (approximately 500 mg/L) in the leachate collected for the duration of the test program. In addition, we can calculate the amount of alkalinity consumed (and thus the amount of alkalinity remaining) in the amended cells based on the cumulative amount of sulfate removed in the control cell leachates assuming that the same degree of oxidation has occurred in all cells. Based on the 0.5:1 and 1:1 amended cells containing 2600 and 5200 mg of alkalinity as calcium, the calculated amounts of alkalinity consumed would be approximately 80% and 40% respectively, which would indicate almost half of the alkalinity still remains within the 1:1 amended cells.

5.0 FIELD EVALUATIONS

5.1 GEOTECHNICAL FIELD TEST
(Gemtec Ltd., 1995)

The first field investigation took place in September 1994 and consisted of sampling sludge from the mine water holding ponds (86-1, 88-1 and 89-2). The next investigation took place on October 28 and November 3, 1994 and consisted of sampling the dredge slurry at the end of the pipe and in the disposal area on the waste rockfill as well as sampling dried slurry from the previous dredge disposal periods near the 1994 dredge disposal area. The final field investigation was conducted in July 1995 and investigated methods to incorporate the sludge into the surface of the waste rock.

5.1.1 DREDGED SLUDGE: 1994 PRODUCTION (Gemtec Ltd., 1995)

The sludge existed at different water contents: from its coagulated state in the mine water holding ponds through its slurry state during pumping and at the pipe discharge to its final state within and on the surface of the rock fill. Because of this significant range, a meaningful comparison of volumes and weights must be based on the weight of sludge "solids", (i.e. particles whose intraparticle voids were filled with water).

Detailed calculations involving the volumes and weights of rock fill and sludge particles are given in Appendix L. They are based on the index properties described in detail in Appendix E.

Even if the determination of index properties in this material were subject to some uncertainties, the observed and the calculated depths of sludge penetration into the waste rock fill were so very far apart that even a major adjustment of index values (within a reasonable range) did not make any significant difference. The explanation other than simply slurry penetration into the normal rock fill voids was the existence of "chimneys" or "vents" which arose from a congregation of large rocks forming large continuous voids through much of the waste rock body as identified by NB Coal Limited reconnaissance in February, 1994. These voids may or may not have extended through the entire depth of the waste rock but, as was identified, the slurry did enter the openings and large quantities of coagulated sludge was deposited at depth within the back filled waste rock.

The impact of these chimneys was highlighted by the field investigation after the fall 1994 dredging project. The four ponds dredged in the fall of 1994 were pumped at a rate of six days per pond which corresponded to about 78 million litres/pond at a rate of 2,000 imp. gal./min. (obtained from the dredge crew). The water content (by dry weight) of the effluent was measured to be between 1,400 and 3,000% which corresponded to an interparticle water content by total volume of between 96.3 and 98.3% (the definition of water content has been previously described in section 3.4). If an average water content of 2,000% was assumed (where the interparticle water content was 97.5%) the mass of (porous) solids pumped was about 3.8 million kg. per pond or a total of about 15 million kg. of porous solids from the four ponds dredged in 1994.

The area covered by congealed effluents was not known exactly but was estimated to be 200 by 200 metres (10 acres). The water content of the congealed material was about 560% (interparticle water content 91.6%) so the total volume of sludge should have been about 91 million litres or 91,000 m^3. This would have corresponded to an average thickness of sludge on the surface of about 2.3 m. whereas the actual thickness sampled was about 0.1 m. or less. This calculation suggested that as much as 96% of the sludge pumped by the dredge penetrated into the voids of the mined rock fill.

5.1.2 DREDGED SLUDGE: 1995 RECONNAISSANCE (Gemtec Ltd., 1995)

The July 1995 reconnaissance was designed to check the extent and depth of the area covered by slurry from the 1994 dredging operations. Because of recent major excavations in the area, it was not possible to check the exact 1994 sludge depositional area but the depth observations carried out showed that the depth was larger than previously assumed. The depth assumed before was 0.2 m. whereas the revised depth is 0.5 m. This highlighted the variance in volumes and weights of pumped sludge which would produce this difference between the calculated and observed depths of congealed slurry.

The field tests with a Cat D-10-N dozer showed that it is possible to mix the sludge, deposited on and in the rock fill with the finer portion of the rock fill to decrease the overall permeabillity of the rock fill.

Photos from the July 11 reconnaissance are shown in Appendix M together with brief descriptions of the tests.

5.2 TRENCH EVALUATION

Dredged sludge from the lime neutralization sludge sedimentation ponds was deposited on the waste rock on the reclaimed mine site four times between fall of 1992 and the fall of 1994. Each operation had a mandate to place the sludge on the waste rock and minimize the amount of sludge that penetrated into the waste rock.

In order to evaluate the physical behavior of the sludge on the waste rock when applied as a surface amendment, four test pits were excavated into the waste rock in the sludge depositional areas.

Observations made at each pit area included surface vegetation and consistency, and thickness and depth of penetration of the sludge.

There was usually little or no evidence of sludge 0.6 to 1m below the waste rock surface. However, in test pit 4, a rock chimney was intersected at the 0.6 to 1m depth. The sludge in the chimney was a mixture of dried granular and powder similar to that found on the surface and moist two to eight centimeter blebs which had retained their gelatinous consistency. The chimney was evidence of the channels that the sludge used to penetrate into the rock fill as discussed in section 5.1.1 as there was little evidence of large volumes of pumped sludge on the rock surface.

Details of the excavation of each trench can be found in Appendix N.

6.0 CONCLUSIONS

6.1 EVALUATION OF LEACHATE QUALITY (CELLS & BARREL REACTORS)
(Edited from Grace Dearborn Inc., June 1996)

The Fire Road lime neutralization sludge has proven to be an effective amendment for the acid generating waste rock at the abandoned Fire Road mine. Current relocation practices of dredging the aged sludge onto the surface of the waste rock has indicated that the procedure has several benefits including providing a low cost final disposal area for the sludge with no adverse environmental effects and providing alkalinity to reduce the mine water acidity.

The weathering cells and reactor barrels illustrated that the aged sludge did not prevent the generation of acidity by pyrite oxidation, nor did it accelerate the acid formation process. The sludge also provided alkalinity for the in-situ neutralization of the acid produced which was evident from the conditions observed within the amended leachate samples in comparison with the control leachates.

In the weathering cells, which contained a high ratio of sludge to waste rock, the following results were obtained from these alkaline conditions:

1. Low acidities (consistently less than 20 mg/L as $CaCO_3$ to pH9)
2. Low *Thiobacillus ferroxidans* counts
3. Low soluble metal concentrations
4. High pH values (between 7 and 8)
5. Same degree of pyrite oxidation in all cells

The metal hydroxides contained in the sludge did not dissolve in the presence of acid generating material in the conditions investigated as evident by the low soluble metal concentrations. In addition, all amended cells have retained their excess alkalinity which indicates that the available alkalinity is released at approximately the same rate as the acid is generated.

The leachate from the reactor barrels was acidic immediately after the reactors were assembled as it leached the stored acidity from the crushed rock. The reactors were more acidic and of a lower pH than the weathering cells throughout the investigation because of the lower sludge application rate.

In both the cells and the reactors, there is no evidence of metals redissolving from the aged sludge in the conditions investigated.

6.2 GEOTECHNICAL EVALUATION OF SLUDGE RELOCATION METHODS (Gemtec Ltd., 1995)

Several methods of depositing the pumped slurry in the rock fill waste area were considered:

a) surface deposition, drying and compaction,
b) filling of rock fill voids with congealed slurry, and;
c) surface deposition and mixing with rock fill.

Method a) was estimated to require about 18 years for the production of a 0.5 m. thick layer of compacted sludge. The calculations and assumptions are presented in Appendix O. The sludge would be compacted at a water content of 150%, as defined in section 3.4, to a dry density of 500 kg/m^3. This combination would, however, yield a coefficient of permeability (k) as high as 10^{-5} to 10^{-4} cm/sec. The rate of seepage through a 0.5 m. thick layer of compacted intact (not cracked) sludge covered with 0.5 m. of water would be in the range of 6,000 to 60,000 mm/year, as compared to an annual rainfall of typically 1,100 mm/year. Therefore, it would be impossible to maintain a body of water on top of the sludge.

Method b) was not feasible since the slurry did not, in general, seem to penetrate much deeper than about 0.3 m. into the rock fill (except in the chimneys and vents described above).

None of the solutions considered above require a permanent seal of water on the sludge. Without the water, the sludge would dry relatively rapidly and crack extensively. Tests have shown that cracking occurred whether the sludge was deposited wet or was compacted in an almost dry state. The cracking increased the sludge permeability. Laboratory tests also showed that the cracking process was not reversible (i.e. the cracks did not close after rewetting).

Method c) appeared to be the most promising method. Calculations indicated that the production of 1 to 2 m. thick layer of mixed rock fill and sludge would take 7 to 25 years to produce (Appendix O), depending on the actual water content of the congealed slurry and on its thickness. This option would slightly decrease the permeability on the surface of the rock fill by the mixing in of the finer grained sludge but would still allow for the utilization of the residual lime in the sludge to neutralize the minewater in-situ within the backfilled waste rock pit.

6.2.1 RECOMMENDATIONS TO CURRENT SLUDGE RELOCATION PRACTICES (Gemtec Ltd., 1995)

The method used presently by NB Coal, viz dredging, pumping and depositing the sludge as a slurry in the waste rock fill area seems to be the most promising method, although the present approach should be somewhat improved and streamlined. The following approach would lead to the best possible use of the sludge to seal the waste rock fill area.

1. Produce a relatively plane sloping rock fill surface by working it with a larger dozer. The best results would be achieved if most of the large rocks could be pushed aside (and stockpiled temporarily) rather than buried. When the contouring has been completed, the rocks could be brought back and placed on the prepared surface.

2. Lay the perforated dredge pipe parallel to the strike of the slope and next to a low overflow ridge so as to provide an even spreading of the slurry.

3. At the end of the dredging season, mix the congealed sludge with the finer portion of the rockfill by pushing and back dragging with a large dozer.

4. Repeat steps 1 - 3 the following year in the same area to increase the depth and concentration of the slurry in the rock fill, or repeat steps 1 - 3 in an adjacent area.

The penetration of the sludge into the rock fill void can be monitored by conducting sample trenching during the spring or summer following the previous years sludge relocation operation. It is possible that the rock fill-sludge mix will not yield a permeability quite as low as that required but this cannot be ascertained without actual field mixing and field or laboratory permeability testing.

ACKNOWLEDGMENTS

Funding for this project was provided in part by CANMET. The September, 1995 Progress Report was reviewed by Dr. P. Ziemkiewicz and Mr. G. Landry.

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APPENDIX A

Neutralization and Acid Generation Determination Procedures, Sample Calculations and Results

(edited from Grace Dearborn, Inc., June, 1996)

Neutralization/Acid Generation Procedure

The most critical parameter of interest with regard to the sludge relates to its neutralization potential or equivalent free available lime content. In order to determine this characteristic, standard acid base accounting was performed on each sample in triplicate (due to the heterogeneous nature of the materials). However, since it is reasonable to assume that all of the sulfur contained in the sludge would be present in the sulfate form as calcium sulfate, the interpretation of results was modified as follows:

- Determine the total sulfur content by Leco furnace (Sobek, et.al., 1978).
- Convert this value to the equivalent calcium sulfate content instead of sulfuric acid which would normally be assumed.
- Determine the standard acid consumed (Duncan and Bruynesteyn, 1979) by the sample and convert this to the equivalent free available calcium oxide content (see sample calculation).

Based on this technique, the equivalent neutralization potential of the sludge samples were determined and the results are presented in Table A-1.

Table A-1
Sludge Neutralization Potentials

Sample Description	Moisture Content (%)	Sulfur Content (%)	Theoretical $CaSO_4$ Content (lb/ton)	Theoretical $CaSO_4$ Content (%)	Acid Consumption (lb/ton)	Theoretical CaO Content (wt. %)
Fresh Sludge	88.9 89.0 88.9	0.55 0.55 0.56	46.5 46.6 47.5	2.33 2.33 2.37	58.8 58.8 59.8	1.68 1.68 1.71
Average	88.9	0.55	46.8	2.34	59.1	1.69
Aged Sludge	88.5 88.7 88.5	0.69 0.69 0.67	58.8 55.4 57.3	2.94 2.77 2.86	66.2 64.1 66.1	1.89 1.83 1.89
Average	88.6	0.67	57.2	2.86	65.5	1.87
Mixed Sludge	88.4 88.4 88.2	0.65 0.63 0.65	55.2 53.4 55.2	2.76 2.67 2.76	62.9 62.5 63.4	1.80 1.79 1.81
Average	88.3	0.64	54.6	2.73	62.9	1.80

Note: All results are wet weight basis.

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Table A-2

Waste Rock Characterization by Acid Generating Potential

(Grace Dearborn Inc., March 1995)

Cell Number	Moisture Content (%)	Sulfur Content (%)	Theoretical Acid Production (lb/ton)	Theoretical Acid Consumption (lb/ton)
1A	5.22	0.16	9.86	<0.5
2A	4.73	0.38	23.34	<0.5
3A	5.10	0.29	18.03	<0.5
1B	6.41	0.37	22.93	<0.5
2B	6.29	0.37	22.96	<0.5
3B	6.10	0.29	17.84	<0.5
1C	7.37	0.44	27.23	<0.5
2C	6.60	0.31	18.87	<0.5
3C	7.81	0.34	20.83	<0.5
Average	6.18	0.33	20.21	<0.5

Note: All results are wet weight basis.

CONVERSION OF % S
TO THEORETICAL ACID GENERATING POTENTIAL (WASTE ROCK) & CALCIUM SULFATE CONTENT (SLUDGE)

FOR ANALYSIS OF ACID GENERATING ROCK:

$$\text{Theoretical AGP (lb/ton)} = \frac{\%S}{100} \cdot 2000 \cdot \frac{MW_{H_2SO_4}}{MW_S}$$

WHERE: Molecular Weight (MW) H_2SO_4 = 98.07
Molecular Weight (MW) S = 32.06
% S = % Sulfur

EXAMPLE: If % S = 0.38%

$$\text{Theoretical AGP} = \frac{0.38}{100} \cdot 2000 \cdot \frac{98.07}{32.06} = 23.34\ \text{lb/ton}$$

FOR ANALYSIS OF SLUDGE:

$$CaSO_4\ \text{Content (lb/ton)} = \frac{\%S}{100} \cdot 2000 \cdot \frac{MW_{CaSO_4}}{MW_S}$$

WHERE: Molecular Weight (MW) of $CaSO_4$ = 136.14
% S = % Sulfur = 0.38%

EXAMPLE: If % S = 0.55%

$$CaSO_4\ \text{Content} = \frac{0.55}{100} \cdot 2000 \cdot \frac{136.14}{32.06} = 46.6\ \text{lb/ton}$$

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CONVERSION OF ACID CONSUMPTION TO THEORETICAL CALCIUM OXIDE CONTENT

BASIS:

$$H_2SO_4 + CaO - H_2O + CaSO_4$$

$$CaO\ Content\ (wt\ \%) = \frac{lbs\ H_2SO_4}{ton} \cdot \frac{MW_{CaO}}{MW_{H_2SO_4}} \cdot \frac{1}{2000} \cdot 100$$

WHERE: Molecular Weight (MW) H_2SO_4 = 98.07
Molecular Weight (MW) CaO = 56.08
lbs H_2SO_4 = Acid Consumption

EXAMPLE: If acid consumption = 58.8 lbs/ton

$$CaO\ Content = 58.8 \cdot \frac{56.08}{98.07} \cdot \frac{1}{2000} \cdot 100 = 1.68\%$$

APPENDIX B

X-ray Diffraction Trace

(Grace Dearborn Inc., June 1996)

Principles Behind X-ray Diffraction

X-ray diffraction involves the interaction of an x-ray beam with a solid sample. The x-rays, when they strike a crystal structure (molecule), experience diffraction characteristic of the crystal structure. This shattered wavelength is directly proportional to the distance between the scattering centers (atoms).

When an x-ray beam strikes a crystal surface at an angle 0, a portion of the beam is scattered by the first layer of atoms on the surface of the crystal structure. The unscattered portion of the beam penetrates to the second layer of the crystal and is also partially scattered. This process occurs until the beam is fully scattered. The results of this process are a diffraction pattern which is highly specific for each individual crystal structure.

From this specific diffraction pattern the molecule present can be identified. Diffraction is only a viable analytical tool if the scattering centers (atoms) of individual molecules are regularly spaced (i.e. a crystalline structure) and if the appropriate radiation wavelength is used. Generally the radiation accepted is produced by a copper tube and has a wavelength of 1.54A.

Interpretation of X-ray Diffraction scans is carried out using the Bragg equation,

$$n\lambda = 2\, d \sin \theta$$

where n = orders of reflection
d = interplanar spacing
θ = angle of diffraction of x-rays
λ = wavelength of x-rays used

From a listing of “d spacings” and relative intensities identified produced by JCPDS and also an elemental analysis, a pattern match on the crystalline substances contained in the samples is carried out using a computer. Since the angular travel of the detector is double the distance of the sample, the angles recorded are noted as 2θ, as shown on the scans. Most crystalline substances exhibit patterns particular to their crystal structure.

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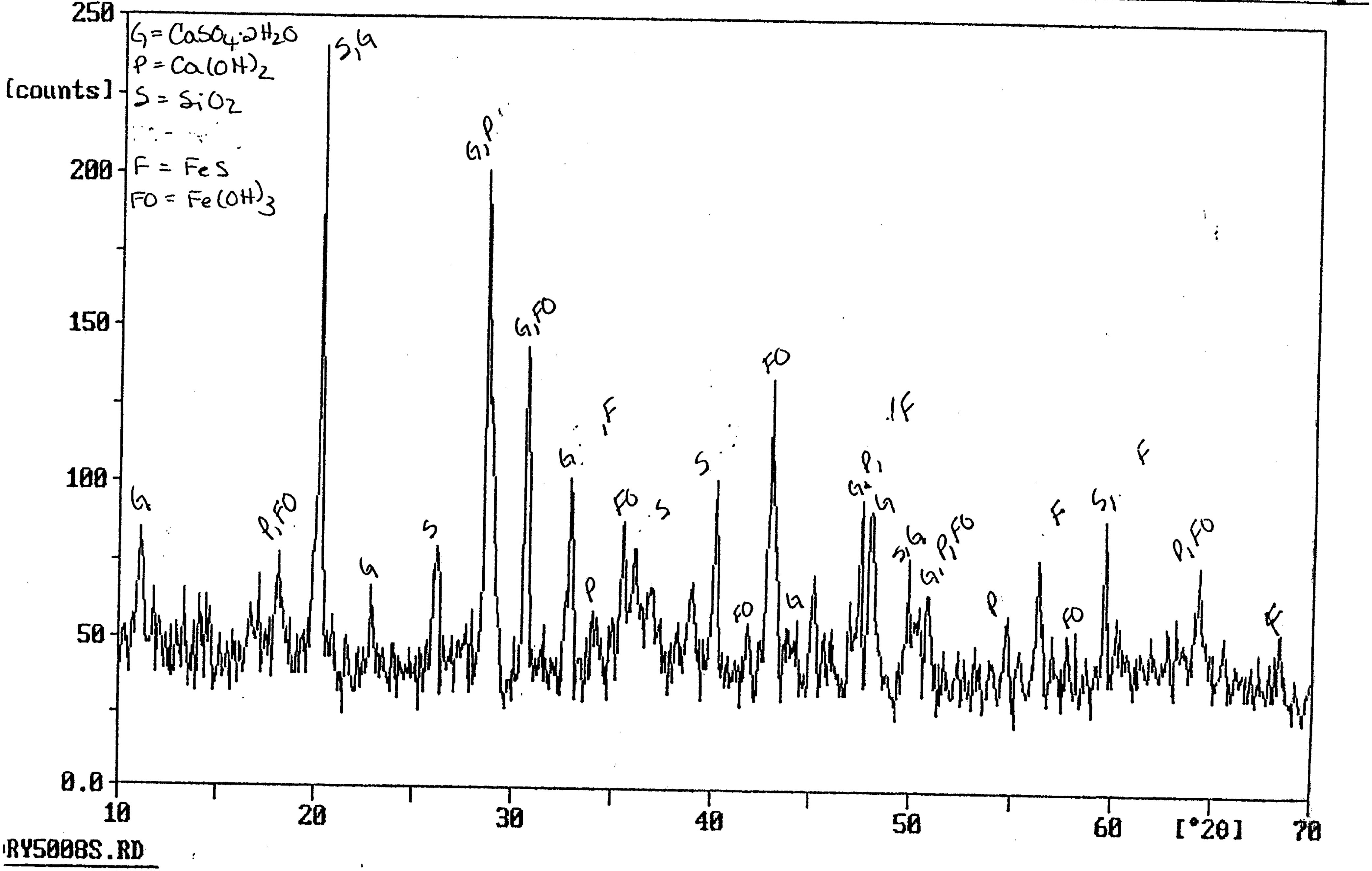


APPENDIX C

Metal Analysis from Digested Sludge Solids

(from Grace Dearborn Inc., June, 1996)

Table C-1

Metals Analysis of Digested Sludge Solids (µg/g)

Parameter	Concentration (µg/g)
Al	114847
Ca	88023
Cd	4.91
Cu	81.98
Fe	57040
Mg	21343
Mn	22815
Ni	476
Pd	< 15
Zn	1359

Note: All results are wet weight basis.

APPENDIX D

Morphological Evaluation of the Sludge Includes:
Index Properties, Grain Size Evaluation & SEM
(Gemtec Ltd., 1995)

SUMMARY OF INDEX PROPERTIES

Material	Date sampled	Pail No.	Moisture content, %	Density kg/m3	Specific gravity
Dredge pipe slurry	94-11-03	1A	1648	1013	
		1B	1920	1038	
Dredge pipe slurry	94-10-28	2A		1043	
		2B		1023	
Dredge sludge	94-10-28	4A	734		
		4B	612		
		4C	710		
		4D	682		
		4E	770		
		4F	735		
		4A-4F			3.17,3.16,2.88,2.87,2.97,2.97 3.02,2.97,2.75,2.83,2.72
86-1,TP2,S1,0-2',1of 2		5	560		
86-1.TP2,S1,0-2',2of2		6			
86-1,TP2,S2,2-4',1of2		7	567		
86-1,TP2,S2,2-4',2of2		8			
88-1,TP1,S1,0-3'		9	874		
88-1,TP2,S1,3-6'		3A,3B	604		
88-1,TP2,S2,6-8'		10	842		2.44,2.39
88-1,TP2,S2,5-8'		11			
89-2,TP1,S1,0-2.5'		12	667		2.77,2.80
89-2,TP1,S2A,2.5-5',1of3		13	937,937		2.50,2.51
89-2,TP1,S2B,2.5-5',2of3		14	891		
89-2,TP1,S3,2.5-5',3of3		15	937		
Dry pond sludge	94-10-28	16	211		
		17	205,208		
Dredge pipe slurry (sampled in mason jars)	94-10-28	Jar 1	3019		Thin slurry,end of pipe
		Jar 2	1411		Thick slurry, end of pipe
		Jar 3	2563		Sampled 0.6m from end of pipe

Atterberg limits

Pail No.	Liquid,%	Plastic,%
5	416	135
9	673	145
15	418	132

Legend
86-1: Holding pond #1,sludge deposited in 1986
TP2: Test pit #2 (excavated October 28,1994 with backhoe)
S1: sample 1

NB Coal Ltd
Fire Road Stabilization
Sludge Seal
Geotechnical Investigation

GEMTEC LIMITED
191 Doak Road
Fredericton, N.B.
Canada, E3B 4X2

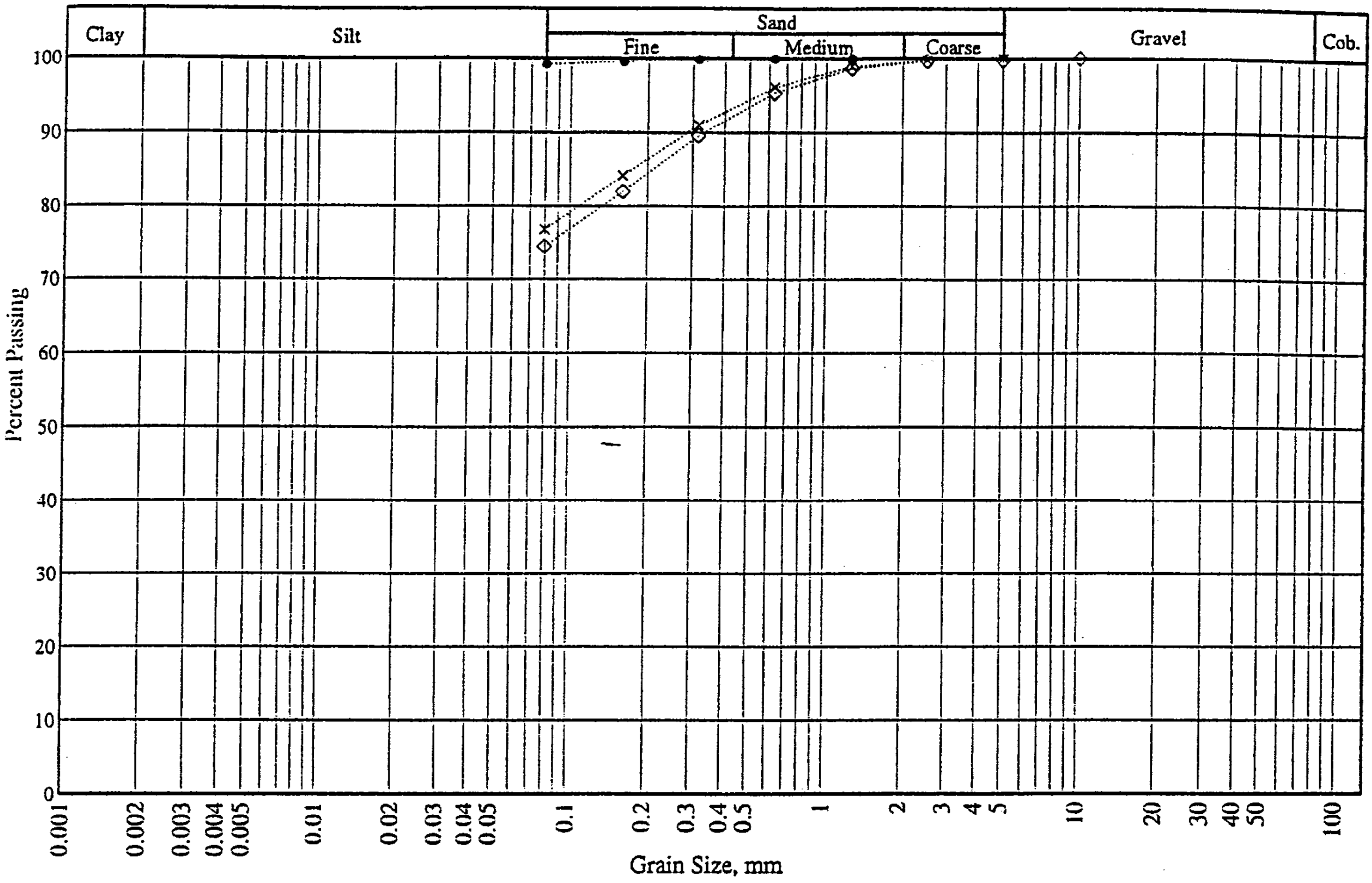
Client: NB Coal

Project: Geotechnical Evaluation Of Sludge Seal, 1994

Project No.: 269.15

Date: 94-11-02

Grading Chart
Soils



Line Symbol	Sample Location	% Gravel	% Sand	% Silt	% Clay	ID Number
····●····	Dredge Sludge 94-10-28 (Not Dried)	0.0	0.7	99.3		000386988
····×····	Freeze Dried Material,Pail #16	0.0	23.2	76.8		000405076
····◇····	Freeze Dried Material,Pail #17	0.2	25.2	74.5		000405552

Line Symbol	Sample Description	D_{10}	D_{15}	D_{85}	% 5-75 um
····●····	Silt	--	--	--	--
····×····	Sandy silt	--	--	0.1768	--
····◇····	Sandy silt	--	--	0.2205	--

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GEMTEC LIMITED
191 Doak Road
Fredericton, N.B.
Canada, E3B 4X2

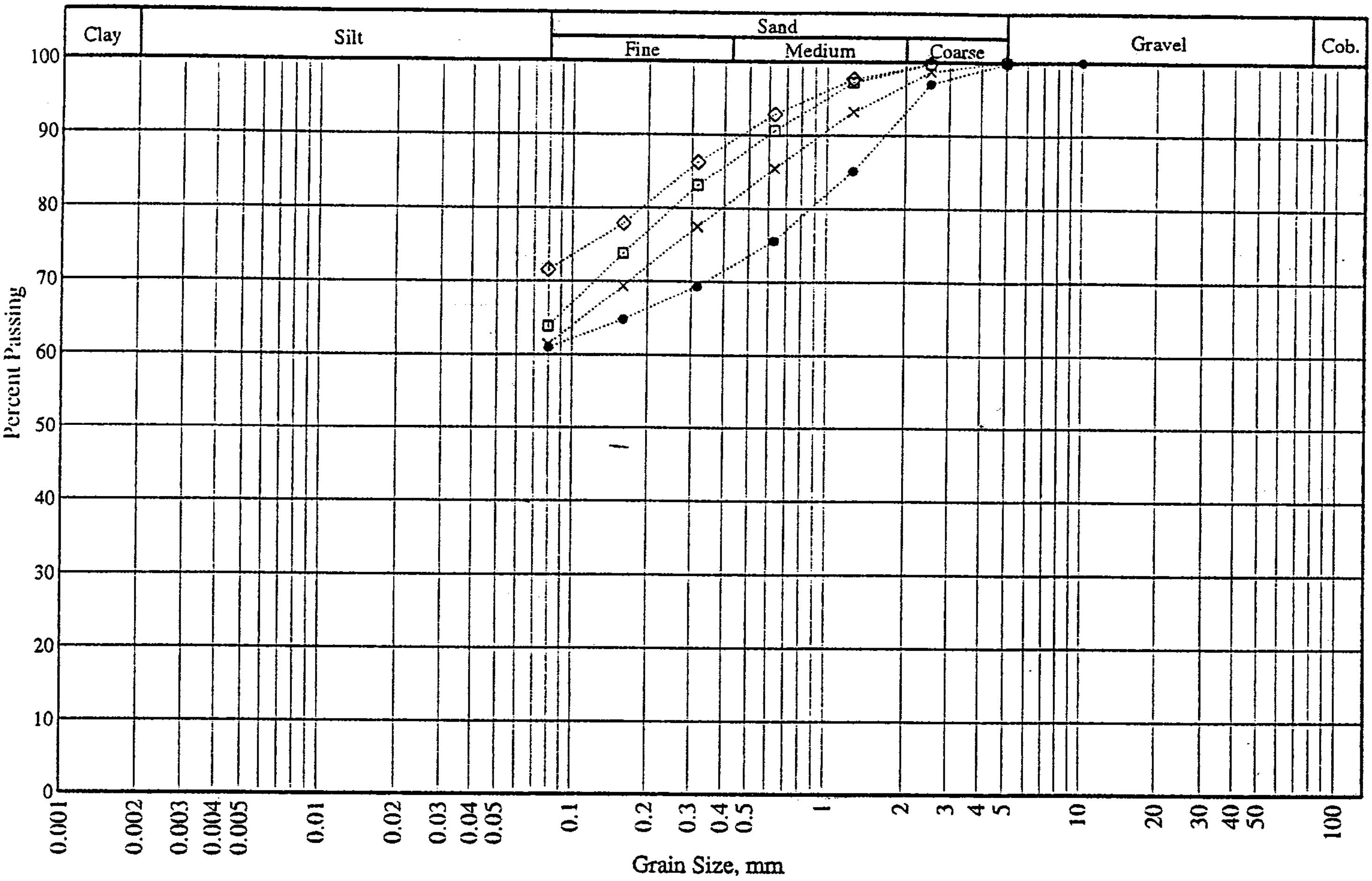
Client: N.B. Coal

Project: Geotechnical Evaluation Sludge Seal 1994

Project No.: 269.15

Date: 94-11-16

Grading Chart Soils



Line Symbol	Sample Location	% Gravel	% Sand	% Silt	% Clay	ID Number
●	Dredge Sludge 94-10-28 (Air Dried)	0.1	39.0	60.9		000394604
×	Dredge Sludge 94-10-28 Dried At 40C	0.0	38.5	61.5		000386512
◇	Dredge Sludge 94-10-28 Dried At 75C	0.0	28.4	71.6		000387464
□	Dredge Sludge 94-10-28 Dried At 110C	0.0	36.1	63.9		000386036

Line Symbol	Sample Description	D_{10}	D_{15}	D_{85}	% 5-75 um
●	Silt and sand	- -	- -	1.2375	- -
×	Silt and sand	- -	- -	0.6094	- -
◇	Sandy silt	- -	- -	0.2911	- -
□	Silt and sand	- -	- -	0.3913	- -

SCANNING ELECTRON MICROSCOPE (SEM) INVESTIGATION

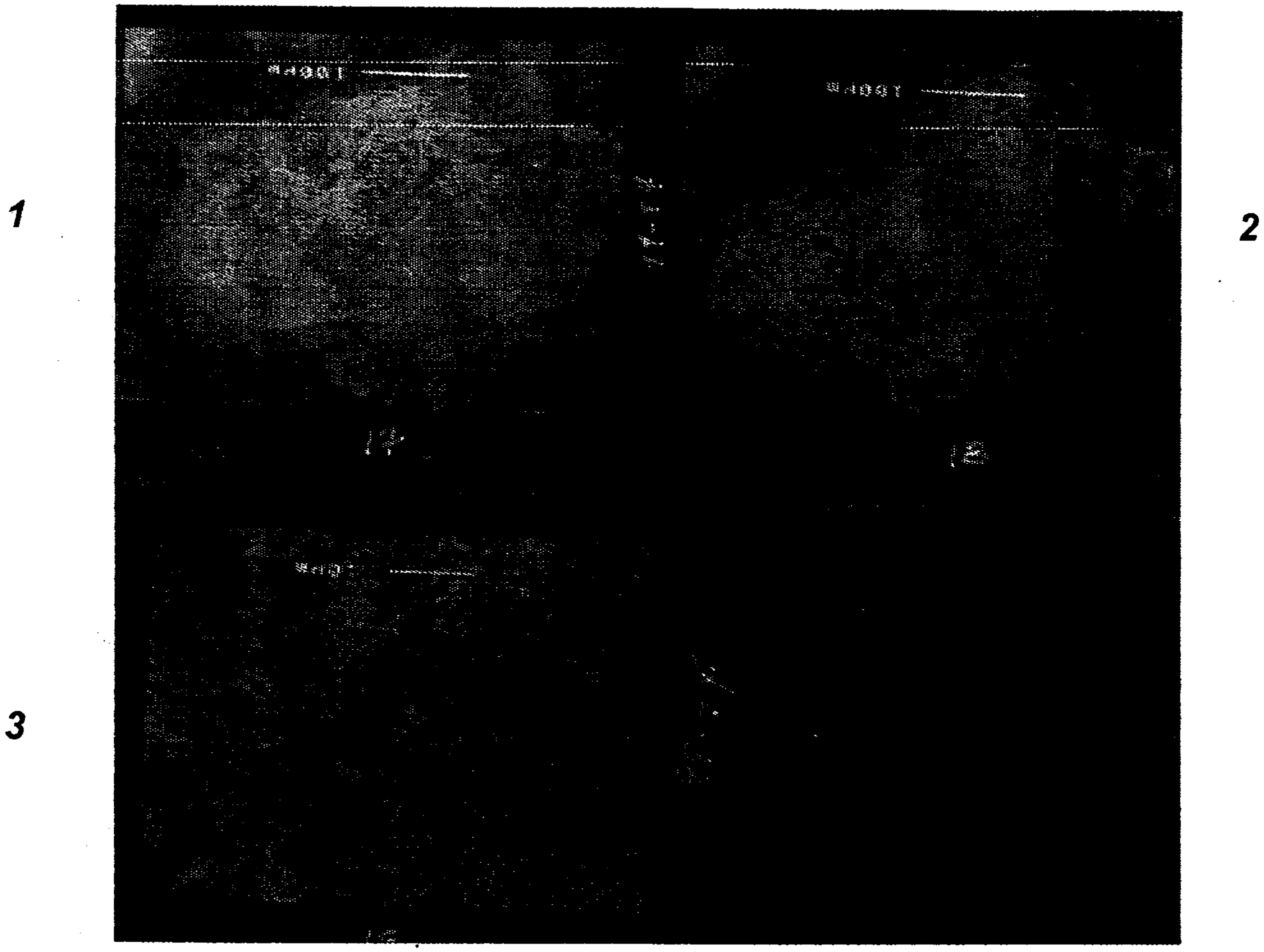
The scanning electron micrographs of various particles of the sludge (SEM I and II attached) show that the sludge particles are porous to varying degrees, either throughout - as in SEM II. 1 and 2 - or locally - as in SEM II. 5 and 6 - or almost non-porous - as in SEM II. 3 and 4. The particles shown in SEM I seem to have a porous (fluffy) cover on a solid core.

The sludge particles were taken from samples of sludge deposited and congealed in ponds 86-1 and 89-2. All particles used in the SEM investigation were oven-dried at 105°C.

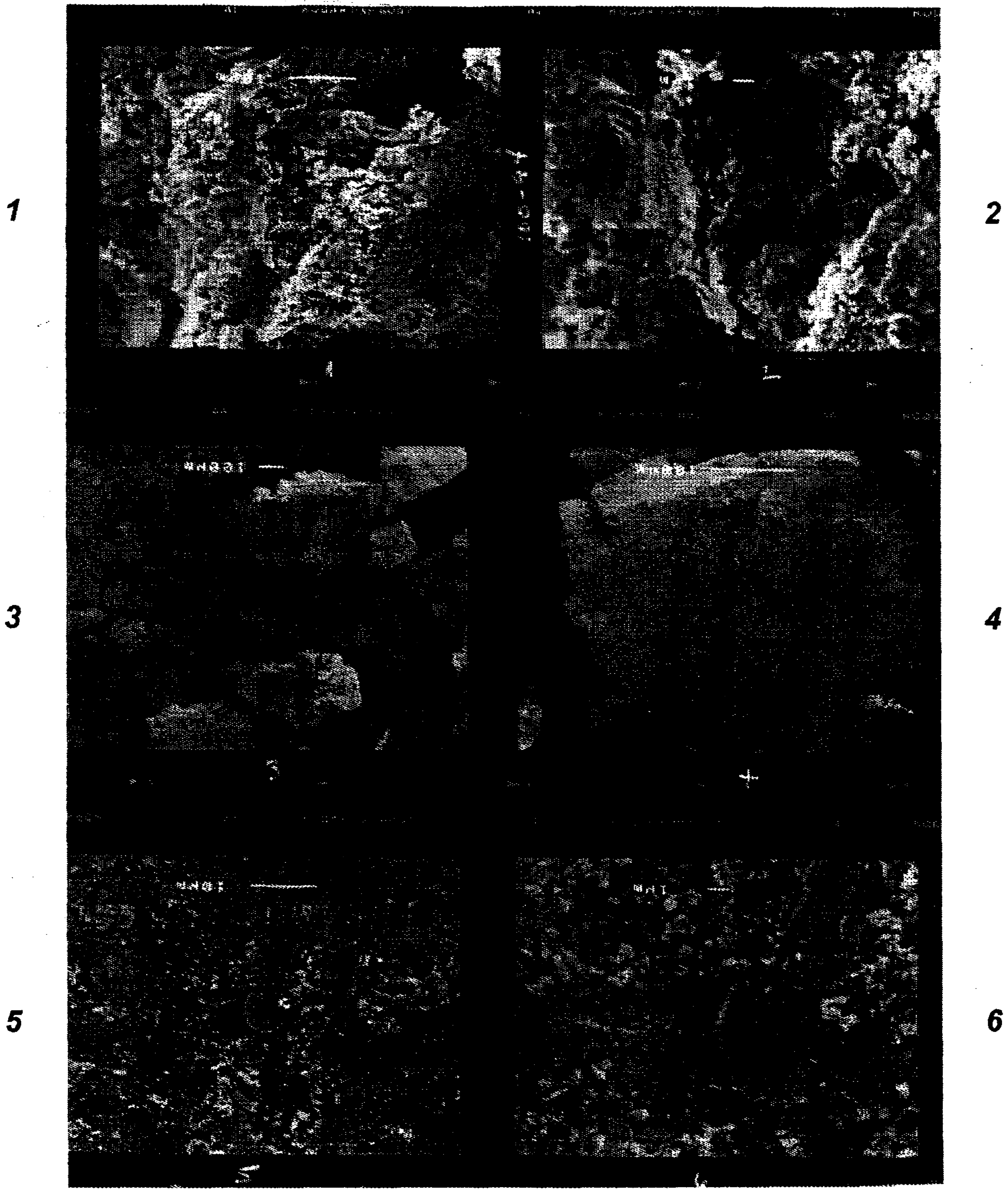
The results of a simple mineralogical analysis are shown in SEM III to VI. The Au presence in the diagram is the gold used for coating the dried particles before the SEM investigation.

Both the fluffy cover (SEM II. 1 and 2) and the apparently bald surface (SEM II. 3 - 6) show relatively high counts of calcium and sulphur, but the bald surface seems to contain more aluminum, iron silica, magnesium, and manganese.

SEM VI shows the mineral counts for a mixture of fluffy cover and bald surface, such as that shown in the SEM I. 2 micrograph, hence the "mixed" type of diagram.



SEM I. Sludge particles from pond 89-2, TP1, S2B, (1 and 2: mag. 138x).
3: isolated bald surface (mag. 1100x).
1994 Oct. 21.



SEM II. 1 and 2: isolated covered surface on SEM I.2
(1: mag. 1100x , 2: mag. 3300x)
3 to 6 : sludge particles from pond 86-1, TP2, S2
(3: mag. 41x , 4: mag. 138x , 5: mag. 1100x , 6: mag. 3300x).
1994 Oct. 21.

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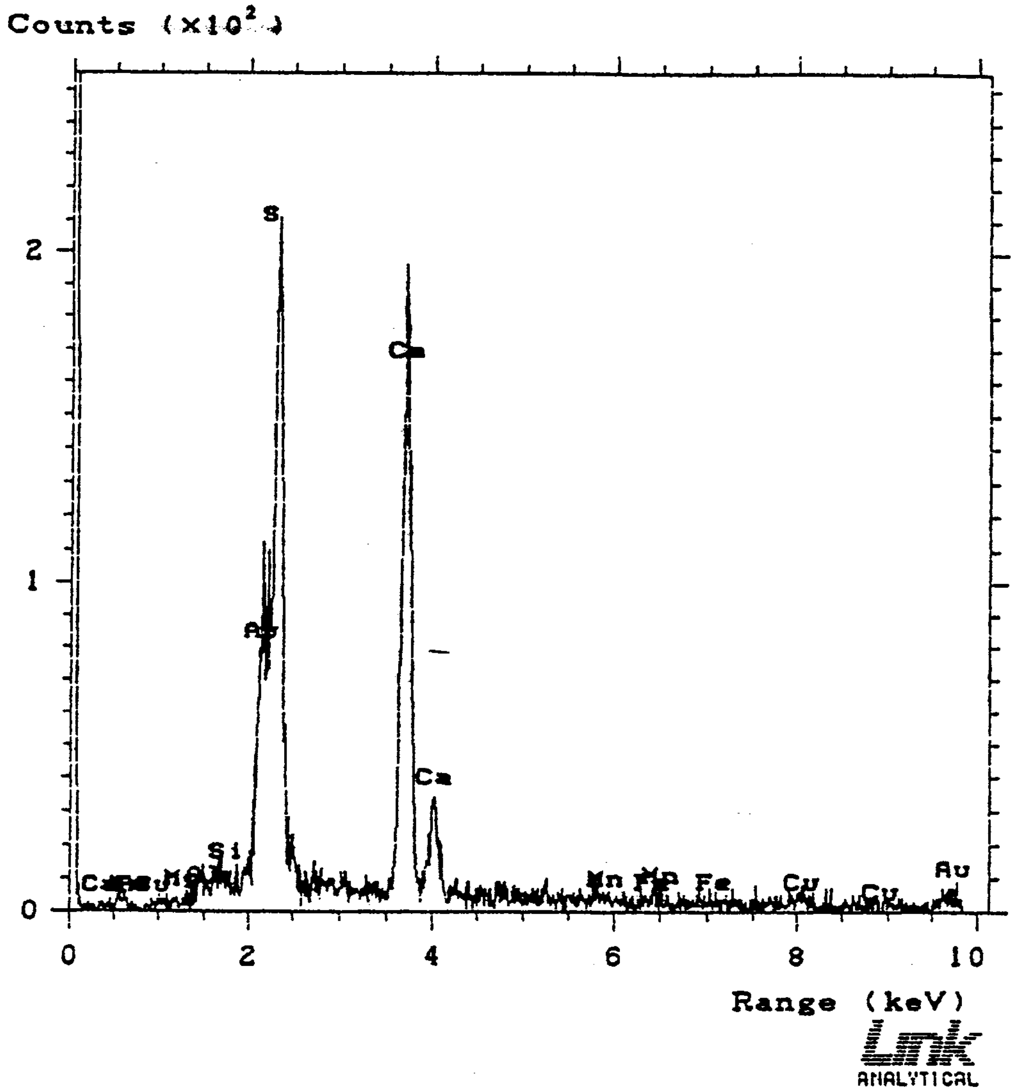

SEM III. Scanning electron microscope mineralogical analysis. Sludge particle from pond 89-2, TP1, S2B, as shown in micrograph SEM I. 2 (calcium sulphate fluffy surface cover).1994 Oct. 21.

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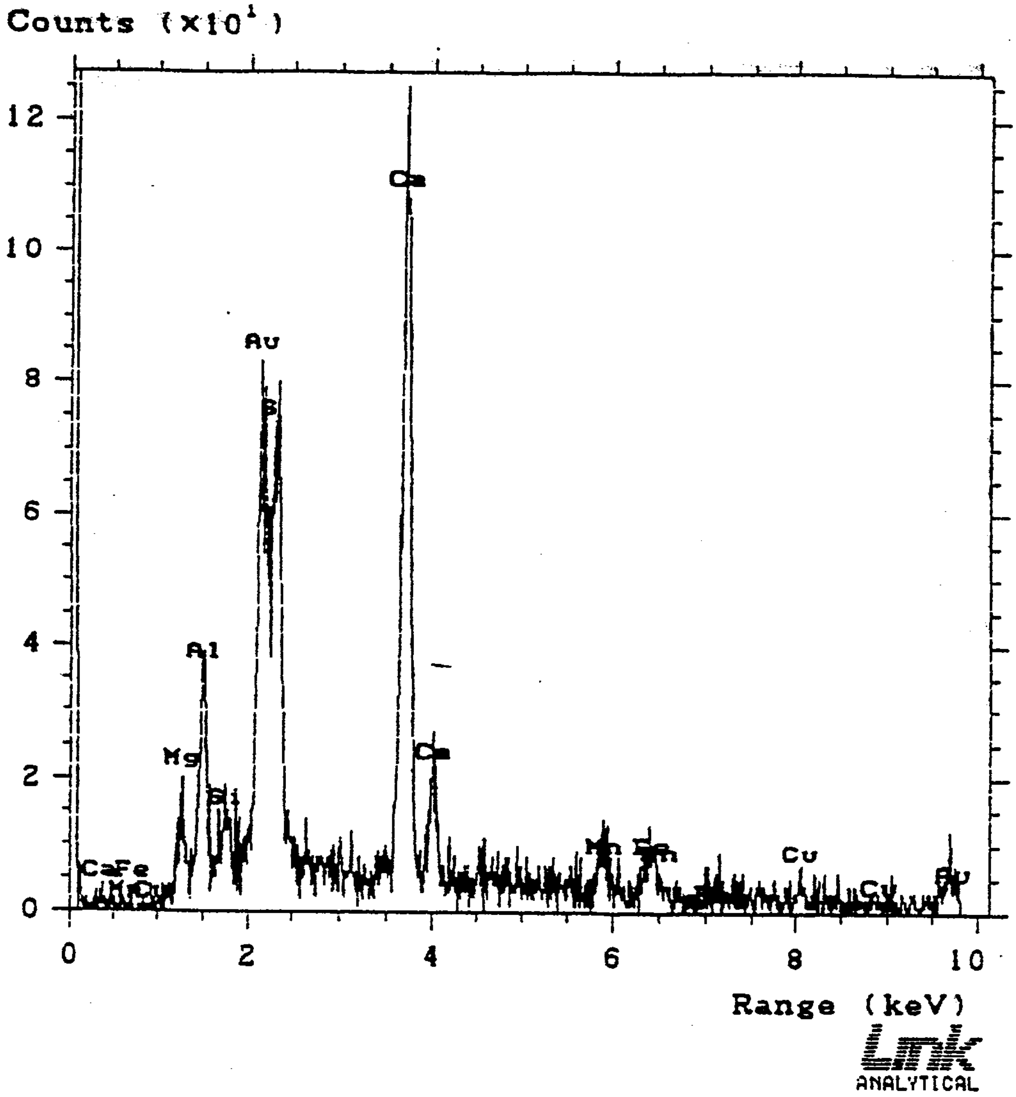

SEM IV. Scanning electron microscope mineralogical analysis. Sludge particle from pond 86-1, TP2, S2, as shown in micrograph SEM II. 3-6 (bald surface from crystallized precipitate). 1994 Oct. 21.

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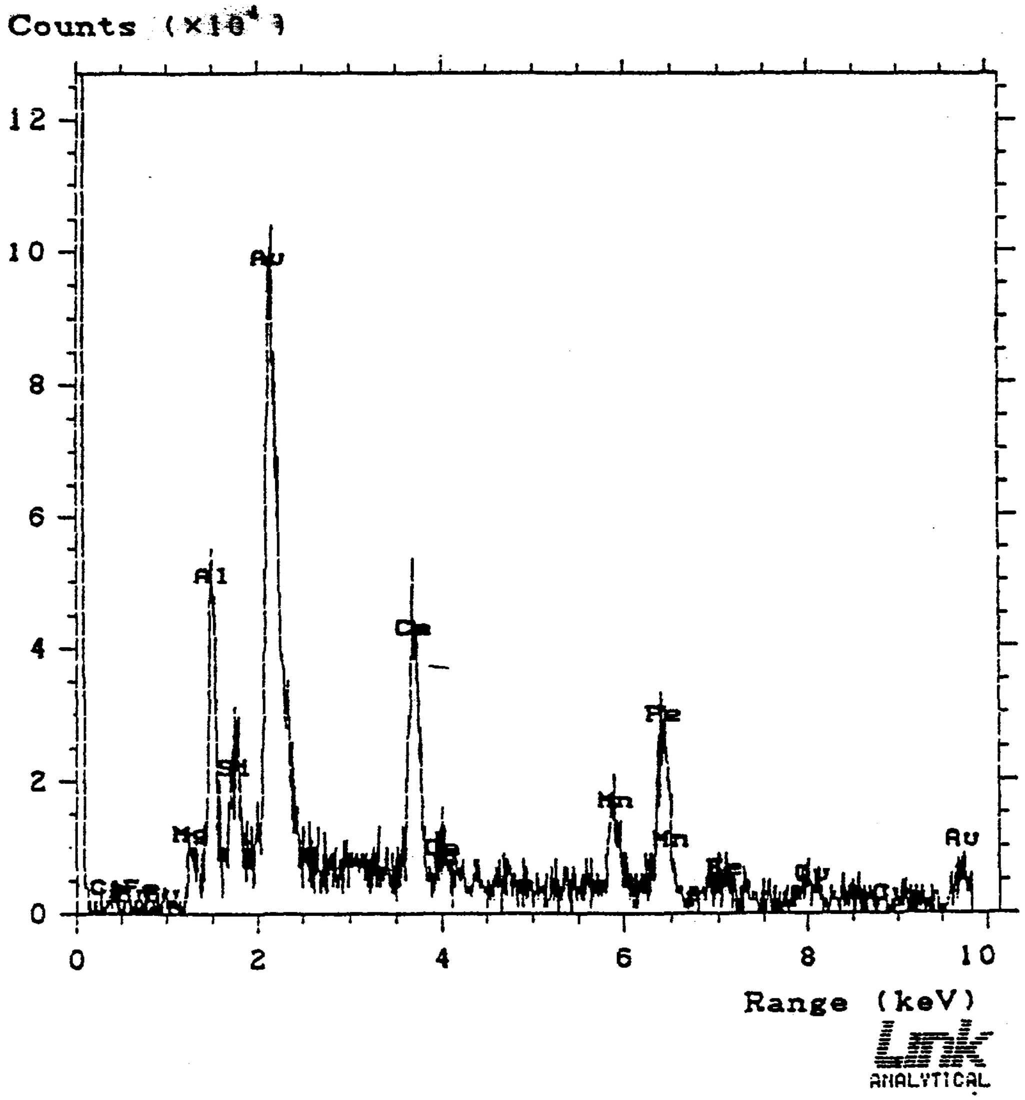
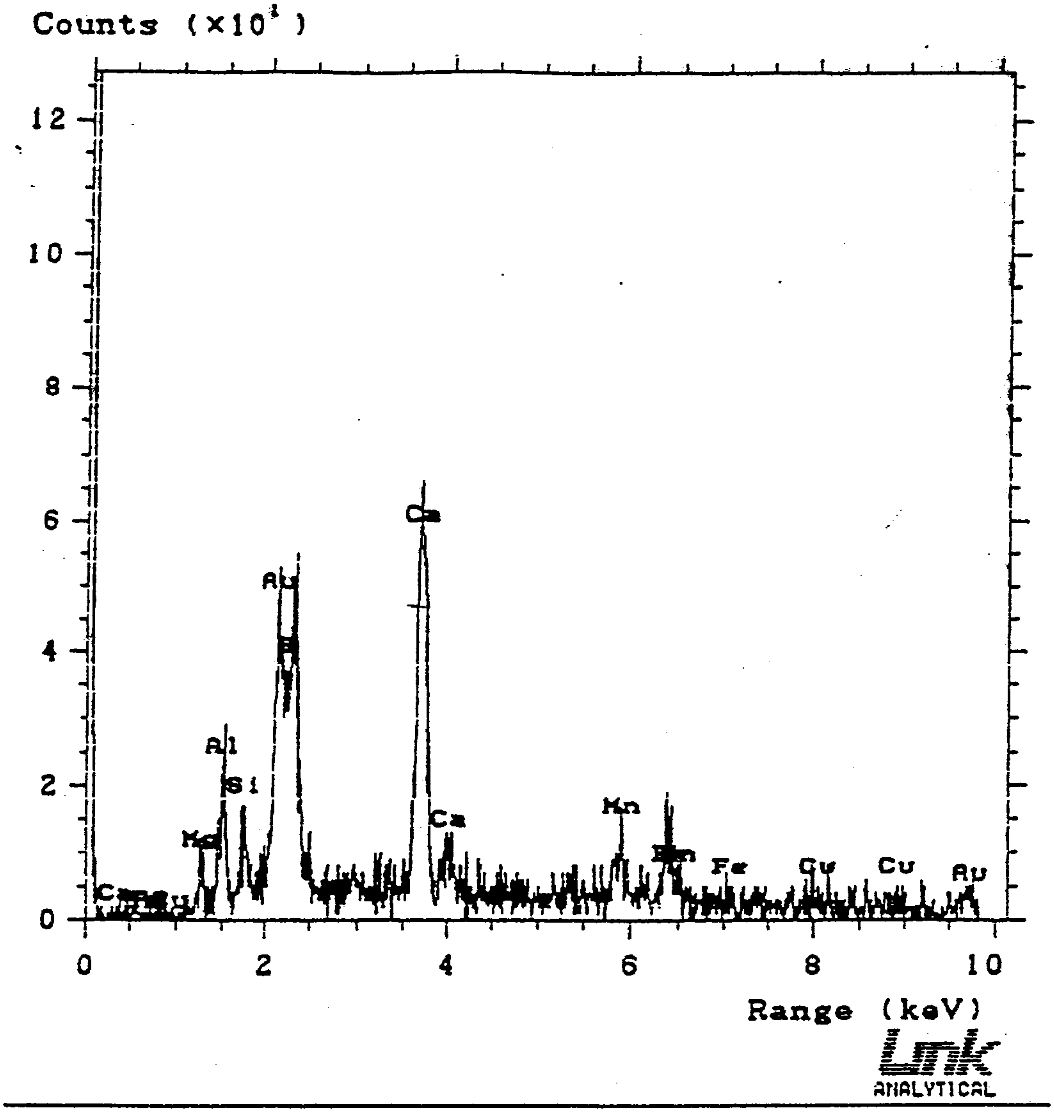


SEM V. Scanning electron microscope mineralogical analysis. Sludge particle from pond 89-2, TP1, S2B, as shown in micrograph SEM I.3 (isolated bald surface). 1994 Oct. 21.



SEM VI. Scanning electron microscope mineralogical analysis.
Sludge particle from pond 88-1, TP2, S2. 1994 Oct. 21.

APPENDIX E

Geotechnical Evaluation Definitions of Specific Gravities, Definitions of Water Content and Dry Densities

(Gemtec Ltd., 1995)

DEFINITIONS OF SPECIFIC GRAVITIES

For porous particles, ASTM (C128) distinguishes between

(i) "bulk specific gravity" S_d, which corresponds to the dry density ρ_d of any one particle ($\rho_d = M_s/V$, where M_s is the dry mass and V = volume of solids and intraparticle voids within the porous particle); $S_d = \rho_d/\rho_w$,

(ii) "bulk specific gravity, saturated surface-dry" S_s, which corresponds to the saturated density ρ_s of any one particle ($\rho_s = (M_s + M_{wia}/V$, where M_{wia} is the mass of the water within the particle); $S_s = \rho_s/\rho_w$, and

(iii) "apparent specific gravity" S_a, which corresponds to the density ρ_a of the solid portion of any one particle ($\rho_a = M_s/V_s$, where V_s is the volume of the solid portion only); $S_a = \rho_a/\rho_w$.

The particles in the holding ponds and those pumped by the dredge may be assumed to be saturated, i.e. their density would correspond to the saturated surface dry condition under (ii) above: $\rho_s = S_s\rho_w$. The average S_s of the sludge material may be taken to be 1.96

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DEFINITIONS OF WATER CONTENTS AND DRY DENSITIES

Standard definitions of water contents of materials with solid constituents

By dry weight M_s: $w = \dfrac{M_w}{M_s}$

(M_w = weight of water)

By total volume V: $w_v = \dfrac{V_w}{V}$

(V_w = volume of water)

These are related by $w_v = \dfrac{wG_s}{wG_s + 1}$

(G_s = specific gravity)

Water contents of materials with porous constituents

It is clear from scanning electron microscopy investigations (Appendix D) that the sludge particles are porous, but the exact porosity is not known and cannot be accurately measured. However, on the basis of a comparison with micrographs of other porous materials, such as peats and paper sludge, we would estimate that the intraparticle porosity (n) of the sludge constituents is of the order of n = 0.30 (30%), i.e. the void ratio *e* is

$$e = \frac{n}{(1-n)} = 0.43$$

This leads to a saturated surface-dry specific gravity of

$$G_s = \frac{2.8}{1 + 0.43} * 1.0 = 1.96$$

where 2.8 represents the average specific gravity (18 tests, range 2.39 - 3.17) of the solid portion of the constituents (i.e. the same as S_a in Appendix), 0.43 is the void ratio of the porous constituents (corresponding to a porosity of 30%), and 1.0 is the density of water.

The water content measured by the standard method of drying the sludge in an oven includes the intraparticle water. This can be accounted for by expressing the water contents in terms of mass or volume of true solids (s), intraparticle water (wia), and interparticle water (wir):

Let M_s = mass of solids in the constituents

V_s = volume of solids in the constituents

M_{wia} = mass of intraparticle water within the constituents

V_{wia} = volume of intraparticle water within the constituents

M_{wir} = mass of interparticle water between the constituents

V_{wir} = volume of interparticle water between the constituents

V = total volume of solids, intraparticle water and interparticle water

ρ_w = density of water

The total water content w by dry weight of a material with porous constituents is

$$w = \frac{M_{wir} + M_{wia}}{M_s}$$

(which is the water content as measured)

The water content by dry weight with respect to interparticle voids only is

$$w_{ir} = \frac{M_{wir}}{M_s + M_{wia}}$$

The porosity of a typical constituent is

$$n_c = \frac{V_{wia}}{V_{wia} + V_s}$$

Hence

$$\frac{V_{wia}}{V_s} = n_c(\frac{V_{wia}}{V_s} + 1)$$

i.e.

$$\frac{V_{wia}}{V_s} = \frac{n_c}{1 - n_c}$$

Since

$$M_{wia} = V_{wia} * \rho_w ,$$

$$\frac{M_{wia}}{M_s} = \frac{V_{wia}}{V_s} * \frac{\rho_w}{\rho_s} = \frac{n_c}{1-n_c} * \frac{\rho_w}{\rho_s}$$

$$M_{wir} = w_{ir} (M_s + M_{wia})$$

from above, i.e.

$$\frac{M_{wir}}{M_s} = w_{ir}(1 + \frac{M_{wia}}{M_s})$$

$$w = \frac{M_{wir}}{M_s} + \frac{M_{wia}}{M_s} = w_{ir} (1+\frac{M_{wia}}{M_s}) + \frac{M_{wia}}{M_s}$$

$$= w_{ir}(1 + \frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s}) + (\frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s})$$

Example:

$$w = w_{ir} (1 + \frac{0.3}{0.7} * \frac{1.0}{2.8}) + \frac{0.3}{0.7} * \frac{1.0}{2.8} = 1.15 w_{ir} + 0.15$$

The water content represented by the interparticle water only is therefore

$$w_{ir} = (w - 0.15)/1.15$$

It should be noted that these water contents are expressed as ratios, i.e. they are not expressed in percent.

Examples:

If the measured water content w is 2000%, then

$$w_{ir} = (20.0 - 0.15)/1.15 = 17.26 \quad (i.e. 1726\%)$$

If the measured water content of the sludge is 70%, then

$$w_{ir} = (0.70 - 0.15)/1.15 = 0.48 \quad (i.e.\ 48\%)$$

The water content w_{vir} by total volume with respect to the interparticle voids only is

$$w_{vir} = \frac{V_{wir}}{V}$$

This water content is often required for volume and mass calculations (see e.g. Appendices L and O).

w_{vir} can not be determined directly and must therefore be determined as a function of w (which is the water content determined on the basis of oven-drying):

$$w_{vir} = \frac{V_{wir}}{V} = \frac{M_{wir}}{\rho_w \, (V_s + V_{wia} + V_{wir})} = \frac{M_{wir}}{M_{wia} + M_{wir} + M_s \, (\frac{\rho_w}{\rho_s})}$$

$$\frac{1}{w_{vir}} = \frac{M_{wia}}{M_{wir}} + 1 + \frac{1}{w_{ir} \, (1 + \frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s})} * \frac{\rho_w}{\rho_s}$$

Writing

$$\frac{M_{wia}}{M_{wir}} \quad as \quad \frac{(\frac{M_{wia}}{M_s})}{(\frac{M_{wir}}{M_s})}$$

and inserting the dimensionless expressions developed above,

$$w_{vir} = \frac{w_{ir} \, (1 + \frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s})}{w_{ir} \, (1 + \frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s}) + \frac{\rho_w}{\rho_s} \, (1 + \frac{n_c}{1 - n_c})}$$

If, as above, $n_c = 0.30$ and $\rho_s = 2.8$,

$$w_{vir} = \frac{1.15 \; w_{ir}}{1.15 \; w_{ir} + 0.51}$$

$$= \frac{1.15 \; (w - 0.15) \; / \; 1.15}{1.15 \; (w - 0.15) \; / \; 1.15 + 0.51}$$

<u>Example</u>:

$$= \frac{w - 0.15}{w + 0.36}$$

$$w = 20 \quad (2000\%)$$

$$w_{ir} = (20 - 0.15) / 1.15 = 17.26 \quad (1726\%)$$

$$w_{vir} = \frac{20 - 0.15}{20 + 0.36} = 0.975 \quad (97.5\%)$$

Dry densities of materials with porous constituents

The dry density normally calculated for the compaction tests does not include any intraparticle water because all water, both interparticle and intraparticle, is removed during oven-drying.

In the field, the sludge constituents are assumed to be saturated, i.e.

$$\rho_d = \frac{M_s + M_{wia}}{V} = \frac{M_s}{V} + \frac{M_{wia}}{V}$$

From page E3,

$$\frac{M_{wia}}{M_s} = \frac{n_c}{1 - n_c} * \frac{\rho_w}{\rho_s}$$

The equation for ρ_d can be written

$$\rho_d = \frac{M_s}{V} + \frac{M_{wia}}{M_s} * \frac{M_s}{V}$$

Hence

$$\rho_d = \rho_d' + \left(\frac{n_c}{1-n_c} * \frac{\rho_w}{\rho_s} * \rho_d'\right) = \rho_d' \left(1 + \frac{n_c}{1-n_c} * \frac{\rho_w}{\rho_s}\right)$$

where

$$\rho_d' = \frac{M_s}{V}$$

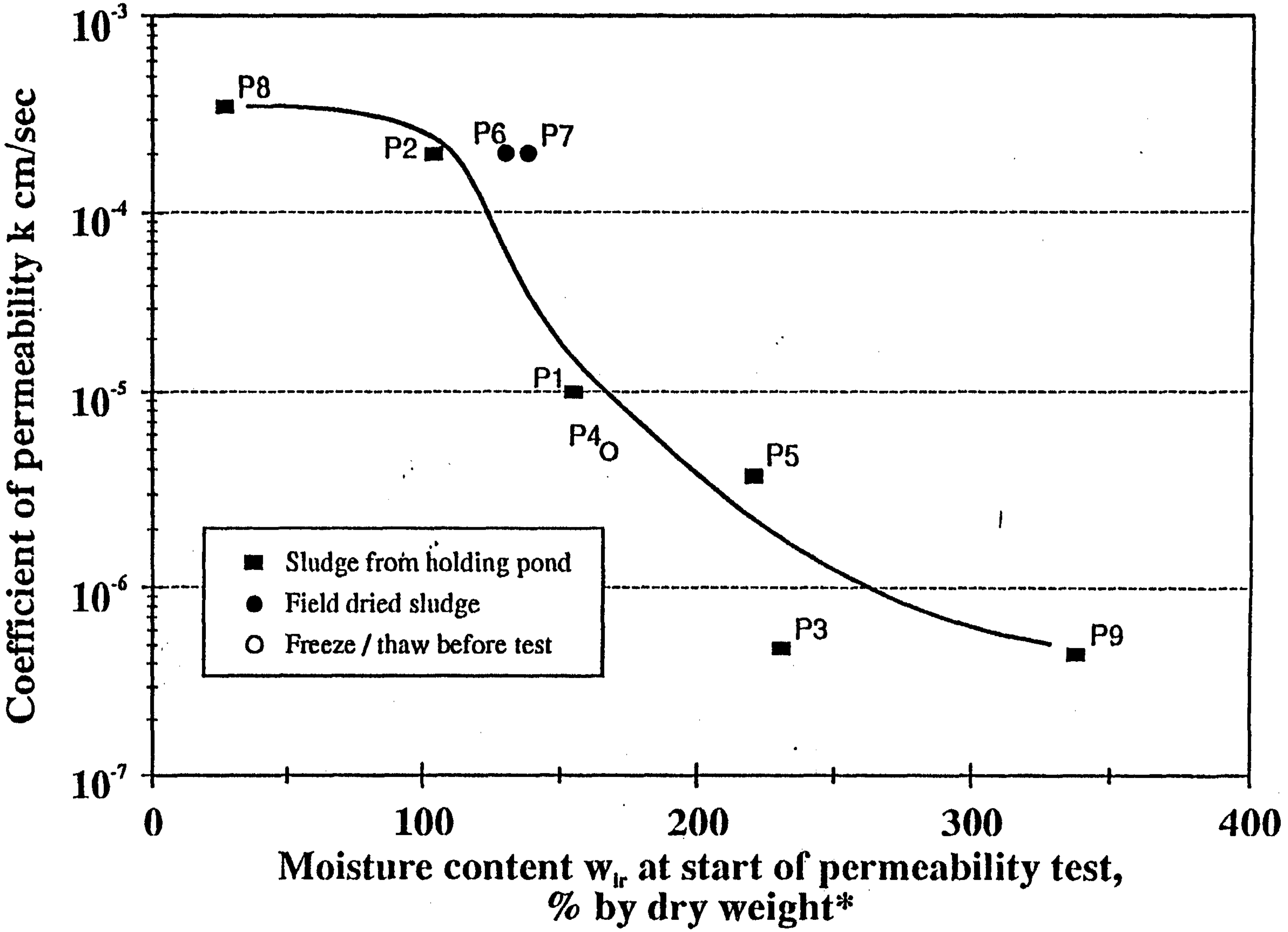
which is the dry density normally calculated on the basis of the oven-dry weight M_s.

Inserting the same values as above

$$\rho_d = 1.15 \ \rho_d'$$

APPENDIX F

Geotechnical Evaluation (Hydraulic Conductivity Results, Compaction Characteristics, Penetration of Slurry into Rockfill (Gemtec Ltd., 1995)



* See appendix E for definition of w_{lr}

Figure 1a Hydraulic conductivity (permeability) of sludge as determined on dried compacted samples (10cm dia. x 12cm height), saturated under a back pressure of approximately 800 kPa and consolidated under an effective pressure of 2 to 65 kPa.

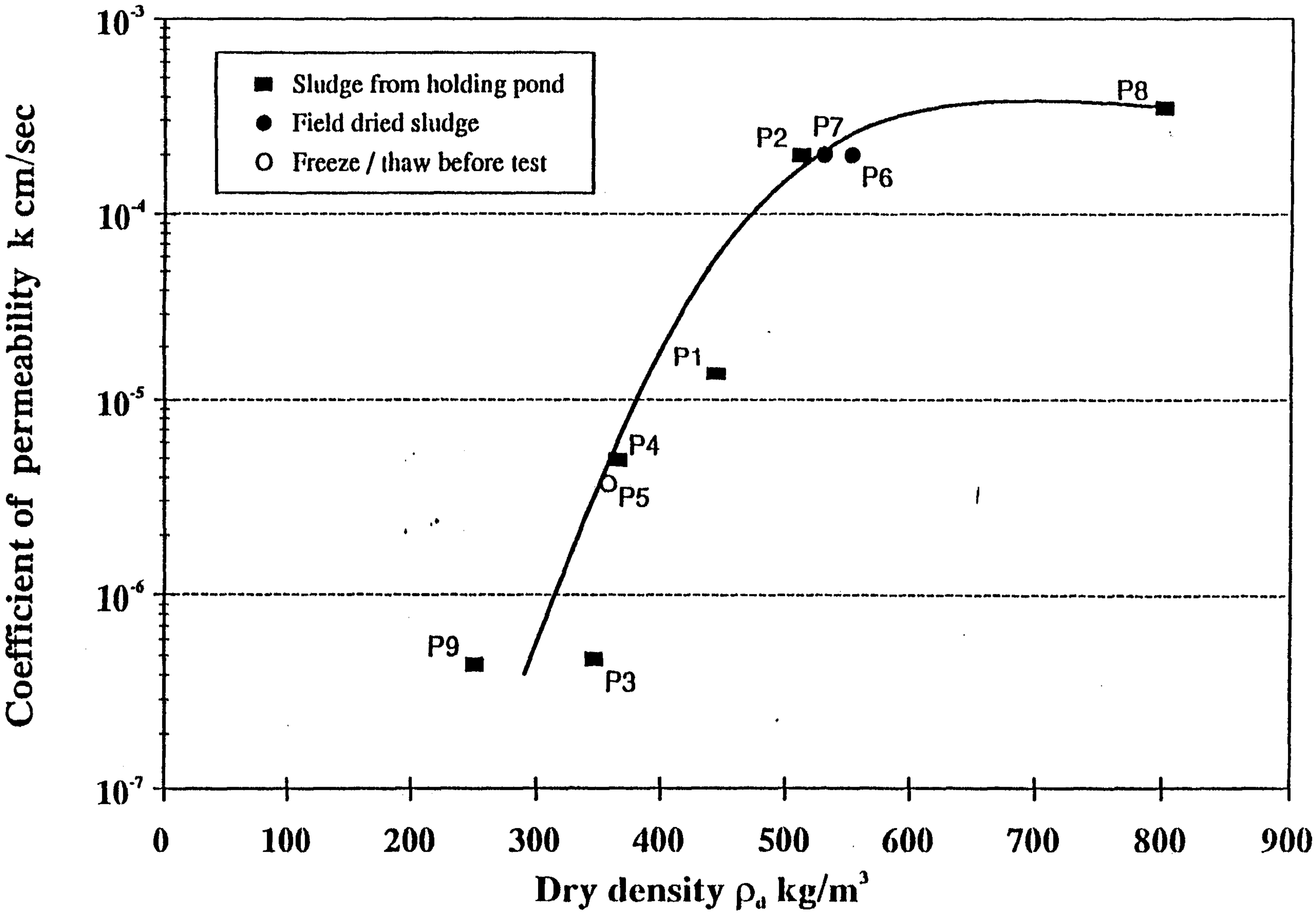


Figure 1b Hydraulic conductivity (permeability) of sludge as determined on dried compacted samples (10cm dia. x 12cm height), saturated under a back pressure of approximately 800 kPa and consolidated under an effective pressure of 2 to 65 kPa.

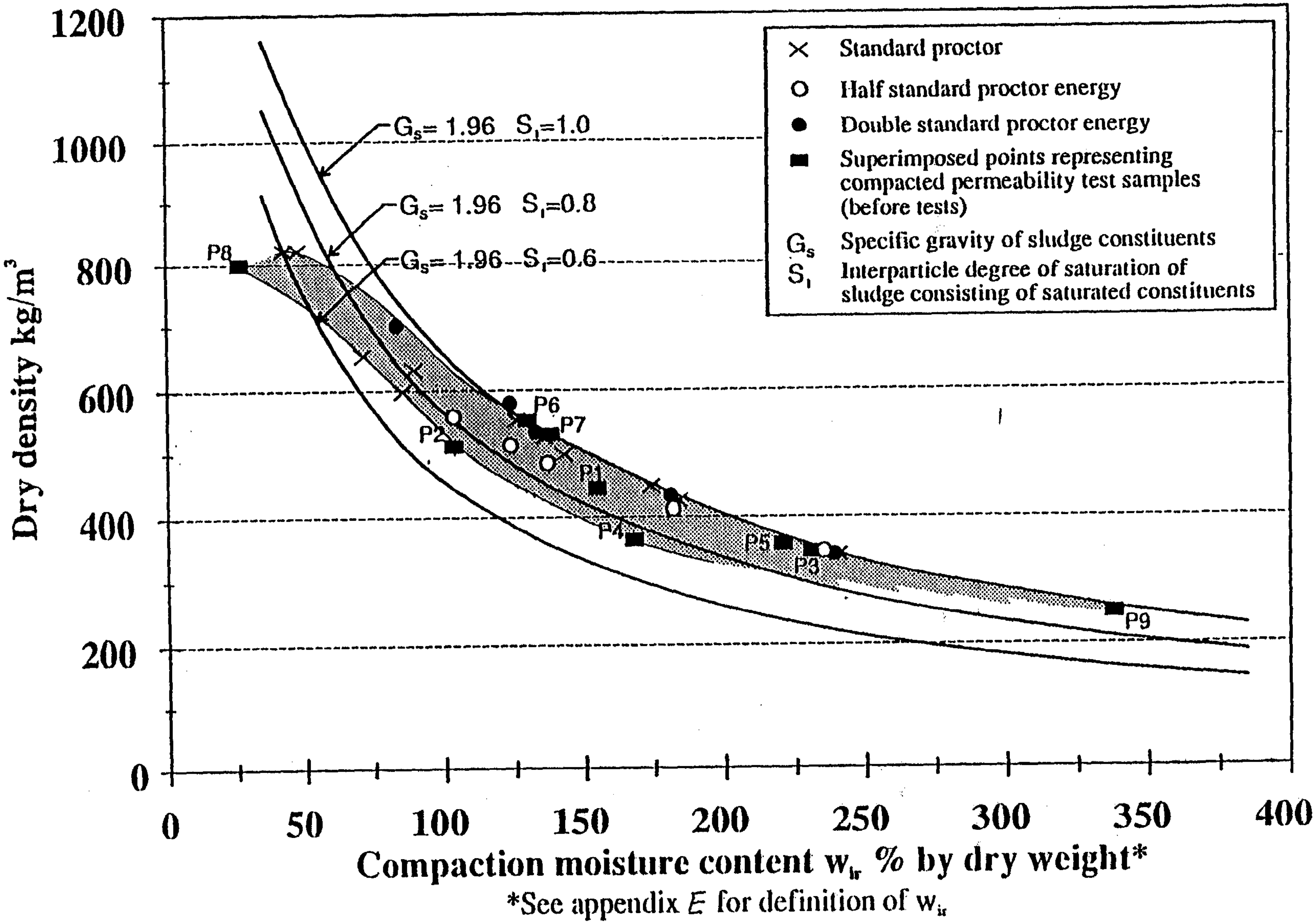
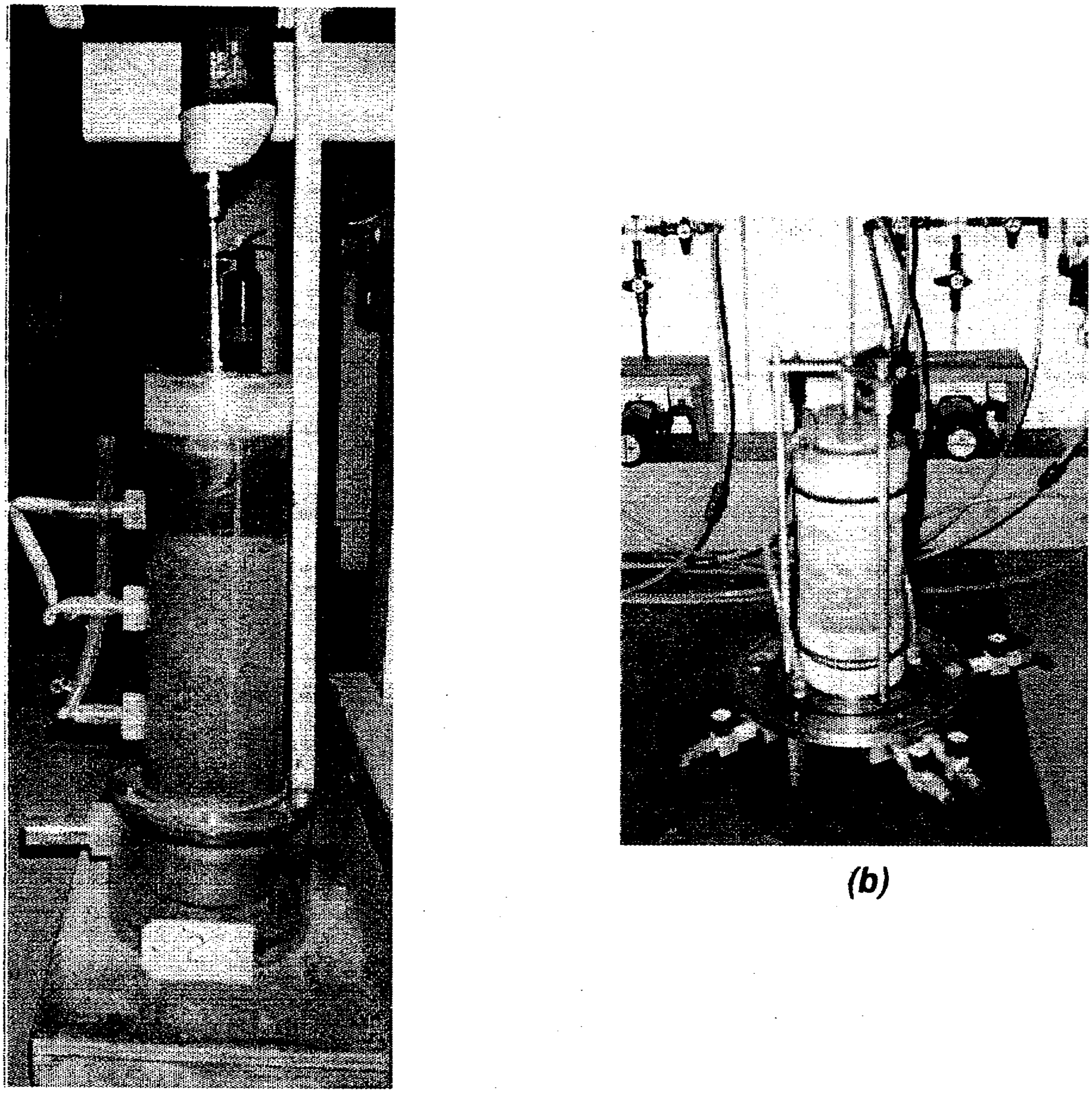


Figure 2 Compaction characteristics of sludge for different compaction energies (6" molds)

Welcome Screen Search Report List



(b)

(a)

Figure 3. (a) 140 mm dia. plexiglass container for slurry penetration tests and permeability tests.
(b) 100 mm triaxial sample as subjected to freeze / thaw tests, followed by permeability test in a triaxial chamber.
1995 March May

PENETRATION OF SLURRY INTO FINE ROCKFILL

Four tests were carried out. On dismantling the first sample, the depth of penetration was determined to be about 10 cm. This was compared with the weighed amounts as follows (M = mass in grams).

M of rockfill + intergranular slurry	10,085
M of dry rockfill	9,239
M of intergranular water + slurry	846
M of intergranular water = 0.046 * 9,239	425
M of intergranular slurry	421

w_{ir} of slurry = 506% (as measured in the slurry scraped off the top of the rockfill after the test), therefore $w_{vir} = (5.06 * 1.96) / (5.06 * 1.96 + 1) = 0.908$ (i.e. 90.8%)

M of slurry = $M_{wir} + M_s + M_{wia} = 421$ g

ρ of slurry = $1.00\ [1.96\ (1 + 5.06) / (1 + 5.06 * 1.96)] = 1.088$

Therefore V of slurry = 421 / 1.088 = 387 cm^3

Rockfill porosity n = 0.32, therefore volume of voids in upper h cm is $(\pi/4)*14.2^2*0.32*h = 51*h\ cm^3$. If the sludge filled the rockfill voids completely, 51*h = 387 and h = 7.6 cm. If the sludge filled 76% of the voids (degree of saturation of voids), h = 10 cm , as observed.

The same calculation for the other three tests led to the following results:

Test #	Observed penetration	Degree of saturation for same calculated penetration
2	3 to 4 cm	100%
3	5 to 7 cm	46 to 64%
4	3.5 cm	66%

These calculations, although the result of small-scale tests, confirm that the slurry does penetrate and does remain in the rockfill voids. The voids appear to be filled with the slurry to between ½ and full volume capacity.

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APPENDIX G

Design of on-site Barrel Reactors

(Grace Dearborn Inc., March 1995)

Design of on-site Barrel Reactors

Cleaned PVC barrels were chosen as test containers because they were water proof, could contain sufficient volume for a closely monitored field test, would not react with the contents and were readily available and economical. To prepare each barrel for the tests, the bottoms were removed and the inside of the barrel was steam cleaned to remove any traces of contaminants. The barrel top then became the reactor barrel bottom.

Each barrel was also fitted with four one inch diameter overflow portholes equally spaced around the circumference of the barrel at a level 33 cm. (13 inches) above the bottom. This area below the overflow portholes would represent the saturated zone in the mine site.

To facilitate the control of the water level in the reactor barrels, the 1.9 cm. (3/4 inch) diameter bung hole was fitted with a 30 cm. (1 foot) length of hose with a PVC ball valve attached to the end. Plastic hose clamps were used on all PVC fittings in contact with the hose.

Each barrel was lined with 240R Terrafix fabric (non-woven geotextile liner) cemented in place to minimize the loss of fines when mine water was removed through the bottom valve or the overflow portholes.

Each reactor received one 91.5 cm. (3 foot) long ground water access pipe. Each 10.2 cm. (4 inch) diameter PVC pipe had been fitted with a sealed PVC cap bottom and a PVC clean-out cap on the top. Ground water had access into the pipe via four 2.54 cm. (1 inch) diameter portholes placed 15.24 cm. (6 inches) from the bottom of the pipe.

The portholes were capped with a double thickness of 240R Terrafix socks to prevent the migration of fines into the sampling pipes. The socks were fastened above and below the holes by plastic hose clamps. The pipe was placed directly on the reactor barrel bottom.

After the collection of the waste rockfill and the preparation of the barrels and monitoring area, the reactor barrels were assembled at the site. The barrels were numbered and arranged on pallets to leave the valve accessible.

APPENDIX G

FIGURE G-1

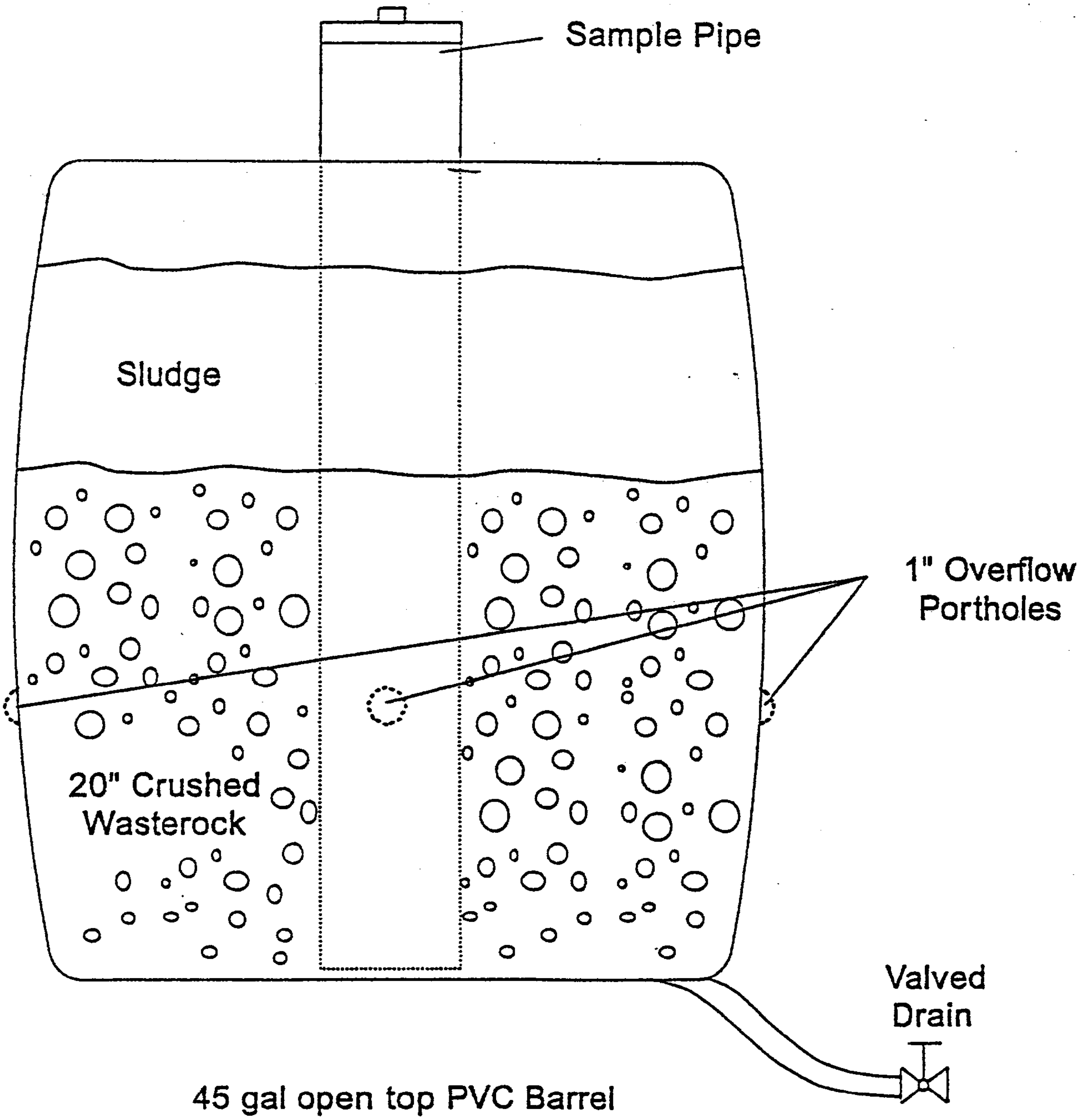

FIGURE G-1
DESIGN OF FIELD REACTOR BARRELS

Not Shown: Non-woven geotextile membranes lining the outside of the sample pipe and the sample pipe portholes located midway in saturated zone.

APPENDIX H

Photographs of Barrel Reactors

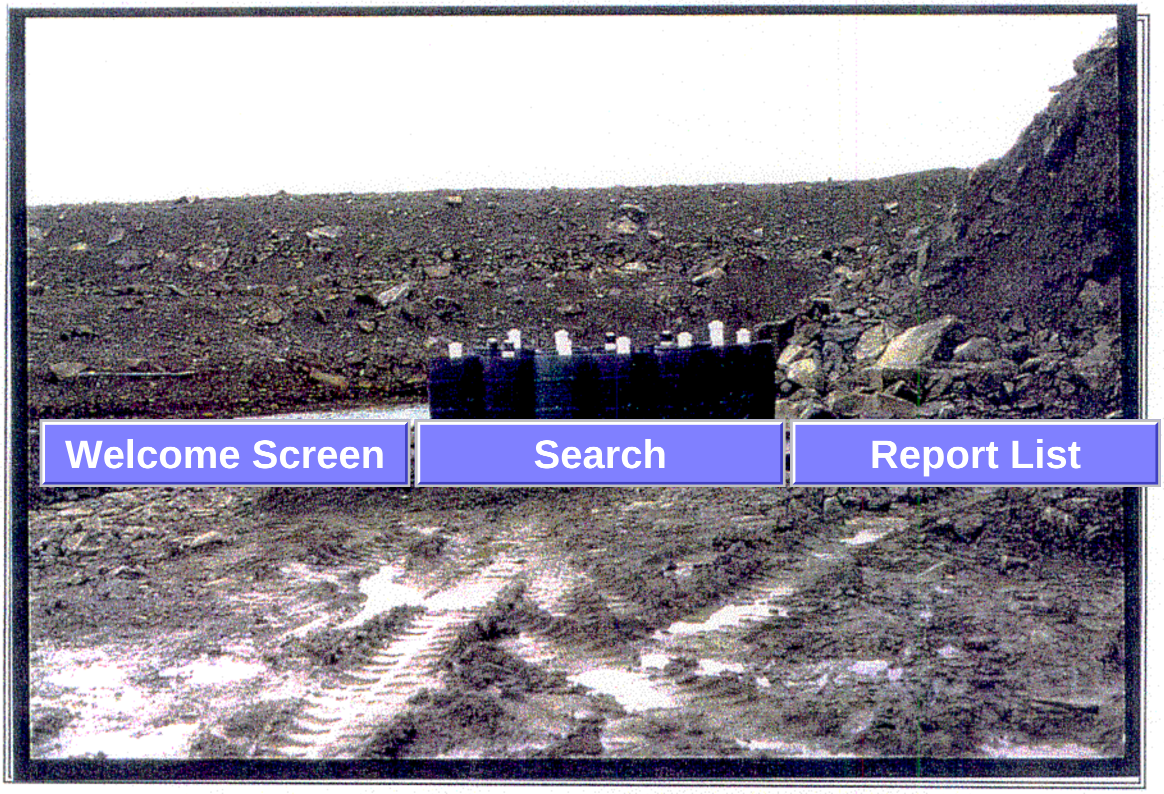

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Figure 14 : Reactor Barrel Overview

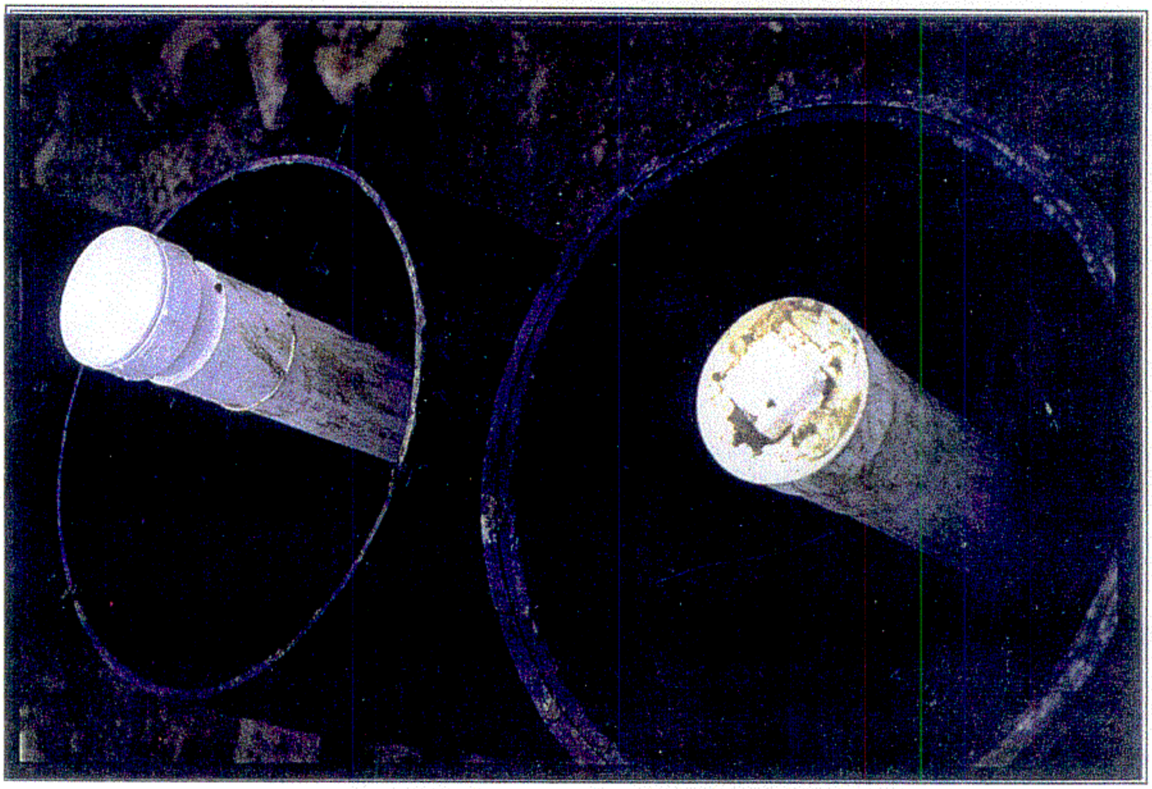

Figure 15 : Reactor Barrel Contents

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Figure 16: Reactor Barrel Material

Figure 17: Reactor Barrel Overflow Porthole

APPENDIX I

Barrel Reactor Results
(Grace Dearborn Inc., June 1996)

Welcome Screen | Search | Report List

APPENDIX I

SUMMARY OF FIELD REACTOR MEASUREMENTS

Table I-1

PARAMETER	CELL	NOV/94	MAY/95	AUG/95	SEPT/95	OCT/95	RANGE
pH (units)	I	4.29	3.67	3.91	3.12	3.42	3.12 - 4.29
	II	4.34	4.22	4.63	3.66	3.94	3.66 - 4.63
	III	4.44	4.16	4.39	3.67	3.99	3.67 - 4.44
	IV	4.33	4.44	5.01	3.81	4.10	3.81 - 5.01
Conductivity (umhos/cm)	I	615	1135	686	1393	1374	615 - 1393
	II	1384	1949	1369	2503	1576	1369 - 2503
	III	1119	1509	740	2227	1218	740 - 2227
	IV	1020	799	298	1153	590	298 - 1153
SO4 (mg/L)	I	269	621	437	1194	1280	269 - 1280
	II	736	1052	811	2348	1331	736 - 2348
	III	599	1017	622	1946	892	599 - 1946
	IV	494	497	265	875	439	265 - 875
Acidity pH 9 (mg/L CaCO3)	I	353	406	189	890	1089	189 - 1089
	II	444	335	113	822	497	113 - 822
	III	306	464	210	611	344	210 - 611
	IV	276	114	37	405	203	37 - 405

NOTE: Field Reactor Groups are as follows:

I	1, 2 & 3	Control ⇒ 51 cm waste rock
II	4, 5 & 6	Amendment 1 ⇒ 15 cm < 1 year old sludge
III	7, 8 & 9	Amendment 2 ⇒ 15 cm > 2 year old sludge
IV	10, 11 & 12	Amendment 3 ⇒ 5 cm < 1 year old sludge

APPENDIX I

Table I-2

Field Reactor Leachate Soluble Metals Analysis

Description	Metals	Nov/94	May/95	Aug/95	Sept/95	Oct/95
Control 51 cm Waste Rock (1, 2 & 3)	Al	7.4	120.6	26.6	144	162.9
	As	< 0.076	< 0.069	< 0.069	< 0.069	< 0.069
	Ca	84	268	242	88.7	91.9
	Cd	0.005	< 0.004	< 0.004	0.10	0.012
	Cr	< 0.008	< 0.007	< 0.007	0.017	0.02
	Cu	0.016	0.135	0.050	0.212	0.201
	Fe	0.02	1.17	0.42	2.86	5.02
	Pb	< 0.043	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	4.16	14.94	8.40	17.3	20.1
	Ni	0.03	0.32	0.19	0.49	0.53
	Zn	0.21	0.83	0.47	1.21	1.43
Amendment 1 15 cm < 1 year old sludge (4, 5 & 6)	Al	45	92	10	143	84.6
	As	< 0.076	< 0.069	< 0.069	< 0.069	< 0.069
	Ca	142	718	242	407	230
	Cd	< 0.004	< 0.004	< 0.004	0.01	0.007
	Cr	0.008	< 0.007	< 0.007	0.007	< 0.007
	Cu	0.06	0.066	0.02	0.155	0.088
	Fe	0.05	0.260	0.05	0.297	0.14
	Pb	< 0.043	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	12.28	15.46	12.43	17.5	11.01
	Ni	0.26	0.24	0.18	0.51	0.31
	Zn	0.62	0.562	0.28	1.38	0.86
Amendment 2 15 cm > 2 year old sludge (7, 8 & 9)	Al	35	127	22	101	48.9
	As	< 0.076	< 0.069	< 0.069	< 0.069	< 0.069
	Ca	103	509	91	398	184
	Cd	< 0.004	< 0.004	< 0.004	0.007	0.005
	Cr	< 0.008	< 0.007	< 0.007	0.011	< 0.007
	Cu	0.05	0.097	0.04	0.132	0.06
	Fe	0.04	0.864	0.10	0.598	0.14
	Pb	< 0.043	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	10.6	23	9.7	15.7	7.56
	Ni	0.23	0.38	0.16	0.43	0.21
	Zn	0.56	0.84	0.39	3.29	0.54
Amendment 3 5 cm < 1 year old sludge (10, 11 & 12)	Al	31.3	22	1.94	56.7	23.7
	As	< 0.076	< 0.069	< 0.069	< 0.069	< 0.069
	Ca	120	306	36	127	56
	Cd	< 0.004	< 0.004	< 0.004	0.005	< 0.004
	Cr	0.009	< 0.007	< 0.007	< 0.007	< 0.007
	Cu	0.033	0.011	< 0.006	0.047	0.025
	Fe	0.04	0.047	0.04	0.087	0.039
	Pb	< 0.043	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	13	9.40	2.87	14.9	7.11
	Ni	0.22	0.07	0.036	0.036	0.17
	Zn	0.49	0.25	0.13	1.04	0.43

APPENDIX I

FIELD REACTOR LEACHATE MICROBIOLOGICAL ANALYSIS

TABLE I-3

ATP Count (ng/mL)				T. Ferroxidans Count (organisms/mL)			
Barrel Number	May/95	Sept/95	Oct/95	May/95	Aug/95	Sept/95	Oct/95
1	29	2.4	1.4	1,000	< 1	>1,000,000	100
2	24	3.1	0.9	100	< 1	>1,000,000	1000
3	12	0.6	1.3	10,000	1	1,000	1000
Average	21.67	2.0	1.2	3,700	1	667,000	700
4	41	0.6	1.1	10,000	< 1	1,000	100
5	4.7	1.1	0.9	100	1	10,000	10
6	5.1	1	1.4	1,000	1	1,000	1000
Average	16.93	0.9	1.1	3,700	1	4,000	370
7	3.9	1.4	1.8	100	< 1	>1,000,000	10
8	4.3	1.6	1.0	1,000	< 1	>1,000,000	1000
9	7	0.4	0.4	100	< 1	>1,000,000	1000
Average	5.07	1.1	1.1	400	< 1	>1,000,000	670
10	3.2	2	0.3	1,000	1	>1,000,000	100
11	1	0.9	0.3	10,000	< 1	>1,000,000	100
12	1.9	1.1	2.3	1,000	< 1	>1,000,000	1000
Average	2.03	1.3	1.0	4,000	1	>1,000,000	400

NOTE: Field Reactor Groups are as follows:

1, 2 & 3 Control ⇒ 51 cm Waste Rock
4, 5 & 6 Amendment 1 ⇒ 15 cm < 1 yr. old sludge
7, 8 & 9 Amendment 2 ⇒ 15 cm > 2 yr. old sludge
10, 11 & 12 Amendment 3 ⇒ 5 cm < 1 yr. old sludge

APPENDIX J

Proposed Weathering Cell Design

(Grace Dearborn, Inc., September, 1995)

Proposed Weathering Cell Design

The bench scale weathering cells and associated piping, valves and fittings were constructed at Grace Dearborn Inc.'s Fredericton Lab Facility in December 1994. Each of the nine waste rock samples were crushed to a top size of 0.3 cm and added to 4.7 L plastic containers which served as the weathering cells. Three test conditions including a control were set up in triplicate and mixed sludge (1:1 <1 yr. old/>2 yr. old) was used for all tests according to Table J-1.

Each cell contains approximately 2 Kg of waste rock and the amended cells include the approximate quantity of sludge based on the sludge to waste rock ratios outlined in Table J-1. After mixing of materials, each cell was sealed in preparation for extended weathering studies.

The air line to each cell is equipped with a 1 cm (3/8") Swagelok needle valve to facilitate precise control of air flow entering the cell. The low pressure air (<5 psig) is supplied by a 2 horsepower compressor into a 1.25 cm (1/2") pipe header which branches into three 1 cm (3/8") sub-headers for each set of 3 cells. Each set of cells (i.e. 1A, 1B & 1C) connect to this header with 1 cm (3/8") copper line. Humidity cells were installed in each of the 3 sub-headers to provide 3 day cycling of wet and dry air to simulate and accelerate natural phenomena weathering. The weathering cells have a 1 cm (3/8") Swagelok air inlet for supply of air and a 1 cm (3/8") plastic drain to allow air to pass through the cell contents. Diagrams are presented in Figures J-1 and J-2.

Leachate samples from each cell will be analyzed weekly for pH, sulfate concentration, conductivity and acidity while solid samples will be analyzed for paste pH only.

The weekly procedure for the production and collection of leachate involves the following steps:

1. Obtain a 500g composite sample from each cell and add water to the samples until they become saturated and measure the paste pH. Raise the volume of water added to each sample to a total of 500 mL and mix thoroughly. Allow the sample to settle until a clear supernatant is obtained. Decant the supernatant and record the quantity obtained. Return the settled material back to each cell and mix. Measure the pH, conductivity and sulfate concentration of each leachate.

   Finally, determine the acidity of the leachate from each of the nine weekly samples obtained by titrating with a 0.1N or 2.5N solution of caustic to a final pH of 9.

2. Seal the lids on each cell and pass dry air through each for three days followed by moist air for another three days. On the last day of the cycle, sample the contents by obtaining 500g of material from each cell and follow the procedure as outlined in part 1. Repeat the cycle of dry air, moist air and sampling for a 52 week period.

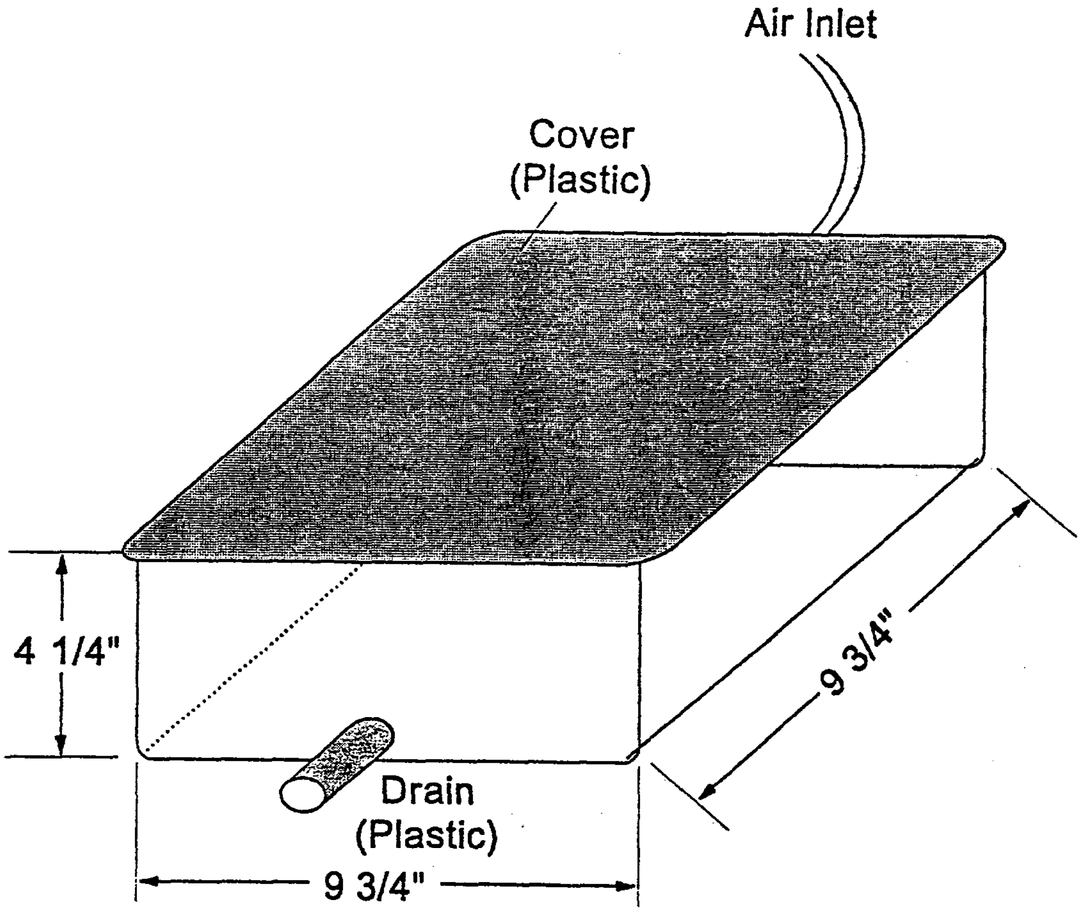
Table J-1
Weathering Cell Test Conditions

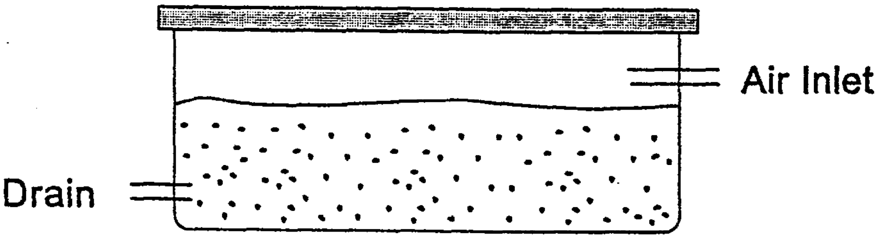
Cell No.	Test Conditions	Mass of Waste Rock (g)	Mass of Sludge Solids (g)
1A	Control I	2004	0
2A	Control II	1999	0
3A	Control III	2005	0
1B	0.5: 1 Sludge to Waste Rock I	1992	998
2B	0.5: 1 Sludge to Waste Rock II	2001	1004
3B	0.5: 1 Sludge to Waste Rock III	1999	999
1C	Sludge to Waste Rock I	1998	1987
2C	Sludge to Waste Rock II	1948	1991
3C	Sludge to Waste Rock III	1998	1987

Note: Quantities are added on an as received basis.

WEATHERING CELL TESTS

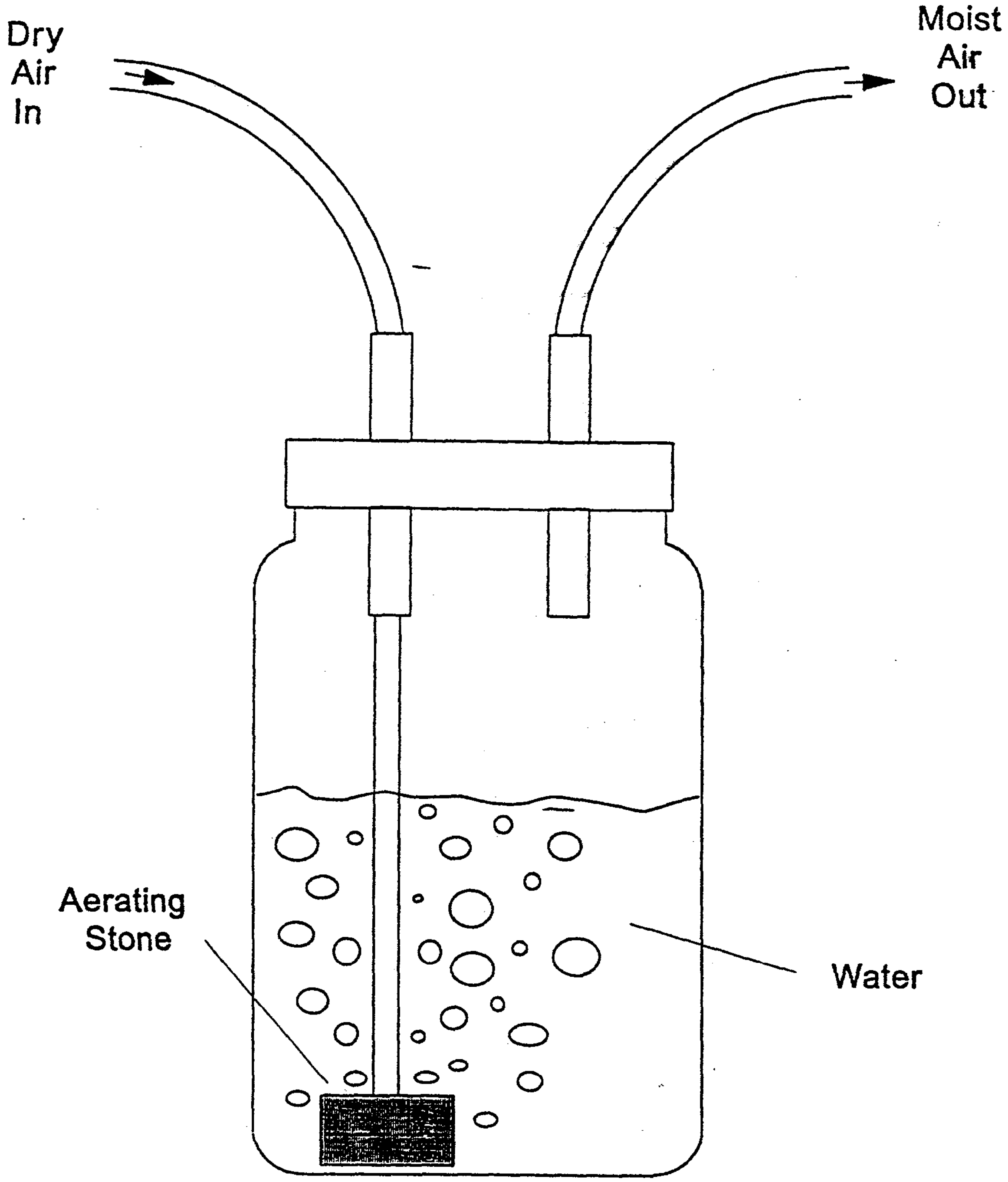
FIGURE 3.1 - WEATHERING CELL DIAGRAM





4.7 L Air Tight
Container (Plastic)

WEATHERING CELL TESTS
FIGURE 3.2 - HUMIDITY CELL DIAGRAM



1 Liter Glass Mason Jar

APPENDIX K

Weathering Cell Analytical Results

(Grace Dearborn, Inc., June 1996)

Welcome Screen Search Report List

SUMMARY OF WEATHERING CELL MEASUREMENTS

TABLE K-1 (Table 1 of 2)

Parameter	Cell	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 20
Paste pH (units)	A	2.32	3.11	3.13	2.99	3.50	3.50	3.47	3.34	3.34	3.14	3.24	3.58	3.44	3.19	3.43	3.41	3.29	3.38	3.24
	B	7.78	7.40	7.63	7.66	7.62	7.69	7.53	7.61	7.73	7.49	7.70	7.65	7.67	7.66	7.59	7.58	7.63	7.56	7.62
	C	8.04	7.46	7.63	7.75	7.68	7.76	7.65	7.79	7.94	7.66	8.03	7.86	7.69	7.85	7.64	7.76	7.76	7.67	7.80
pH (units)	A	4.09	3.41	3.68	3.39	3.48	3.37	3.35	3.51	3.64	3.33	3.40	3.52	3.32	3.33	3.32	3.30	3.29	3.31	3.24
	B	7.60	6.65	7.16	7.64	6.57	7.55	7.76	7.77	7.75	7.17	7.53	7.51	7.52	7.52	7.04	6.73	7.14	7.58	7.56
	C	7.76	7.13	7.65	7.92	6.82	7.68	7.85	7.83	7.84	7.38	7.63	7.64	7.67	7.63	7.10	7.12	7.47	7.74	7.70
Conductivity (umhos/cm)	A	1599	-	974	-	1486	-	1710	1320	764	658	600	677	720	789	866	757	692	635	673
	B	2820	-	2990	-	3270	-	3110	3020	2620	2440	2340	2430	2490	2560	2723	2553	2530	2523	2597
	C	3197	-	3250	-	3440	-	3400	3210	2780	2620	2530	2700	2780	2890	2913	2793	2777	2677	2813
SO4 (mg/L)	A	812	1120	438	967	720	749	1023	775	570	521	336	408	435	469	460	420	422	360	394
	B	1564	1789	1498	1680	1763	1353	1502	1459	1518	1621	1384	1199	1182	1105	1500	1716	1716	1559	1837
	C	2035	2060	1745	2280	1899	1766	1780	1840	1588	1878	1500	1459	1430	1446	1716	1743	1742	1739	2194
Acidity pH 9 (mg/L CaCO3)	A	285	614	216	638	525	509	618	188	145	172	177	192	217	308	279	243	203	196	207
	B	-	127	51	30	37	24	23	23	22	12	10	11	10	11	16	14	13	12	10
	C	-	70	62	26	37	28	25	17	26	14	13	12	9	12	17	16	16	14	14

NOTES: Cell Groups are described as follows:

A - Control (Waste Rock Only)
B - 0.5:1 Sludge to Waste Rock
C - 1:1 Sludge to Waste Rock

SUMMARY OF WEATHERING CELL MEASUREMENTS

TABLE K-1 (Table 2 of 2)

Parameter	Cell	Week 22	Week 24	Week 26	Week 28	Week 30	Week 32	Week 34	Week 36	Week 38	Week 40	Week 42	Week 44	Week 46	Week 48	Week 50	Week 52	Range
Paste pH (units)	A	3.33	3.23	3.26	3.40	3.26	3.24	3.23	3.20	2.90	3.27	3.07	2.97	3.14	3.29	2.79	3.50	2.32 - 3.58
	B	7.68	7.70	7.59	7.57	7.74	7.78	7.54	7.44	7.60	7.55	7.76	7.29	7.51	7.62	7.27	7.41	7.27 - 7.78
	C	7.83	7.86	7.67	7.72	7.84	7.88	7.70	7.56	7.93	7.79	7.92	7.61	7.89	8.04	7.67	7.54	7.46 - 8.04
pH (units)	A	3.25	3.22	3.09	3.11	3.17	3.19	3.11	3.21	3.24	3.34	3.19	3.23	3.29	3.30	3.29	3.40	3.09 - 4.09
	B	7.44	7.49	7.48	7.52	7.51	7.52	7.19	7.41	7.45	7.41	7.35	7.29	7.35	7.38	7.33	7.17	6.57 - 7.77
	C	7.62	7.70	7.56	7.67	7.75	7.65	7.49	7.62	7.63	7.65	7.58	7.60	7.63	7.60	7.54	7.38	6.82 - 7.92
Conductivity (umhos/cm)	A	664	637	698	675	676	597	595	584	576	450	606	574	551	504	519	440	440 - 1710
	B	2507	2440	2353	2253	2153	1578	1770	1806	2153	1520	2103	2037	1973	1746	1820	1535	1520 - 3270
	C	2733	2607	2503	2443	2407	2317	2247	2283	2377	2113	2410	2427	2427	2427	2397	2377	2113 - 3440
SO4 (mg/L)	A	349	363	440	406	383	379	374	385	318	332	389	373	379	340	317	289	289 - 1120
	B	1716	1861	1670	1559	1271	858	1052	1125	1328	993	1419	1422	1196	1196	1122	862	858 - 1861
	C	2075	1835	1939	1886	1673	1538	1559	1085	1130	1072	1260	1523	1254	1650	1271	1519	1072 - 2280
Acidity pH 9 (mg/L CaCO3)	A	223	221	269	248	256	208	211	223	198	164	213	191	185	171	161	137	137 - 638
	B	12	11	14	12	13	20	10	8	12	9	13	12	11	11	11	8	8 - 127
	C	14	13	16	14	16	22	12	10	13	10	16	16	13	14	15	11	9 - 70

NOTES: Cell Groups are described as follows:

A - Control (Waste Rock Only)
B - 0.5:1 Sludge to Waste Rock
C - 1:1 Sludge to Waste Rock

Table K-2

Analysis of Selected Metals in Weathering Cell Leachate

Description	Metals	Week 1	Week 2	Week 10	Week 26	Week 52
Control Cells Waste Rock Only (1A, 2A & 3A)	Al	32.5	102	23.1	30.4	18.2
	As	< 0.069	< 0.069	< 0.069	< 0.069	< 0.072
	Ca	161	143	42	25	8.1
	Cd	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004
	Cr	0.009	0.016	0.012	< 0.007	< 0.007
	Cu	0.116	0.211	0.114	0.119	0.134
	Fe	0.362	1.29	0.416	1.012	0.465
	Pb	< 0.039	0.043	< 0.039	< 0.039	< 0.041
	Mn	9.89	20.6	7.48	4.69	1.59
	Ni	0.223	0.53	0.16	0.14	0.07
	Zn	0.526	1.31	0.42	0.54	0.808
0.5:1 Cells Mass Ratio Sludge to Waste Rock (1B, 2B & 3B)	Al	0.138	0.190	0.180	< 0.029	< 0.029
	As	< 0.069	< 0.069	< 0.069	< 0.069	< 0.072
	Ca	542	541	550	597	358
	Cd	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004
	Cr	< 0.007	< 0.007	< 0.007	< 0.007	< 0.007
	Cu	< 0.006	< 0.008	< 0.006	< 0.006	< 0.006
	Fe	0.132	0.034	< 0.009	< 0.009	0.016
	Pb	< 0.039	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	0.266	0.275	0.052	< 0.004	< 0.004
	Ni	< 0.015	< 0.02	< 0.02	< 0.02	< 0.02
	Zn	0.02	0.012	0.006	< 0.005	< 0.005
1:1 Cells Mass Ratio Sludge to Waste Rock (1C, 2C & 3C)	Al	0.054	0.199	0.081	< 0.029	< 0.029
	As	< 0.069	< 0.069	< 0.069	< 0.069	< 0.072
	Ca	516	489	590	587	590
	Cd	< 0.004	< 0.004	< 0.004	< 0.004	< 0.004
	Cr	< 0.007	< 0.007	0.008	< 0.007	0.008
	Cu	< 0.006	< 0.006	< 0.006	< 0.006	< 0.006
	Fe	0.042	0.032	0.010	0.009	0.014
	Pb	< 0.039	< 0.039	< 0.039	< 0.039	< 0.041
	Mn	0.646	0.619	0.01	0.02	0.027
	Ni	< 0.015	< 0.02	< 0.02	< 0.02	< 0.02
	Zn	0.007	0.007	< 0.005	< 0.005	< 0.005

WEATHERING CELL LEACHATE MICROBIOLOGICAL ANALYSIS

TABLE K-3

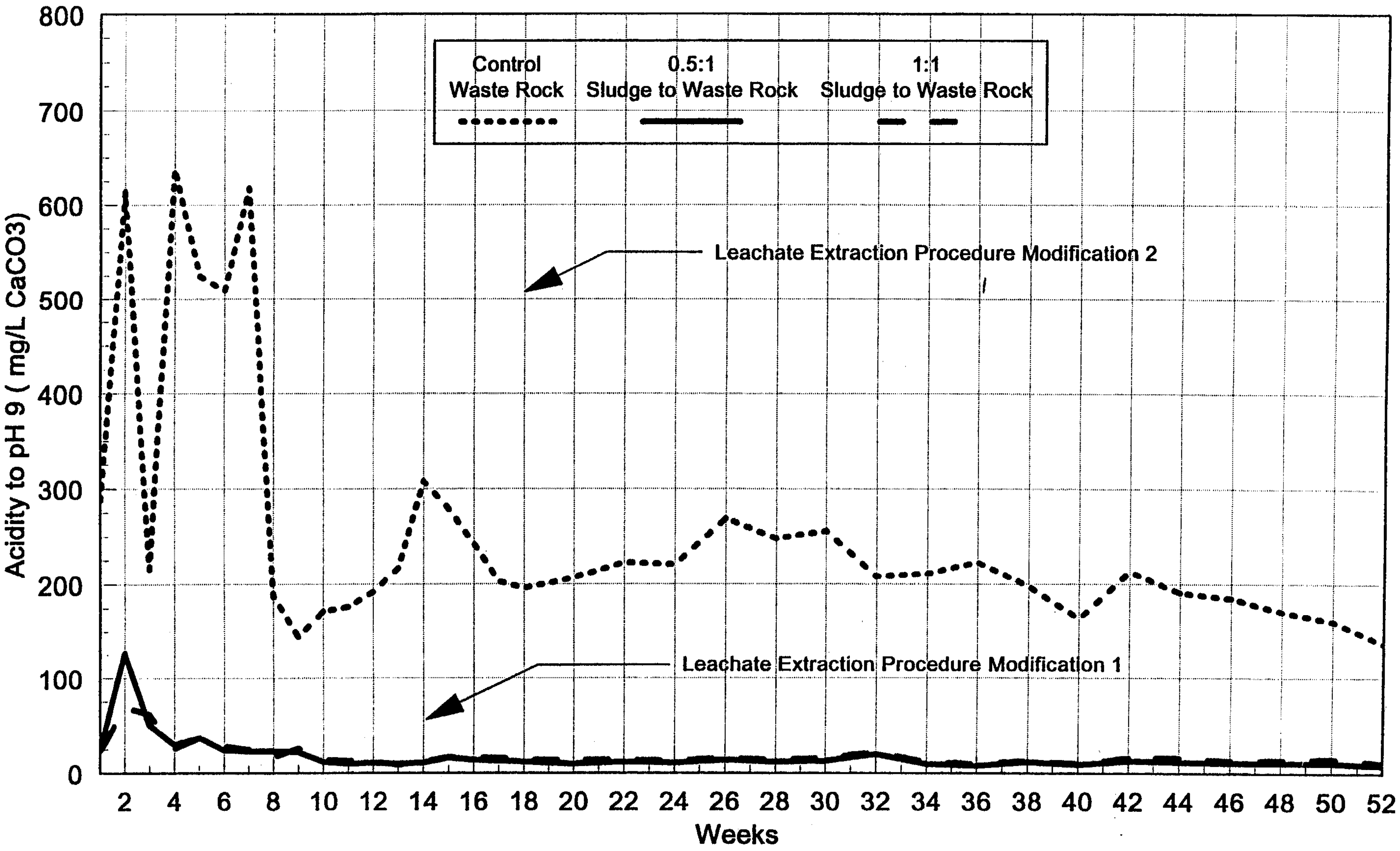
Cell Number	ATP Count (ng/mL)					T. ferroxidans Count (organisms/mL)				
	Week 2	Week 7	Week 26	Week 40	Week 52	Week 2	Week 7	Week 26	Week 40	Week 52
1A	0.2	0.42	0.3	0.1	< 0.1	100	10000	10	< 1	< 1
2A	0.2	0.24	0.2	0.1	0.1	1000	1000	1000	< 1	1
3A	1.5	0.1	0.3	< 0.1	0.1	10	10000	100	< 1	< 1
Average	**0.63**	**0.25**	**0.27**	**0.10**	**0.10**	**370**	**7000**	**370**	**< 1**	**1**
1B	0.7	0.1	0.1	0.2	0.1	100	10	1	< 1	< 1
2B	2	0.39	0.1	0.2	< 0.1	100	1	1	< 1	< 1
3B	1	0.24	0.1	0.2	< 0.1	1000	100	1	< 1	< 1
Average	**1.23**	**0.24**	**0.10**	**0.20**	**0.10**	**400**	**37**	**1**	**< 1**	**< 1**
1C	1.6	0.22	0.2	0.2	< 0.1	100	10	10	< 1	< 1
2C	8.1	< 0.1	< 0.1	0.2	< 0.1	10	10	1	1	< 1
3C	1	0.27	0.2	0.2	< 0.1	10	10	1	< 1	< 1
Average	**3.57**	**0.20**	**0.17**	**0.20**	**< 0.1**	**40**	**10**	**4**	**1**	**< 1**

NOTES: Weathering Cell Groups are described as follows:

A - Control (Waste Rock Only)
B - 0.5:1 Sludge to Waste Rock
C - 1:1 Sludge to Waste Rock

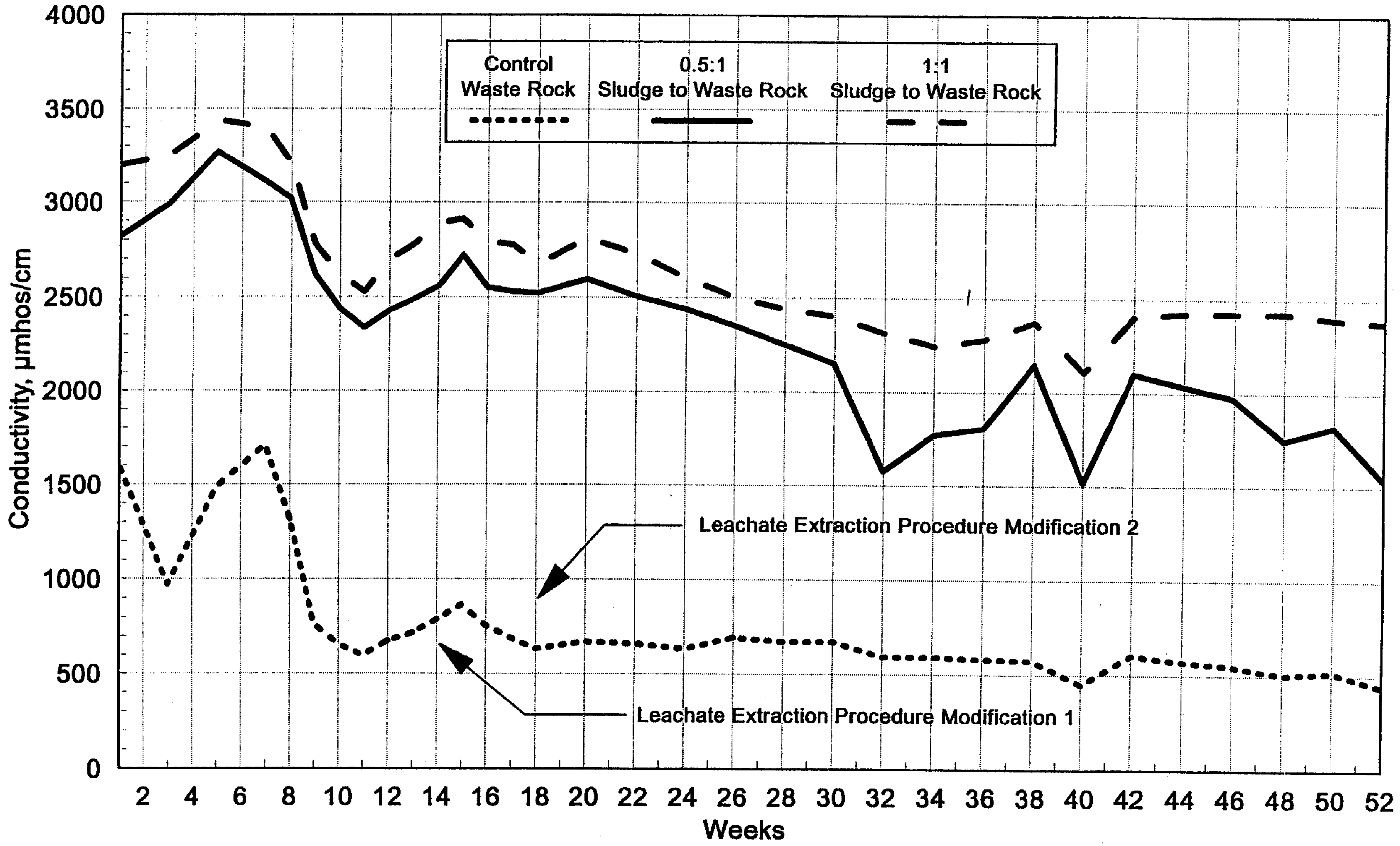
WEATHERING CELL TRENDS

FIGURE K-1 - LEACHATE ACIDITY



WEATHERING CELL TRENDS

FIGURE K-2 - LEACHATE CONDUCTIVITY



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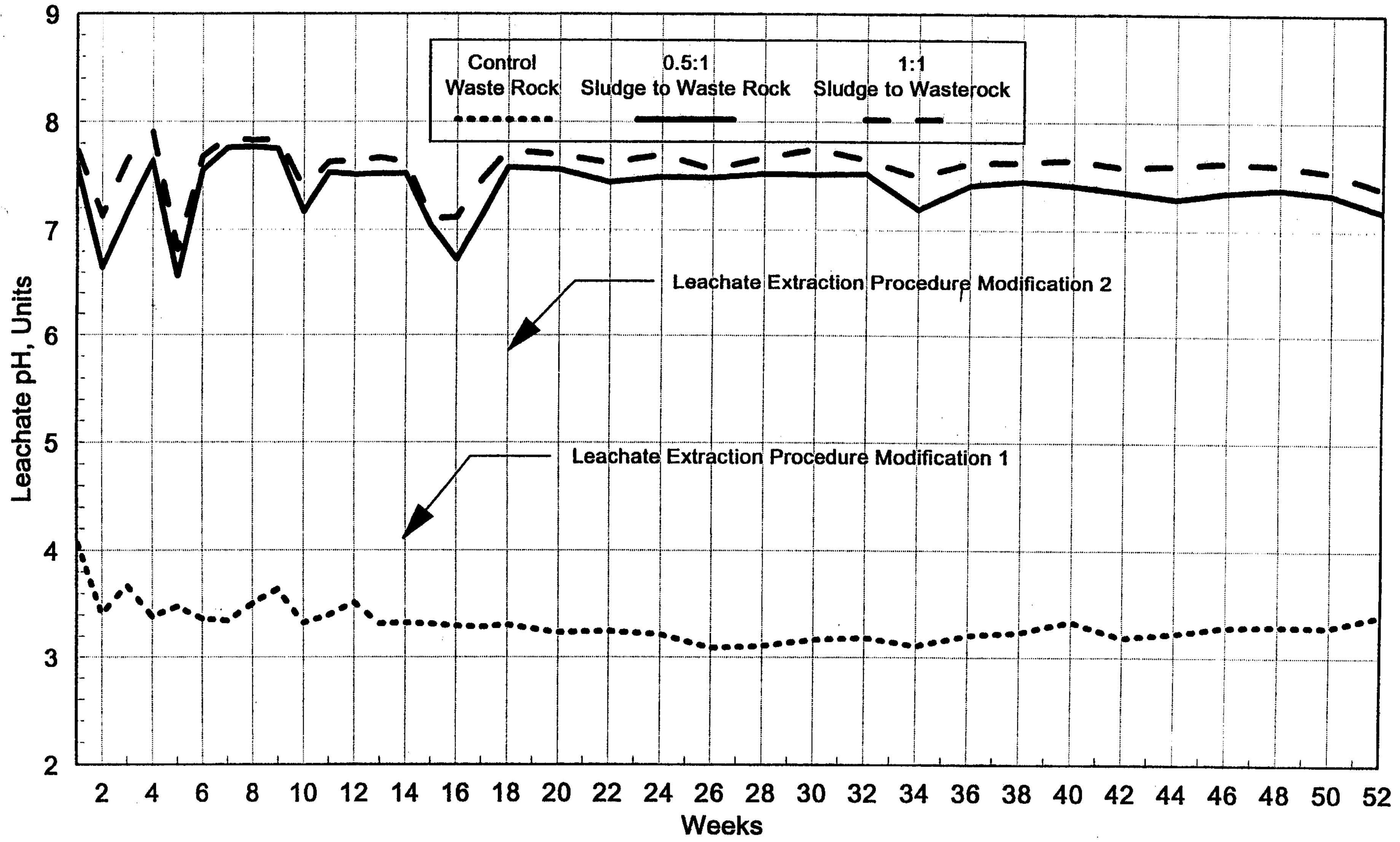
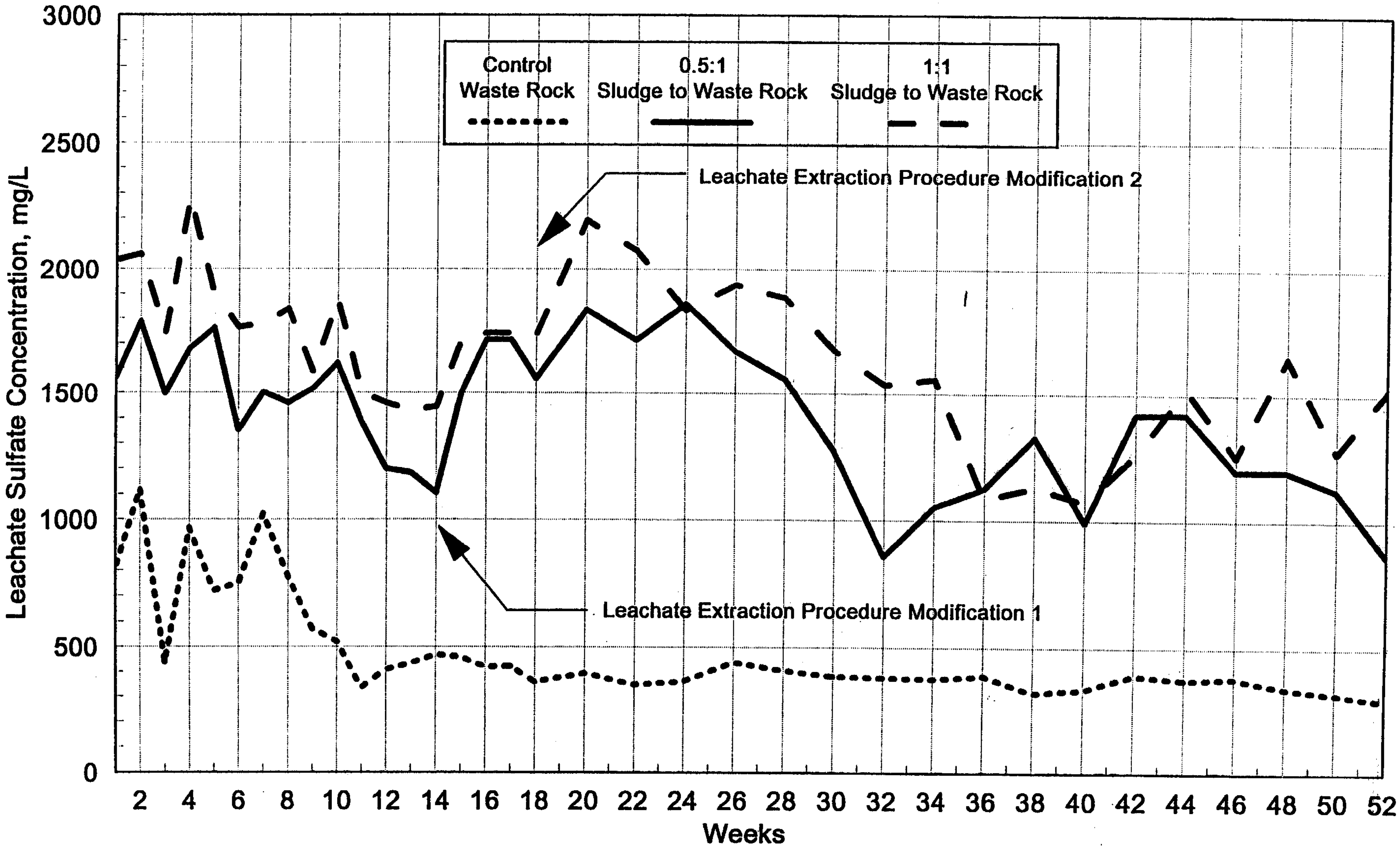
WEATHERING CELL TRENDS

FIGURE K-3 - LEACHATE pH



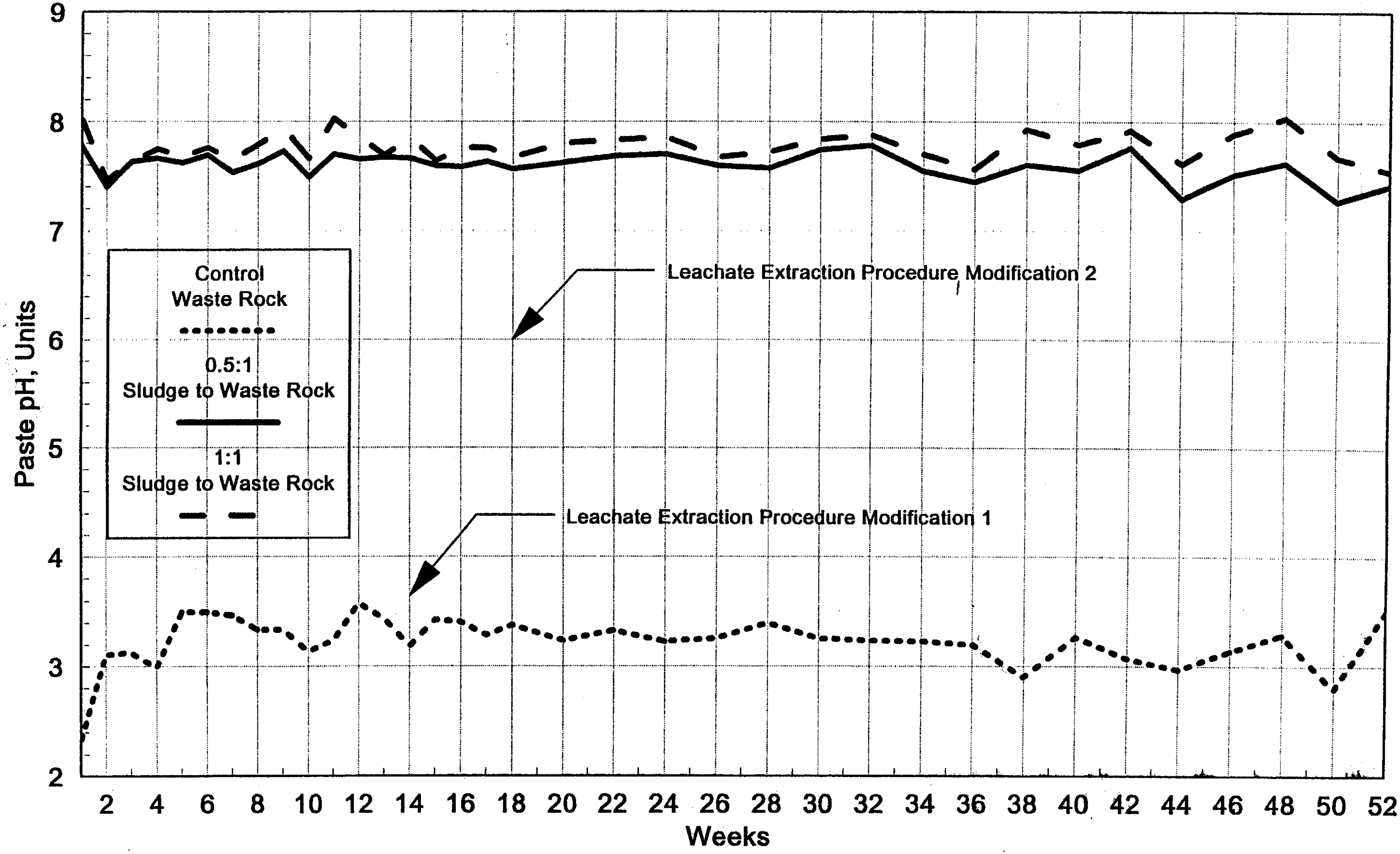
WEATHERING CELL TRENDS

FIGURE K-4 - LEACHATE SULFATE CONCENTRATION



WEATHERING CELL TRENDS

FIGURE K-5- PASTE pH



APPENDIX L

Dredged/Pumped Sludge: 1994 Production
(Gemtec Ltd., 1995)

DREDGED/PUMPED SLUDGE: 1994 PRODUCTION

The average interparticle water content of the pumped slurry as it exited the pipe was determined to be $w \approx 2{,}000\%$, i.e. $w_{vir} = 97.5\%$ if $G_s = 1.96$ (G_s is the same as S_s, Appendix E).

If dredging was carried out at a nominal rate of 2,000 Imp. gal./min and at a scheduled rate of 6 days/pond, we would have (allowing for ½ day down-time per week and a pump efficiency of 80%)

0.8 x 2,000 gal * 4.5 L/gal * 1440 min/day * 5½ days = 57 mill. L/pond (average) of slurry. This gives a total quantity of interparticle water V_{wt} of

$$V_{wt} = 0.9750 * 57{,}000{,}000 = 55{,}600{,}000 \text{ L/pond}$$

and a total volume of saturated surface dry particles V_{st} of

$$V_{st} = 57{,}000{,}000 - 55{,}600{,}000 = 1{,}400{,}000 \text{ L/pond.}$$

This corresponds to a total weight of these particles M_{st} of

$$M_{st} = 1{,}400{,}000 * 1.96 \approx 2.75 \text{ mill. kg/pond.}$$

The area over which the pumped material was deposited was approximately 140 * 300 m (about 10 acres). The water content of the <u>congealed</u> material was $w \approx 560\%$ ($w_{vir} \approx 91.4\%$). The total volume of slurry pumped in 1994 ($w_{vir} \approx 97.5\%$) was

$$V_{tp} = 57{,}000{,}000 \text{ L/pond} * 4 \text{ ponds} = 228{,}000{,}000 \text{ L} = 228{,}000 \text{ m}^3$$

Hence the total volume of water pumped was 0.975 * 228,000 = 222,300 m^3 and the total volume of saturated particles pumped (V_{tp}) was therefore 228,000 - 222,300 = 5,700 m^3.

For an interparticle water content of w_{vir} = 91.4%, this corresponds to a total volume V_{tc} after coagulation of

$$V_{tc} = V_{wt}/0.914 = V_{tp}/(1-0.914) = 5{,}700/0.086 \approx 66{,}300\ m^3$$

where V_{wt} = total volume of water after coagulation = 66,300 * 0.914 = 60,600 m^3

The thickness of congealed slurry in this area is estimated to be not more than 0.5 m average, i.e. the volume of congealed slurry would be 0.5 * 42,000 = 21,000 m^3 or less. On this basis, about 66,300 - 21,000 = 45,300 m^3 of slurry would have entered the rockfill voids, i.e.

$$\frac{45{,}300}{66{,}300} * 100 = 68\%$$

of the congealed slurry could be located in the rockfill. If the porosity of the rockfill is taken to be 40% (n = 0.40) and if the quantity of 45,300 m^3 of congealed slurry were to completely fill the rockfill voids in the 140 * 300 m area, the depth of sludge-filled rockfill would be

$$45{,}300\ /\ (140 * 300 * 0.40) = 2.7\ m$$

This is far in excess of the observed depths of penetration of the slurry, which are in the order of 10 times smaller, i.e. up to about 0.3 m. The only possible explanation for this very large discrepancy is that there must exist a relatively large number of "porous chimneys" or "vents" in the rockfill, presumable formed as a result of congregations of large-size rocks

Since the total volume of water pumped during the 1994 dredging was 222,300 m^3 and the volume of water in the congealed sludge was only 60,600 m^3, a quantity of water of 222,300 - 60,600 = 161,700 m^3 must have seeped through the rockfill, below the congealed sludge.

APPENDIX M

Dredged/Pumped Sludge: 1995 Reconnaissance

(Gemtec Ltd., 1995)

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DREDGED/PUMPED SLUDGE: 1995 RECONNAISSANCE

Photographs from our 95 July 10 and 11 reconnaissance are shown in photo series G at the end of this appendix.

Sampling at various locations in the 1994 deposit area (photos G1-1 and G1-2) showed sludge depths of 0 to about 100 cm. The ridge of sludge shown in photo G1-2 had been piled up by a dozer in preparation for excavating a deep trench (behind the ridge).

The operation shown in photos G2-1 to 5 was carried out in an area of about 10 cm sludge thickness. The dozing and backdragging operation resulted in a very smooth surface. Some mixing of fine rockfill and sludge was effected, but the sludge was too viscous to flow into the voids of the rockfill.

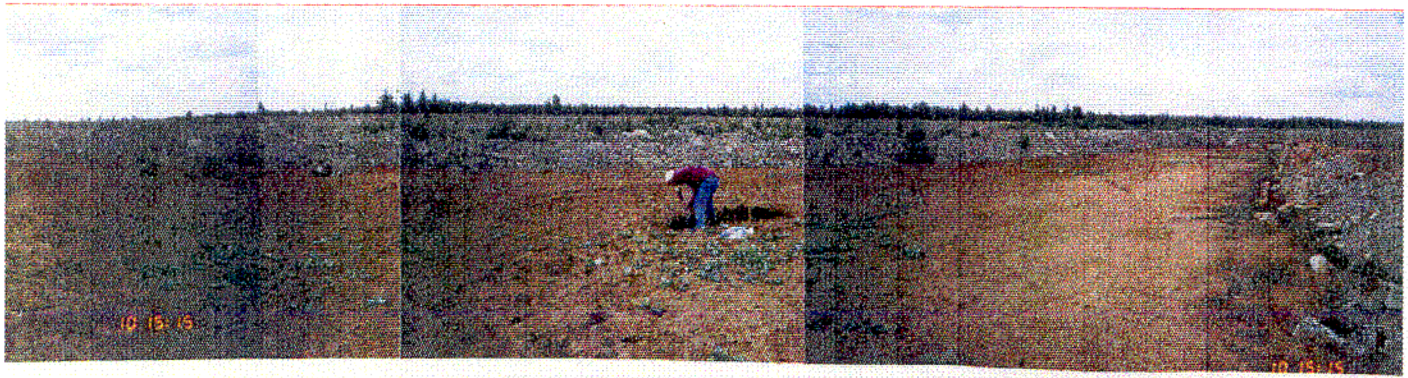
The operation shown in photos G3-1 to 4 was carried out in the same area (photo G1-2), but closer to the ridge, where the sludge thickness was about 50 cm. Again the resulting surface was relatively smooth, but little actual mixing of sludge and rockfill took place.

The G4-1 to 6 operation was carried out across the G2 and G3 strips. A blade-full of piled-up sludge was taken from the ridge (G4-1) in another effort to mix sludge with rockfill. This time some mixing did take place, and the resulting surface was again relatively even. It was observed that some of the larger rocks were buried and some were crushed to varying degrees.

The area between the G2 to G4 strips and the 1994 dredge pipe exit is covered with a large amount of very coarse rockfill. The G5 series of photos shows that the coarse rockfill can be dealt with very effectively with a large dozer (here: a Caterpillar D10N) and a skilled operator. The large rocks which are not buried or crushed to smaller sizes may (i) be left on the prepared and relatively smooth surface, (ii) be buried in existing or excavated depressions, or (iii) be pushed to the edge of the rockfilled area. The latter alternative may not, however, be environmentally acceptable.

The G6 operation (photos G6-1 to 6) is another demonstration of how it is possible to transform an extremely uneven rocky area to a relatively even surface.

G1-1



G1-2

Photo series G1.

G1-1: part of 1994 deposit area

G1-2: part of 1994 deposit area plus ridge of sludge piled up by dozer along deep trench. 1995 July 11.

M3

1

3

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2

4

5

Photo series G2. Dozing and backdragging (Cat D10N) in an area covered with about 10 cm of sludge deposited by dredge in 1994. 1995 July 11.

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Photo series G3. Same general area as G2, but closer to the ridge (photo G1-2). Sludge thickness about 50 cm. 1995 July 11.

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Photo series G4. Mixing of piled-up and pumped sludge (G4-1) with near-surface rockfill (Caterpillar D10N). 1995 July 11.

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1

2

3

4

5

6

Photo series G5. Transforming an extremely rocky area to a relatively even surface by burying, crushing or removing the larger-size rocks (Caterpillar D10N). 1995 July 11.

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Photo series G6. Same as the G5 series, but in an area covered with even larger rocks (up to about 1.8m). 1995 July 11.

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APPENDIX N

Trench Evaluation Results

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APPENDIX N

TRENCH EVALUATION RESULTS

Dredged sludge from the lime neutralization sludge sedimentation ponds was deposited on the waste rock on the reclaimed mine site four times between fall of 1992 and the fall of 1994. Each operation had a mandate to place the sludge on the waste rock and minimize the amount of sludge that penetrated into the waste rock.

The success of this mandate was more visible during the operations in the fall of 1992 and early summer of 1994. The operation conducted during the fall of 1993 resulted in only a very minor amount of sludge being retained on the waste rock surface. This was also evidenced by the volume of sludge that migrated into the mine water holding pond during and shortly after the dredging operation.

The volume of solids entrained in the slurry during the dredging operations was monitored in the field by recording the volume of saturated solids that had settled in a 500ml bottle after the sample had been frozen and thawed. This action broke the weak sludge/water bonds which were responsible for the thixotropic behavior of the sludge. Samples were collected at the discharge of the dredge pipe. This field method can not be correlated to the laboratory methods applied in the geotechnical evaluation as it did not take into consideration the volume of water contained in the interparticle and intraparticle void porosity.

The volume of solids in the slurry was reported as being in excess of 40% on grab samples during the fall of 1992 dredging campaign. During the fall of 1993, the volume of saturated solids ranged from 14 to 18% per pond. A rigorously monitored program during the early summer of 1994 dredging operation yielded average solids concentrations of between 35 and 41% per pond. The same method during the fall of 1994 dredging operation yielded concentrations between 22 and 24%. This method of evaluation was used to investigate options in applying the sludge as a cover to the waste rock or for its potential incorporation as a near surface penetrating seal.

In order to evaluate the physical behavior of the sludge on the waste rock when applied as a surface amendment, four test pits were excavated into the waste rock in the sludge depositional areas.

The test pits were excavated during October of 1994 after a below average precipitation summer and fall. The sludge on the surface of all pre-fall 1994 depositional areas was powder dry. The pits were excavated with a Komatsu excavator and were approximately 1.5 meters wide by 1.5 meters in length. The pits were excavated to a depth of 1.5 meters or until sludge was no longer visible and major boulder-size waste rocks prevented further excavation.

Observations made at each pit area included surface vegetation and consistency, and thickness and depth of penetration of the sludge.

Although the vast majority of sludge deposited on the waste rock surface during each dredging operation disappeared into the reclaimed waste rock , the percentage varied depending on the consistency of the slurry being discharged. All test pits excavated had several centimeters (minimum five to fifteen centimeters) power dry sludge on the surface regardless of the solids content of the slurry when deposited.

With the exception of pit 1, the sludge surfaces of all areas showed evidence of desiccation cracks varying from less than two centimeters deep to more than fifteen centimeters deep. The crusty upper layer seemed to protect the sludge from erosion. The test pit 1 area, however, eroded drainage paths carved into the powder dry unvegetated sludge directed surface run-off and eroded sludge into porous rock chimneys in the waste rock.

Vegetation varied between test pits. Two test pit areas had no vegetation on the surface. One area still contained grasses, 0.6 to one meter tall yellow birch and goldenrod which had been established before the sludge was deposited. All of the roots from these plants were still firmly anchored in the underlying weathered waste rock.

Sludge during the fall of 1993 dredging operation was also deposited in an adjacent area which had not been naturally revegetated. The surface vegetation after the sludge deposition consisted of a naturally revegetated rhubarb-shaped leaf and type-habitat plant growing on the powder dry sludge surface. The roots of the plants were anchored in the sludge. The roots did not penetrate into the waste rock. This plant was also observed thriving in the dried sludge on the edges of sedimentation ponds but was not observed to be prevalent in the undisturbed areas adjacent to the mine site nor on bare waste rock.

Most areas showed evidence of the sludge having penetrated into the upper layer of weathered sandstone waste rock. In most samples, the sludge was powder dry. Deposits of more than fifteen centimeters usually exhibited stratification of sludge applications. In one, 0.3 to 0.5 meter thick deposits of sludge stratification based on particle size indicated that several applications of sludge had been deposited in this area with a low energy period between each application. The upper layer of each sequence consisted of the finest sized particles which were powder dry to the touch. The lowest layer of each depositional sequence consisted of granular sized particles which still contained residual moisture.

There was usually little or no evidence of sludge 0.6 to 1m below the waste rock surface. However, in test pit 4, a rock chimney was intersected at the 0.6 to 1m depth. The sludge in the chimney was a mixture of dried granular and powder similar to that found on the surface and moist two to eight centimeter blebs which had retained their gelatinous consistency.

TEST PIT 1

During the fall of 1992 dredging operation, sludge was deposited in unlined ponds on the waste rock to a depth of approximately 0.6 to one meter. In October 1994 the dried sludge was fifteen to fifty centimeters thick on the waste rock. Eroded drainage paths carved into the powder dry unvegetated sludge directed surface run-off from precipitation and eroded sludge into porous rock chimneys in the waste rock.

Below the original waste rock surface the sludge was present as the matrix in the weathered sandstone and silt. There was no evidence of sludge below 0.75 to one meter depth at this location.

TEST PIT 2

During the fall of 1993 dredging operation, sludge was deposited on an area of the waste rock which had been previously revegetated naturally with grasses, yellow birch (0.6 to one meter in height) and goldenrod. After the sludge depositional operation, the vegetation continued to grow through the dried sludge. All of the roots were, however, firmly anchored in the underlying weathered waste rock.

The vast majority of the sludge deposited on the waste rock surface during this operation disappeared into the reclaimed mine site.

The sludge at this location was fifteen to twenty centimeters thick above the waste rock surface and was powder dry as evidenced by the presence of desiccation cracks. There was very little evidence of sludge in the matrix of the weathered sand and silt sized particles on the waste rock.

TEST PIT 3

Sludge during the fall of 1993 dredging operation was also deposited in an adjacent area which had not been naturally revegetated. The surface vegetation after the sludge deposition consisted of a naturally revegetated rhubarb-shaped leaf and type-habitat plant growing on the powder dry sludge surface. The roots of the plants were anchored in the sludge. The roots did not penetrate into the waste rock. This plant was also observed thriving in the dried sludge on the edges of sedimentation ponds but was not observed to be prevalent in the undisturbed areas adjacent to the mine site nor on bare waste rock.

The 0.3 to 0.5 meter thick deposit of sludge exhibited stratification based on particle size indicating that several applications of sludge had been deposited in this area with a low energy period between each application. The upper layer of each sequence consisted of the finest sized particles which were powder dry to the touch. The lowest layer of each depositional sequence consisted of granular sized particles which still contained residual moisture. At the base of the sludge deposit was a saturated deposit of weathered clay/sand waste rock which acted as a water seal. Sludge was not found either in or below this saturated material.

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TEST PIT 4

During the fall of 1993 dredging operation, sludge was also deposited in an area which was recently recontoured with artificial baffles constructed of waste rock from the surface of the mine site. The baffles theoretically increased the path length of the slurried sludge allowing more of the sludge to be deposited closer to where it exited the dredge pipe. However, because of the consistency (low solids content) of the slurry and the recent reworking of the mine site surface to construct the baffles, the low viscosity slurry flowed on the surface until it encountered a high porosity chimney in the waste rock and then proceeded to drain into the chimney. This chimney would continue to be the receptacle for the slurry until either the congealed sludge became too thick and the slurry found a new flow path, seasonal temperatures for November created an ice bridge over the chimney and hence sealed it from the surface or the chimney filled with congealed sludge.

Test Pit 4 was excavated in the artificially baffled area on the waste rock. The top five to eight centimeters of the powder dry unvegetated sludge showed evidence of desiccation cracking. This was followed by a fifteen centimeter thick section of stratified sludge units. Beneath these units the sludge was intermixed with the waste rock.

At the 0.6 to one meter depth a massive inclusion of sludge more than twelve inches across and two feet deep, was found below a layer of waste rock boulders and gravel. The sludge was a mixture of dried granular and powder similar to that found on the surface and moist two to eight centimeter blebs which had retained their gelatinous consistency. Not all exposed surfaces of the test pit exhibited sludge to this depth, concentration and consistency indicating that this pit had intersected one of the rock chimneys observed during the dredging operations.

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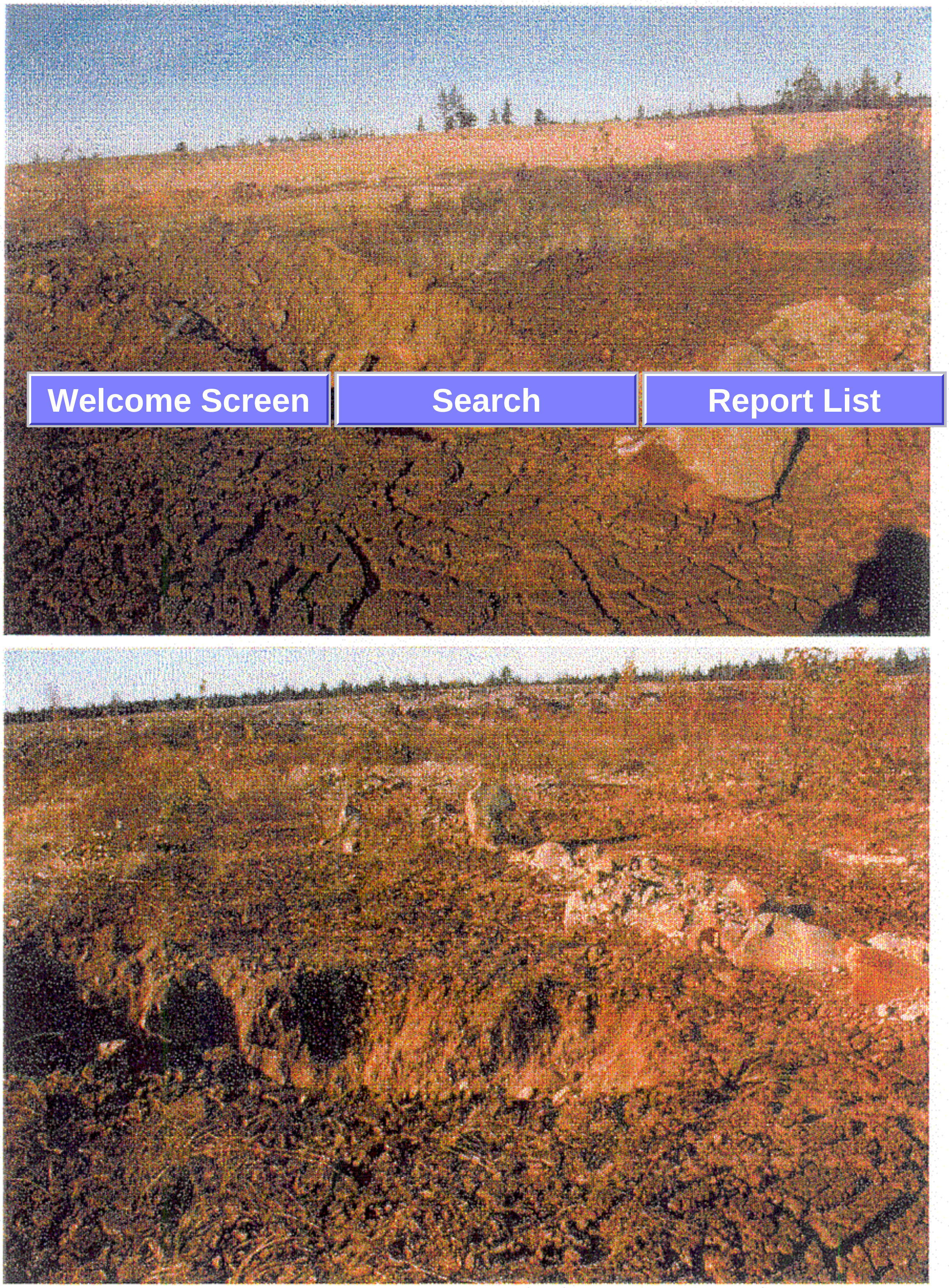

Photo E-1. Test pit 2 sludge deposited fall '93. Area previously vegetated. Vegetation (mostly grasses and yellow birch(?) continued to grow through sludge. Neutralization plant is at upper left (on top picture). Dried sludge layered above weathered waste rock.

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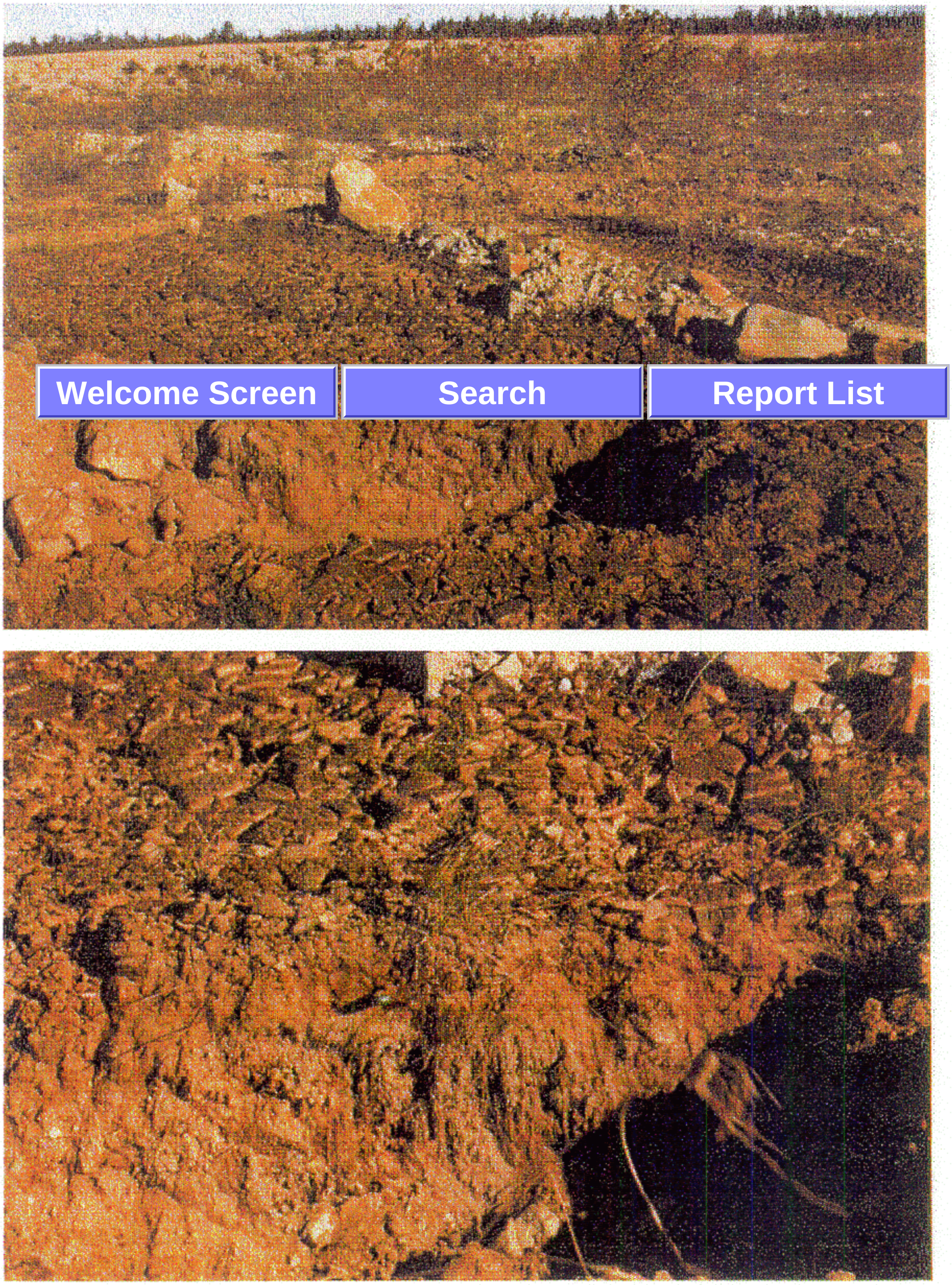

Photo E-2. Roots are in weathered waste rock. Plant stems grew up through the dried sludge.

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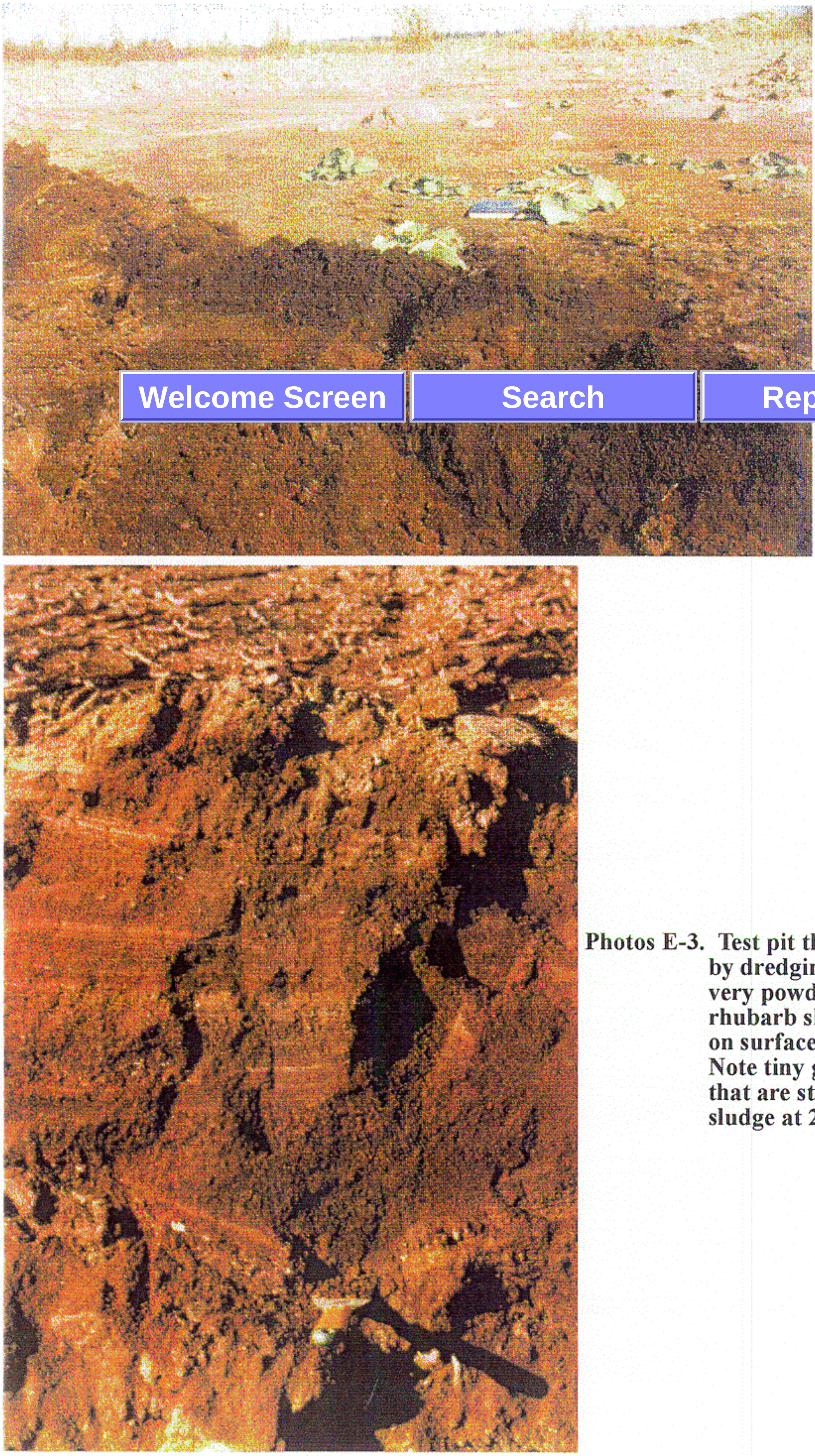

Photos E-3. Test pit three - sludge deposited by dredging, fall '93. Sludge very powdery. Weeds with rhubarb shaped leaves / growth on surface. Sludge is stratified. Note tiny granules on figure 3 that are still undehydrated sludge at 24" below surface.

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Photos E-4. Test pit four - artificially baffled area on waste rock used to deposit / contain sludge deposited fall '93. Sludge layered 1) top 2-3" cracked 2) stratified layers 3) still moist sludge beneath upper waste rock. Looks like a "low porosity chimney" or vent which was filled with sludge.

APPENDIX O

Dredged/Pumped Sludge: General
(Gemtec Ltd., 1995)

DREDGED/PUMPED SLUDGE: GENERAL

(a) Surface deposition, drying and compaction

If all the pumped solids could be retained - after pumping - on the surface and later compacted (at a water content w of about 150%, or w_{vir} = 72.5%) to an overall dry density ρ_{ds} of 500 kg/m^3, the total volume of compacted sludge available from each pond would be

$$V_{pc} = \frac{2{,}750{,}000}{500} = 5{,}500\ m^3/pond$$

If it is assumed that a thickness of compacted sludge of at least 0.5 m would be required, and if the total area to be covered is taken to be A_t = 1,200,000 m^2, then the total volume required would be at least

$$V_{tr\ min} = 1{,}200{,}000 * 0.5 = 600{,}000\ m^3.$$

This quantity corresponds to a number of ponds N_p of

$$N_p = 600{,}000/5{,}500 = 109\ ponds.$$

If the filling of ponds is carried out at a rate of 6 ponds/year, it would thus take about 109/6 = 18 years to produce the required material.

(b) Filling of rockfill voids with congealed slurry

The total volume of rockfill waste in the entire area, above the groundwater table, is about 11,500,000 m^3 (see longitudinal section). The total volume of voids within the rock above the groundwater table in the approximately 350 * 3,500 m area is thus about 11,500,000 * 0.4 = 4,600,000 m^3. If these voids were completely filled with sludge congealed at w = 560% (w_{vir} = 91.4%), the volume of water in the sludge would be

$$V_w = 0.914 * 4{,}600{,}000 = 4{,}204{,}400\ m^3$$

and the volume of porous, saturated particles would be

$$V_s = 4{,}600{,}000 - 4{,}204{,}400 = 395{,}600\ m^3.$$

The weight of these particles would be

$$\begin{aligned} M_s &= 395{,}600 * 1000\ L/m^3 * 1.96 \\ &\approx 7.8 * 10^8\ kg \end{aligned}$$

The total quantity of solids in each holding pond was found to be 2.75 * 10^6 kg (page C1). If it is assumed that the filling of the ponds is carried out at a rate of 6 ponds/yr, the weight of particles produced per year would be

$$M_{st} = 6 * 2.75 * 10^6 \approx 1.7 * 10^7\ kg/year$$

It would therefore take

$7.8 * 10^8/1.7 * 10^7 \approx$ 46 years to completely fill the voids above the groundwater level.

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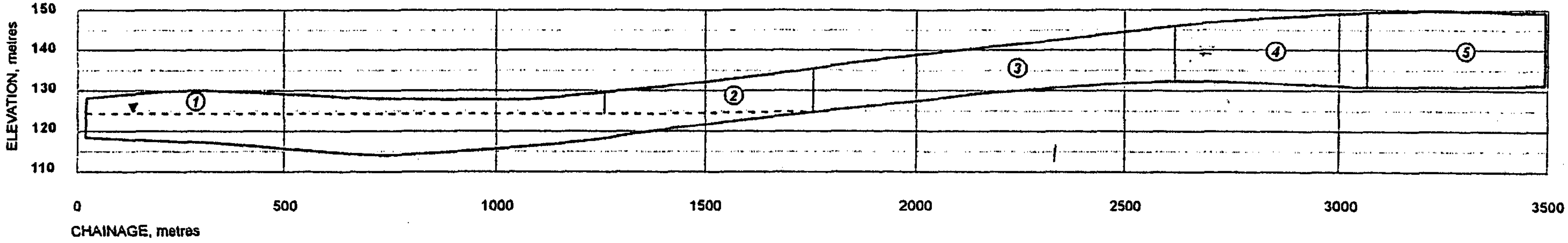

$$\text{Average width} \simeq \frac{1{,}200{,}000\ m^2}{3{,}450\ m} = 348\ m$$

$$\text{Volume above GWL} \simeq 348[(5 \overset{①}{x} 1{,}228) + (7.5 \overset{②}{x} 498) + (10.5 \overset{③}{x} 857)+(14.5 \overset{④}{x} 442) + (18 \overset{⑤}{x} 425)]$$

$$\simeq 11{,}460{,}500\ m^3$$

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LEGEND

PROJECT
NB COAL
GEOTECHNICAL EVALUATION OF SLUDGE SEAL

GEMTEC LIMITED
GROUND ENGINEERING
& MATERIALS TECHNOLOGY

DRAWING LONGITUDINAL SECTION THROUGH WASTE ROCK AREA

SCALE 1:1000 H 1:100 V	PROJ. No. 269.15	DWG. No FIGURE 6
DATE FEBRUARY 1995	DRN. BY SAF	CHKD. BY DPD

(c) Surface deposition and mixing with rockfill

Another possible approach to the sealing of the rockfill would be to introduce the slurry on to the rockfill surface through a pipe perforated at certain intervals. The rockfill surface would first have to be made relatively smooth and to be given a slope so as to allow the slurry to flow. The pipe would be laid parallel to the slope and next to a low overflow ridge so as to provide an even spreading of the slurry.

A portion of the slurry would penetrate the rockfill and some would be retained on the surface. After a build-up of perhaps 20 to 30 cm of congealed sludge on the surface, at which time its moisture content could be expected to be around 500% by dry weight (90.5% by volume), the slurry would be mixed with the finer rockfill by dozing and backdragging.

Assume that it would be possible in this way to eventually produce a layer of rockfill saturated with sludge at a water content of say 250% by dry weight (82.2% by volume), allowing for some drying. Assume further that a total thickness of such a sludge-saturated rockfill of 2.0 m would be required to provide a proper seal, and that the porosity (n) of the rockfill would be 50% (n = 0.50). The total amount of sludge required would be approximately

$$1{,}200{,}000\ m^2 * 2.0\ m * 0.50 = 1{,}200{,}000\ m^3$$

The corresponding amount of sludge solids of specific gravity $G_s = 1.96$ would be

$$1{,}200{,}000\ (1 - 0.872) = 213{,}600\ m^3$$

and the corresponding weight of these solids would be

$$213{,}600 * 1{,}000\ L/m^3 * 1.96 = 4.2 * 10^8\ kg$$

It would therefore take

$$4.2 * 10^8 / 1.7 * 10^7 = \underline{25\ years}$$

to produce a 2.0 m layer of rockfill saturated with sludge of water content 82% by volume.

The assumed water content of the sludge is an important factor in the prediction of the number of years required to produce a given layer of saturated rockfill. For example, if the water content of sludge were to be 90% (instead of 82.2%) by volume, and the thickness of the layer were to be 1.0 m (instead of 2.0 m), the time required would be reduced to 7 years.

APPENDIX P

Initial and Final Weathering Cell Analysis
(Grace Dearborn Inc., June, 1996)

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TABLE P-1

ANALYSIS OF INITIAL WASTE ROCK AND SLUDGE SOLID SAMPLES

Sample Description	Sample No.	Initial Total Sulfur Content (%)	Acid Consumed (lb/ton)
Waste Rock	1	0.17	<0.5
	2	0.4	<0.5
	3	0.31	<0.5
	4	0.4	<0.5
	5	0.4	<0.5
	6	0.31	<0.5
	7	0.48	<0.5
	8	0.33	<0.5
	9	0.37	<0.5
Average		**0.35**	**<0.5**
Mixed Sludge Average	1	5.6	542.0
	2	5.42	539.0
	3	5.5	537.2
Average		**5.51**	**539.4**

NOTE: Sample Analysis were completed on January 6, 1995.
All results are on a dry weight basis.

TABLE P-2

ANALYSIS OF FINAL WEATHERING CELL CONTENTS

Weathering Cell No.	Sample No.	Final Total Sulfur Content (%)	Final Pyritic Sulfur Content (%)	Acid Consumed (lb/ton)
1A	1	0.22	0.09	8.8
	2	0.20	0.07	8.5
	3	0.21	0.06	9.0
Average		**0.21**	**0.07**	**8.8**
1B	1	0.26	0.09	25.2
	2	0.28	0.12	25.1
	3	0.27	0.10	25.1
Average		**0.27**	**0.10**	**25.1**
1C	1	0.61	0.20	58.3
	2	0.59	0.17	53.6
	3	0.55	0.12	54.0
Average		**0.58**	**0.16**	**55.3**
2A	1	0.20	0.07	8.0
	2	0.21	0.09	7.9
	3	0.21	0.07	7.2
Average		**0.21**	**0.08**	**7.7**
2B	1	0.27	0.12	40.5
	2	0.23	0.09	38.1
	3	0.25	0.10	39.7
Average		**0.25**	**0.10**	**39.4**
2C	1	0.46	0.12	56.9
	2	0.48	0.14	58.9
	3	0.46	0.13	60.5
Average		**0.47**	**0.13**	**58.8**
3A	1	0.18	0.08	9.8
	2	0.20	0.09	10.2
	3	0.21	0.10	10.2
Average		**0.20**	**0.09**	**10.1**
3B	1	0.33	0.11	47.7
	2	0.29	0.08	43.8
	3	0.31	0.10	40.4
Average		**0.31**	**0.10**	**44.0**
3C	1	0.48	0.08	48.0
	2	0.49	0.11	48.6
	3	0.51	0.12	51.2
Average		**0.49**	**0.10**	**49.3**

NOTE: 1) Sample Analysis were completed on March 6, 1996
2) All results are on a dry weight basis
3) Cell Groups are described as follows:
A - Control (Waste Rock Only)
B - 0.5:1 Sludge to Waste Rock
C - 1:1 Sludge to Waste Rock

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TABLE P-3

INITIAL CELL CONDITIONS

Cell Number	Cell Description (wet wt ratio)	Waste Rock Mass - Dry (g)	Sludge Mass - Dry (g)	Total Cell Mass - Dry (g)	Waste Rock Sulfur Content (%)	Sludge Sulfur Content (%)	Initial Total Sulfur Cell Content (%)	Initial Pyritic Sulfur Cell Content (%)
1A	Control (Waste Rock Only)	1899.39	0.00	1899.39	0.17	-	0.17	0.17
2A		1904.45	0.00	1904.45	0.40	-	0.40	0.40
3A		1902.75	0.00	1902.75	0.31	-	0.31	0.31
1B	0.5:1 Sludge to Waste Rock	1864.31	116.77	1981.08	0.40	5.51	0.70	0.38
2B		1875.14	117.47	1992.61	0.40	5.51	0.70	0.38
3B		1877.06	116.88	1993.94	0.31	5.51	0.61	0.29
1C	1:1 Sludge to Waste Rock	1850.75	232.48	2083.23	0.48	5.51	1.04	0.43
2C		1819.43	232.95	2052.38	0.33	5.51	0.92	0.29
3C		1841.96	232.48	2074.44	0.37	5.51	0.95	0.33

NOTE: All results are on a dry weight basis.

TABLE P-4

COMPARISON OF INITIAL AND FINAL CELL CONDITIONS

Cell Number	Cell Description	Initial Total Sulfur Cell Content (%)	Initial Pyritic Sulfur Cell Content (%)	Final Total Sulfur Cell Content (%)	Final Pyritic Sulfur Cell Content (%)
1A	Control (Waste Rock Only)	0.17	0.17	0.21	0.07
2A		0.40	0.40	0.21	0.08
3A		0.31	0.31	0.20	0.09
Average		0.29	0.29	0.21	0.08
1B	0.5:1 Sludge to Waste Rock	0.70	0.38	0.27	0.10
2B		0.70	0.38	0.25	0.10
3B		0.61	0.29	0.31	0.10
Average		0.67	0.35	0.28	0.10
1C	0.5:1 Sludge to Waste Rock	1.04	0.43	0.58	0.16
2C		0.92	0.29	0.47	0.13
3C		0.95	0.33	0.49	0.10
Average		0.97	0.35	0.51	0.13

NOTE: All results are on a dry weight basis.

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TABLE P-5

COMPARISON OF INITIAL AND FINAL THEORETICAL ACID GENERATING AND NEUTRALIZATION POTENTIALS

Cell Number	Initial Theoretical Acid Generating Potential (lb/ton) Ai	Initial Theoretical Neutralizing Potential (lb/ton) Bi	Net Acid Production (A-B)i	Final Theoretical Acid Generating Potential (lb/ton) Af	Final Theoretical Neutralizing Potential (lb/ton) Bf	Net Acid Production (A-B)f	Pyrite Oxidation (%)
1A	10.41	<0.5	10.41	4.29	8.80	-4.51	58.82
2A	24.50	<0.5	24.50	4.90	7.70	-2.80	80.00
3A	18.99	<0.5	18.99	5.51	10.10	-4.59	70.97
Average	17.97	<0.5	17.97	4.90	8.87	-3.97	69.93
1B	23.28	31.79	-8.52	6.13	25.10	-18.98	73.68
2B	23.28	31.80	-8.52	6.13	39.40	-33.28	73.68
3B	17.76	31.62	-13.86	6.13	44.00	-37.88	65.52
Average	21.44	31.74	-10.30	6.13	36.17	-30.04	70.96
1C	26.34	60.19	-33.86	9.80	55.30	-45.50	62.79
2C	17.76	61.22	-43.46	7.95	58.80	-50.85	55.25
3C	20.21	60.45	-40.24	6.13	49.30	-43.18	69.70
Average	21.44	60.62	-39.19	7.96	54.47	-46.51	62.58

NOTES:

1) Cell Groups are described as follows:
   - A - Control (Waste Rock Only)
   - B - 0.5:1 Sludge to Waste Rock
   - C - 1:1 Sludge to Waste Rock
2) All results are on a dry weight basis
3) Pyrite oxidation calculations are based on (Ai-Af)/Ai * 100%