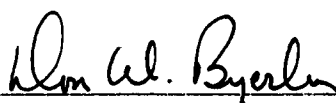


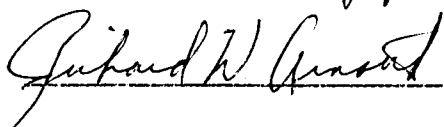
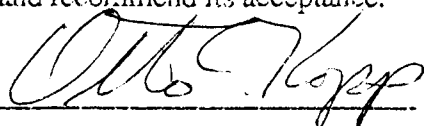
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Don W. Byerly, Major Professor

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GEOCHEMICAL ASSESSMENT OF ACID DRAINAGE IN THE BLUE
RIDGE PROVINCE OF TENNESSEE AND NORTH CAROLINA

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

William Kevin Jago
May 1989

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Finally, I wish to express special thanks to my wife Robin for her complete support, review and editing assistance and patience.

ABSTRACT

Highway construction in the southern Blue Ridge province of Tennessee and North Carolina encountered sulfide-bearing, Precambrian strata that produced acid drainage (AD) upon exposure and weathering. The situation prompted the development of pre-construction evaluation techniques and encapsulation measures for these materials.

The present study proposed to: examine effluent quality over time in a series of laboratory leaching tests incorporating sulfidic material from a constructed highway segment; aid in the development of a more economical encapsulation method using field-scale leaching tests; review current Federal Highway Administration predictive and mitigative measures using the leach test results and surface water data; examine reaction pathways, rates and mechanisms of sulfide oxidation; and examine mineralogical changes in leached or encapsulated material over time.

Seven bench-scale leaching tests were constructed using 1 kg of material from various intervals of the highway corridor which demonstrated acid-base accounting values ranging from +50 to -50 tons CaCO_3 per 1,000 tons material. Eight field-scale variations of the present encapsulation method were constructed with similar source material in 30 gal (100 liter) polyethylene tanks. Baseline water quality comparisons were done using effluents from an encapsulation site underdrain and several surface water points draining from untreated roadcut exposures. Comparisons of pH, conductivity, sulfate, acidity, Al, Fe, Mn, Cu, and Zn were made among both laboratory and field models, as well as to actual fill leachates, in order to meet the study objectives. A mineralogical characterization using XRD and visual methods and sulfur phase distribution studies were performed on leachates and rock material to examine species redistribution patterns in both the leaching studies and the roadfills.

Major conclusions of the study include:

1. Sulfur bound in sulfide minerals is redistributed to sulfate forms or flushed from a system during oxidation and leaching. Sulfur present as organic phases seems to remain relatively constant. The duration of this process and hence, the significant acid-production life of Ocoee rocks, is about two years in laboratory leaching studies such as those used in this study.
2. Accelerated weathering in the laboratory leaching tests indicates that sulfidic Ocoee rocks appear to be capable of significant acid production for several decades in the field.

3. The oxidation of sulfides, along with leaching and hydration of other primary minerals such as albite, muscovite and chlorite, in acidic water, provides a source for species which result in abundant secondary mineral formation. Mineral phases resulting from the weathering of Ocoee rocks include jarosite, copiapite, ferrihydrite, aluminum oxides and hydroxides, and kaolinite.
4. Current predictive methods generally appear to have good correlation with lab leaching tests using similar source materials.
5. Field-scale models of encapsulation sites show that separate reductions in the thickness of limestone underblankets and topsoil cover used in current roadfills by 60% and 50% respectively, do not significantly affect water quality.
6. Current encapsulation site design seems to be an effective long-term method to mitigate AD in highway construction settings. A more economical variation, however, might include reductions in the amount of limestone underblanket and/or topsoil cover.

PREFACE

Acid mine drainage (AMD) or acid drainage (AD) is generally defined as waters having pH values of approximately 4.5 or less. Typically associated with AD are elevated levels of sulfate, conductivity, acidity and many metals, notably Fe, Mn, Zn, Cu, Al. Additional dissolved metal constituents may vary with the nature of the source. The adverse environmental effects of acidic effluents have almost always accompanied mining or construction activities where sulfide or sulfur-bearing strata have been disturbed and exposed. In many cases, however, these effects were either unknown or of small extent, so that little attention was given to environmental concerns. With the emergence of strip mining as the primary coal and base metal mining method, very large volumes of sulfide-bearing material were excavated and AMD began to be recognized as a serious problem. Often, reclamation and water quality controls failed to adequately address environmental problems posed by surface mining. Significant research into the nature and occurrence of acid mine drainage was initiated in the 1930's and 1940's, but did not begin in earnest until the 1950's when the extent of the problem was finally realized.

A study of the problem at a national level was instigated in 1976 by the Environmental Protection Agency (EPA) (Martin and Mills, 1976). The study examined 100 abandoned or inactive mineral mine sites in 18 states. Only known, point-source generators of acidic waters were surveyed. Acid drainage from these sites had moderately to severely affected over 740 miles of surface streams. Furthermore, this study estimated that over 19,000 inactive or abandoned coal and mineral mines alone may exist, many of which have the potential to produce, or are producing, AMD. During the 1970's and 80's, with increased public environmental awareness and the passage of numerous state and federal clean water provisions, research expanded into the causes, effects, and mitigation of AD.

Presently, several federal institutions, such as the U.S. Bureau of Mines, EPA, U.S. Forest Service and the Federal Highway Administration (FHWA), are involved in AD research. In addition, many states, universities and private companies have participated in research and initiated programs dealing specifically with the subject. The present study began in this atmosphere. This particular research deals with acid drainage in a rather unique setting, that of highway construction. Mitigation technology in this situation poses some unique problems in that engineering design of highways normally requires the balancing of quantities of excavated materials with the volume of material to be used in road construction, and the limitation that only rarely can sulfidic materials be transported off site

to a disposal area. A primary objective of this study was to examine present technology for handling these acid-producing materials and attempt to suggest viable alternatives or modifications in order to improve the economics of highway construction in such settings and to enhance environmental protection.

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CHAPTER I

INTRODUCTION

Statement of Problem

Highway construction in the southern Blue Ridge province of Tennessee and North Carolina during the 1970's disrupted sulfide-bearing rock within Precambrian strata of the Ocoee Series. These materials were exposed to weathering on a large scale and indiscriminantly incorporated as roadfill. Products formed by the oxidation of the sulfide minerals were subsequently leached by infiltrating precipitation resulting in AD which adversely affected several local watersheds. The situation required retroactive chemical treatment of runoff waters and roadfill. Due to the necessity of volume balance during construction, all excavated materials had to be included in engineering design so that cost efficiency could be maintained. Ultimate recognition of the adverse environmental impact of this practice prompted the development of expensive encapsulation techniques and pre-construction evaluation methods to minimize contamination.

Topographic and Physiographic Setting

This study encompasses a 2.8 mile segment (TNFLH 1-1(14)) of the Tellico Plains - Robbinsville Scenic Highway. Construction of this segment of highway was completed during 1981 by the Direct Federal Division of the Federal Highway Administration (FHWA). The project site is located within the Blue Ridge physiographic province in the Cherokee National Forest, Monroe County, approximately 20 miles (32 kilometers) northeast of Tellico Plains, Tennessee (Figure 1). This segment, traversing the steep, rugged topography of the Unicoi Mountains, ranges in elevation from 3,600 to 4,400 feet (1,097 to 1,341 meters) above sea level (Figure 2). Details of topography traversed by TNFLH 1-1(14) are found on the Big Junction, Tennessee - North Carolina 7.5 minute USGS or TVA quadrangle.

Geologic Setting

The sulfide-bearing stratigraphic unit examined during this study is within the Precambrian Great Smoky Group which, in turn, forms the middle portion of the Ocoee

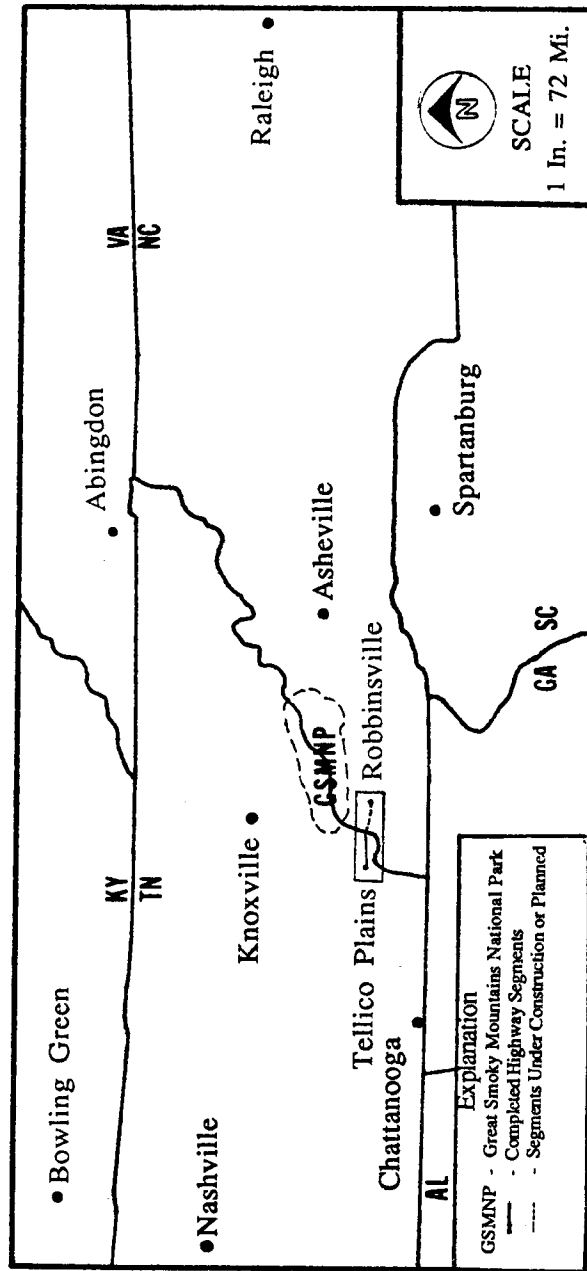


Figure 1. Location of Study Area

Series (Byerly, 1980). Lithologically, the unit is represented by a composite of low-grade, regionally-metamorphosed pelitic rocks consisting of argillite, phyllite, meta-graywacke, meta-siltstone and meta-sandstone. A previous study involved the mapping of lithologies along TNFLH 1-1(14) and noted that three major assemblages were exposed along the project (Byerly, 1980). Based on that study and field observations during the present research, these assemblages consist of:

1. A massively-bedded, medium- to coarse-grained, medium- to light-gray, well-cemented, metamorphosed sandstone assemblage. The rock weathers to light-gray to pale-yellow, often as friable masses easily broken by hammer. Observed weathering depths have been as much as several feet into an outcrop face. The assemblage often contains dark-brown concretionary bodies. These concretions may reflect a localized concentration of carbonate minerals since they weather more rapidly than the surrounding bedrock.
2. A medium- to thinly-bedded, dark-gray to brown to black, meta-sandstone /meta-siltstone and interbedded argillite assemblage. Sandstone in this unit is usually more poorly sorted than in assemblage 1. The sandstone often contains quartz having a bluish coloration.
3. A thinly-bedded to fissile, dark-gray to brown to black, meta-shale or argillite assemblage.

In general, lithology and approximate stratigraphic position suggests a correlation with the stratigraphic interval of the Thunderhead and Anakeesta Formations of the Great Smoky Group as described in detail in the Great Smoky Mountains National Park (Hadley and Goldsmith, 1963 ; King, 1964). Sulfide mineralization may occur in any of the three described assemblages, although it is more likely to occur in the argillites. Sulfides typically occur in finely-disseminated form or as sheet-like masses along foliation or bedding planes. In the sandstone, however, mineralization tends to occur randomly throughout a specimen, and the minerals may exhibit euhedral crystals. Sulfide minerals sampled from TNFLH 1-1(14), as identified in composite XRD samples and binocular microscope examinations, include pyrite, marcasite, chalcopyrite and possibly smythite with pyrite as the dominant species. Sulfide mineralization in other locales outside of the study area, but probably within the same unit, may include pyrite, pyrrhotite, chalcopyrite and sphalerite (Merschlat and Larson, 1972). In some areas south of the study site, pyrite cubes up to 0.5 inches (1.3 centimeters) have been observed within argillite outcrops.

Structurally, the bedrock is complexly folded and faulted and exhibits features indicative of multiple deformation events.

Project History

During construction of TNFLH 1-1(8), the segment constructed prior to TNFLH 1-1(14), deleterious material was inadvertently disturbed and incorporated as roadfill. As mentioned, the resulting AD required costly post-construction mitigation, including the trickling of NaOH into headwaters of affected streams and the application of liquified lime and additional topsoil cover to the constructed fills. These measures were labor intensive, in addition to expensive, and the results not entirely successful (McKinney and Melgaard, 1979). These factors necessitated the development of an encapsulation method and pre-construction evaluation techniques for implementation on subsequent segments. TNFLH 1-1(14) was the first project in which these measures were applied. A complete description of current procedure is covered later. Five intervals of the highway corridor, ranging from 200 to 1,000 feet (61 to 305 meters) in length and containing a total of approximately 34,000 yd³ (26,000 m³) of material, were identified as having sufficient potential for producing AD to merit special handling (Byerly, 1980). The materials with the greatest acid potential were encapsulated in one of three fills and, where evaluations indicated little potential for acid production, blended with lime and rock having very low or zero acid production potential (Table 1). One of these encapsulation sites at station 996+50, completed during 1979, is evaluated in this study.

Purpose of Study

Acid drainage due to the disturbance of sulfide-bearing strata during highway construction has occurred in other areas of the Blue Ridge province, most notably during construction of US 441 across the Great Smoky Mountains National Park (Huckabee et al., 1975). The toxic effects on aquatic biota were examined in detail along with possible remedial actions (Mathews and Morgan, 1982 ; Mathews et al., 1976). Since problems with AD due to highway construction have historically occurred throughout the southern Blue Ridge province, the FHWA determined that a comprehensive study of the subject was merited. The objectives set forth in this thesis constitute a portion of this study. These objectives were as follows:

Table 1. Locations and Encapsulation Zones of Sulfidic Rock*

Approximate Location of Removal	Estimated Volume	Burial Zone/Volume Emplaced			Volume Placed as Blend
		954 -955	963+50 - 967+00	994+50 - 996+50	
959+30 - 969+30 (1000 ft.)	14,200	4,000	10,200	--	--
988+00 - 990+50 (250 ft.)	4,000	--	--	4,000	--
996+50 - 998+50 (200 ft.)	8,000	--	--	8,000	--
1019+00 - 1022+00 (300 ft.)	3,600	--	--	--	3,600
1048+00 - 1058+00 (1,000 ft.)	4,300	--	--	--	4,300

* Refer to Figure 2 for approximate locations of encapsulation sites. All volumes are yd³.

1. To review current FHWA evaluation and encapsulation technology and determine the effectiveness of present burial techniques to provide long-term abatement of AD.
2. To examine the reaction pathways, rates, mechanisms, catalysts, and inhibitors involved in the oxidation of sulfides and the development of AD.
3. To examine effluent quality versus time in a series of laboratory leaching tests incorporating material from TNFLH 1-1(14) and compare these results to present FHWA predictive evaluations. In addition, the feasibility of using laboratory tests to extrapolate field conditions was examined and general comparisons of lab and field leaching data were made.
4. To attempt to develop a more economical encapsulation method through data generated by a battery of field scale leaching models. In addition, the effects of seasonal variations in temperature and rainfall were examined and an attempt to develop a model of internal fill sulfide oxidation and chemical distribution patterns was made.

5. To implement a surface water sampling program to establish baseline water quality for comparisons to field models and to meet the dictates of the first objective.
6. To attempt to define mineralogical changes and species redistribution trends in an actual fill interior and laboratory models utilizing core data, leachate chemistry and sulfur redistribution studies.

CHAPTER II

CURRENT TECHNOLOGY FOR AD TREATMENT AND IDENTIFICATION

AD Mitigation Technology

Intensive research into acid drainage has produced a myriad of treatment technologies which have been applied mostly to mining situations. Many of the methods, however, are uneconomical, labor intensive and may not constitute long-term solutions to the problem. Table 2 provides a partial listing of current AD mitigation measures and some associated advantages and disadvantages. Among the popular mitigation programs to date are the use of wetlands to treat effluent, lime/limestone applications in order to induce alkalinity to discharge waters or overburden, and capping of sulfidic material to inhibit primary sulfide oxidation through O_2 removal and reduced rainfall infiltration. Several methods, other than those listed, have been cited in the literature and implemented with varying degrees of success either in laboratory or field settings. These include reverse osmosis, in-line aeration, silicate treatments, zeolite applications, mine sealing and others.

Preconstruction Evaluations Utilized on TNFLH 1-1(14)

Several procedures have been developed in order to determine the tendency or potential for material to produce AD. Visual evaluation of sulfide content, acid-base accounting and simulated weathering tests all provide qualitative and quantitative assessments of acid production potential (Sobek et al., 1978 ; Carrucio, 1984). Additional factors that may affect the potential extent of AD development include the hydrologic environment within overburden materials and the buffer capacity of surrounding bedrock (Ferguson and Erickson, 1987). During the drilling program prior to construction of TNFLH 1-1(14), samples were inspected visually and subjected to acid-base accounting analyses.

An acid-base accounting analysis compares a sample's buffering capacity or neutralization potential (NP) to its acid production potential (AP). NP is determined by reacting a sample with a stoichiometric amount and normality of HCl and determining the amount of acid consumed by titration with NaOH to a specific endpoint pH. The acid production potential is determined by analyzing the sample for total or pyritic sulfur. The AP and NP values are expressed as tons $CaCO_3$ equivalent per 1000 tons material through unit recalculations (Sobek et al., 1978). These data may then be balanced to obtain a net

Table 2. Partial Listing of Current Mitigation Technologies

Measure	Relative Costs	Relative Maintenance Requirements	Long Term Solution	Effectiveness	Reference(s)
Artificial Wet-land Treatment	Moderate	Periodic siltation may require removal in areas with high input	Yes	Effective at raising pH reducing Fe, Mn, Ni, Cu, Zn, SO ₄ , poor at Al removal	Skousen et al., 1987 Nakamura, 1988 Kleinmann, 1985 Eger and Lapakko, 1988
Chemical Injection of Ammonia, NaOH	High	Replenishment of chemicals machinery maintenance, sludge removal in treatment ponds	Only if program is maintained	Removal of primary pollutants through pH increase	Skousen et al., 1987 McKinney and Melgaard, 1979
Clay or Polymer Capping	Mod.-High	Periodic damage repair	Not determined	Decreases discharge volumes, O ₂ influx	Skousen et al., 1987 Murray et al., 1988
Induced Alkaline Recharge	Moderate	May require renewal of alkaline source	Only if program is maintained	Removal of primary pollutants through pH increase at the sulfide source	Skousen et al., 1987 Ladwig et al., 1985 Caruccio and Geidel, 1984
Lime/Limestone Applications to Overburden	Low - Mod.	May require periodic renewal	Limited long-term success	Removal of primary pollutants through pH increase at the sulfide source	*FWPCF, 1970 FWPCF, 1971
Application of Ionic Surfactants	Low - Mod.	Requires reapplication every 2 - 3 years	If program integrity is maintained	Removal of primary pollutants through bactericide effects on <i>Thiobacillus ferrooxidans</i>	Kim et al, 1982 Kleinmann and Erickson, 1983

* FWPCF = Federal Water Pollution Control Federation

neutralization potential (NNP) value. When the NP exceeds AP, the sample will produce alkalinity (positive NNP) and, if NP is less than AP (negative NNP), the sample will produce AD. A general guideline recognized in coal mine reclamation is that material having an NNP value of less than or equal to -5 tons CaCO_3 equivalent per 1000 tons material is classified as toxic. Laboratory kinetic or artificial weathering tests were not utilized during highway construction due to the length of time required for accurate assessment of acid production potential.

Additional evaluation techniques such as geophysical methods (induced polarization) have been employed on future segments to give rapid, reconnaissance style data to augment drilling programs.

Encapsulation Technology

Due to the necessity of including all acid-producing materials in the balance of cut and fill volumes during construction, the fairly remote location and rugged terrain of the construction area, and the need for maintenance-free remedial technologies, many of the mitigation measures in Table 2 were not feasible. The adaptation of encapsulation fills allowed for the inclusion of necessary volumes in order to meet engineering requirements. In addition, the method allows for nearly "in situ" disposal of deleterious rock, in that haul distances are not very great. The design utilized on TNFLH 1-1(14) involves the construction of a typical bench style excavation, as would be used for a roadfill to maintain grade, in line with the route of construction. Sulfidic material is placed as fill into the bench excavation which is lined with a layer of limestone aggregate approximately 1 foot (0.3 meters) thick between layers of BIDIM-U14 filter fabric. Drainage is provided by an underdrain network located at the base of the limestone aggregate layer. Deleterious material is placed in lifts approximately 2 feet (0.6 meters) in thickness with application of agricultural lime at a rate of 500 pounds (227 kilograms) per 1,000 ft^2 (93 m^2) between each layer. Each lift is separately compacted by sheepsfoot roller to reduce permeability and increase stability. The entire fill is covered by topsoil to a depth of 6 feet (1.8 meters) (Figure 3). Final closure involves hydroseeding the encapsulation site slopes for stabilization. Normal road construction can then commence along the upper fill surface.

CHAPTER III

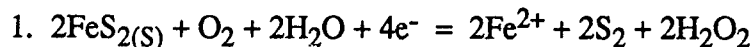
SULFIDE WEATHERING AND REACTION SERIES

Reaction Pathways

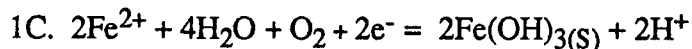
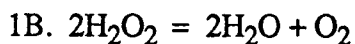
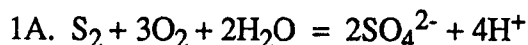
The oxidation of sulfide minerals is a complex process involving redox reactions, electrochemical reactions and microbial catalysis. Most studies dealing with reaction pathways have utilized pyrite for experimental purposes. Only two studies were found which included a brief discussion of the inhibitory or catalytic effects of other minerals such as chalcopyrite, marcasite, pyrrhotite and sphalerite. In consideration of the data base available, the term sulfide is used throughout the remainder of this report to refer specifically to iron-bearing sulfides.

Sulfide oxidation is considered as a three phase process involving an initiation stage, an intermediate step and a propagation cycle (Singer and Stumm, 1970). Each of these phases contains one or more steps which contribute to the overall breakdown of sulfides and development of secondary minerals. The set of reactions and half-reactions described below show the sulfide oxidation pathway.

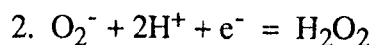
The initiation phase begins with sulfide oxidation in the presence of water having a neutral pH. An acidophilic bacterium (*Thiobacillus ferroxidans*) may have a very minor role in the process through direct contact with the sulfide surface. The effects of biological organisms, however, are more pronounced in later stages and only the chemical initiation reactions are described here. The first reaction of the pathway is shown by:



The reaction products sulfur and hydrogen peroxide are unstable and rapidly oxidize or decompose. Ferrous iron oxidizes more slowly (Nordstrom, 1982) :



At pH values above 4.0 to 4.5, the rate limiting step of reaction 1 is the electrochemical reduction of oxygen to produce hydrogen peroxide:



The stability field relationships for the aqueous ferric - ferrous system indicates that reaction 1C proceeds as indicated as long as pH stays above 4.8 (Figure 4) (Hem and Cropper, 1962). As the initiation cycle progresses, the generation of acidity in reactions

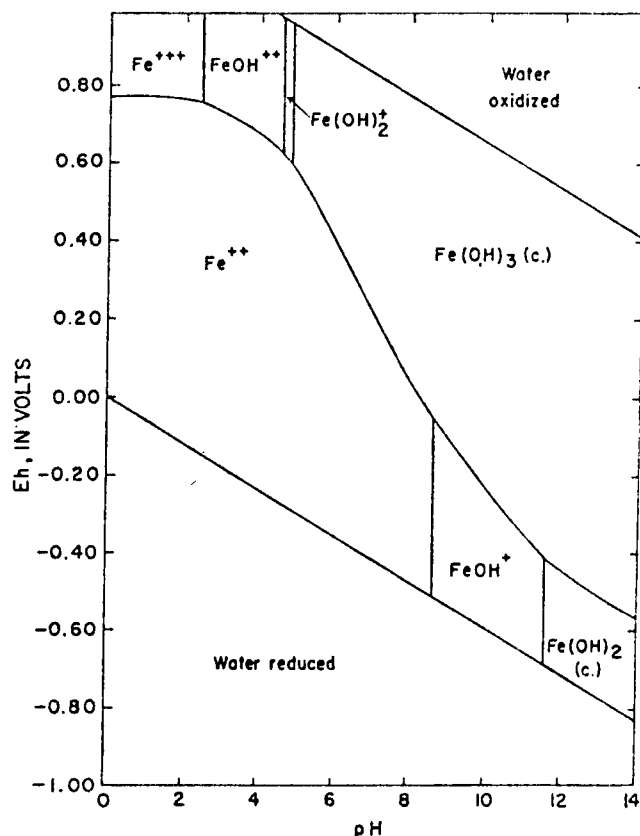
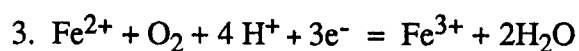


Figure 4. Stability Field Relationships for the Aqueous Fe^{2+} - Fe^{3+} System
(From Hem and Cropper, 1962)

1A and 1C begins to lower pH in the solution surrounding the sulfide source. Consequently, the solubility of ferric iron hydroxides increases and ferric hydroxide no longer is the stable end product of reaction 1C. As the pH approaches 3.0 the reaction pathway enters the intermediate phase where ferrous iron oxidizes to ferric iron:



The oxidation rate of ferrous iron by oxygen is a function of pH at values greater than 4.5 with a second order dependence on OH⁻ activity as shown by the relationship:

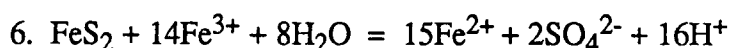
$$4. \frac{-d[\text{Fe}^{2+}]}{dt} = k [\text{Fe}^{2+}] [\text{O}_2] [\text{OH}^-]^2$$

where $k_{\text{STP}} = 8.0 \times 10^{13} \text{ L}^2 \text{ mole}^{-2} \text{ atm}^{-1} \text{ min}^{-1}$ (Singer and Stumm, 1970). The half time for reaction 3 at pH = 4.5 is 300 days (Kleinmann et al, 1981). At pH values of 3.5 or less, the reaction rate is independent of pH and is expressed by:

$$5. \frac{-d[\text{Fe}^{2+}]}{dt} = k [\text{Fe}^{2+}] [\text{O}_2]$$

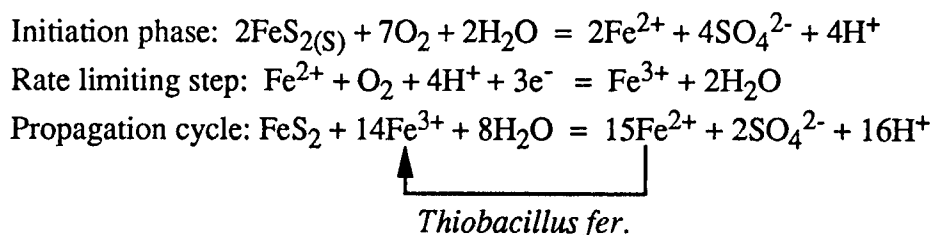
The rate constant (k_{STP}) in this case is $1.0 \times 10^{-7} \text{ atm}^{-1} \text{ min}^{-1}$ with a half time of approximately 1000 days (Singer and Stumm, 1970).

Once pH levels have decreased to around 3.0, the third phase is initiated whereby ferric iron becomes the primary oxidizing agent of unaltered sulfide minerals:



This reaction step proceeds to completion very rapidly, k_{STP} ranges from 0.389 to 17.4 day⁻¹, and is controlled by the supply of sulfides or ferric iron (Nordstrom, 1982). In most natural environments a ready supply of sulfide minerals is available; therefore, the ferric iron generated in reaction 3 becomes the limiting factor. The intermediate phase (reaction 3) is the rate limiting step of the sulfide oxidation pathway due to the large discrepancy in the rates of reactions 3 and 6 under acidic conditions. Under normal circumstances, the third phase would rapidly deplete any available ferric iron generated by the rate limiting step. The production of acidity would decrease to insignificant levels very quickly given that typical ferric iron concentrations in acid mine waters are 100 mg/L or less (Barnes and Romberger, 1968). However, at this stage the role of microorganisms becomes a major factor. Microbial catalysis by acidophilic bacteria in reaction 3 disrupts any equilibria approach in natural, aerobic settings. *Thiobacillus ferroxidans*, *Thiobacillus thiooxidans* and *Metallogenium* species catalyze the oxidation of ferrous iron although the latter two are essentially insignificant when in the presence of the first. *Thiobacillus* becomes active at pH values around 3.0, can tolerate acidic waters to a pH of

0.8 and increases the rate of reaction 3, the pathway limiting step, by a factor of 106 (Kleinmann et al, 1981 ; Singer and Stumm, 1970). Reaction 6 in the presence of these bacteria, becomes a self-propagating cycle since ferric iron is continuously generated in large quantities. A summary of the sulfide oxidation pathway is as follows:



Secondary oxidation products resulting from the weathering of sulfide minerals are principally hydrated iron sulfates or iron hydroxides. Mineral species may result either from the dehydration of soluble phases or through precipitation of insoluble products (reaction 1C). Acid mine waters containing iron in a fully oxidized state may become saturated with respect to $\text{Fe}(\text{OH})_3$ (ferrihydrite) or $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$ (jarosite). Depending on pH conditions, either of these minerals can precipitate directly from the aqueous state. Additional species form either during various dehydration stages of melanterite ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) or oxidation of these compounds as in the case of copiapite ($\text{Fe}^{2+}\text{Fe}_4^{3+}(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$) (Nordstrom, 1982). Table 3 summarizes the principal mineral phases that may be formed during the sulfide oxidation pathway.

Influence of Morphology

As expected, the oxidation rate of sulfides is also highly dependent on crystal morphology. Sulfides in coal seams and overburden may occur in one or more of five forms: massive, mossy-pitted, euhedral crystals, cleat coatings and framboidal (Caruccio, 1984). Framboidal sulfides are extremely fine-grained (less than 45 μm), spherical and consequently are the most reactive form. Of the iron-bearing sulfides, this crystallographic habit is almost exclusive of pyrite. Hematite has also been found to exhibit this form. Framboidal sulfides usually develop in sedimentary environments with depositional rates slow enough to permit crystallization and agglomeration of colloidal size microcrystals. Framboids have also been found in rocks ranging from volcanics to limestones (Rickard, 1970). Sulfide occurrences on TNFLH 1-1(14) include euhedral forms, sheet-like masses along foliation or bedding, and disseminated. The disseminated

Table 3. Principal Oxidation Products of Sulfide Weathering*

Phase	Chemical Formula	Aqueous Conditions	General Reaction
Ferrihydrite	$\text{Fe}(\text{OH})_3$	pH > 4.8	Hydrolysis of ferric iron, dissolution of copiapite, ppt. from saturated media, decomposition of jarosite
Jarosite	$\text{KFe}(\text{SO}_4)_2(\text{OH})_6$	low pH, high SO_4^{2-}	Ppt. from a saturated media
Goethite	$\text{FeO}\cdot\text{OH}$	--	Dehydration of jarosite
Hematite	Fe_2O_3	--	Dehydration of goethite, oxidation of Fe^{2+}
Melanterite	$\text{FeSO}_4\cdot 7\text{H}_2\text{O}$	high Fe^{2+} , SO_4^{2-}	Evaporation
Rozenite	$\text{FeSO}_4\cdot 4\text{H}_2\text{O}$	--	Dehydration of melanterite
Szomolnokite	$\text{FeSO}_4\cdot \text{H}_2\text{O}$	--	Dehydration of melanterite, rozenite
Copiapite	$\text{Fe}^{2+}\text{Fe}_4^{3+}(\text{SO}_4)_6(\text{OH})_2\cdot 20\text{H}_2\text{O}$	--	Oxidation and hydration of melanterite, rozenite or szomolnokite

*Sources: Nordstrom , 1982 ; Barnes and Romberger, 1968

form is most prevalent and exists in all three lithologic assemblages. The sheet-like form may be considered as analagous to cleat coatings in coal. Framboidal sulfides probably exist along with the finely-disseminated forms in the argillite and phyllite lithologies although reflected light microscopy was not used to examine hardrock samples from the project leg.

Field Studies

Studies of sulfide oxidation have universally concentrated on strictly controlled laboratory studies with short time frames. In well-oxygenated, natural settings, one study has determined that microbial catalysis of ferrous iron oxidation and subsequently, sulfide oxidation, proceeds at rates very near those generated under optimum laboratory conditions (Nordstrom, 1985). Rainfall events which flush the system temporarily slow the oxidation process through dilution of Fe^{2+} and microbe populations. After the flushing event, the rate quickly increases. The present study proposes to examine long-term trends in acid production both in lab and field settings.

CHAPTER IV

EXPERIMENTAL METHODS

Laboratory Leaching Columns

Purpose of Lab Columns

Laboratory leaching studies have often been used to predict acid production potential in field settings. Experimental apparatus have varied in design and specific purpose, but most tests react sulfide-bearing materials with an aqueous solution and study the effluent composition over time. Literature review indicates that few studies have proceeded beyond 16 to 20 weeks. As part of this study, laboratory leaching tests were constructed to examine sulfide oxidation over a longer time frame.

The purpose of the bench scale tests was to examine effluent quality and consequently, acid production over a minimum period of 45 weeks. Changes in pH, conductivity, sulfate, total iron, Mn, Cu, Zn and Al were monitored on a weekly basis. These parameters were measured in order to determine:

1. Long-term trends in leachate quality versus time under controlled conditions;
2. If valid comparisons to, or predictions of, effluent quality generated in natural or field settings may be made on the basis of laboratory data;
3. How present predictive measures utilized on TNFLH 1-1(14) compare to laboratory generated results.

In addition, mineralogical and sulfur phase distribution examinations were conducted to determine the distribution and fate of various species during long-term oxidation of sulfides.

Design of Columns

The leaching column design chosen for the experiments was a modified version of a design developed in a previous study (Hood and Oertel, 1984). The construction details are shown in Figure 5. The apparatus consists of a glass tube 41 inches (104 centimeters) long with an inside diameter of 1.5 inches (3.8 centimeters). A two-hole rubber stopper with a glass wool filter caps the base of the leaching tube. Two tubes inserted through the stopper function as an inlet and outlet for water. Perforated, 0.25 inch (6.4 millimeter) I.D. flexible tubing runs the entire length of the tube to provide

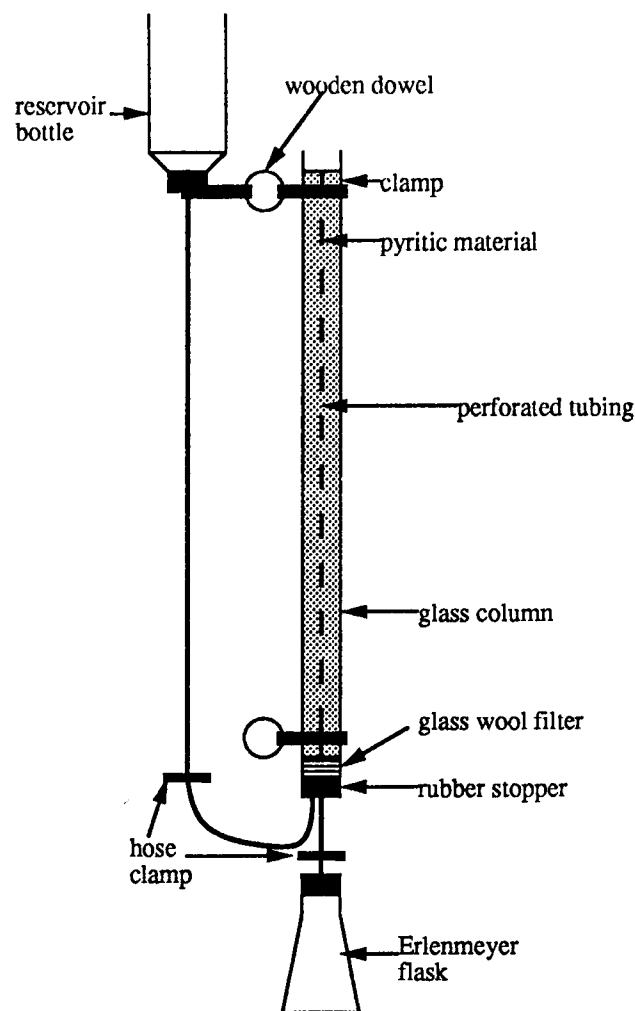


Figure 5. Laboratory Leaching Test Schematic

equal and complete saturation of the material while displacing most of the atmosphere inside the column out the top. A distilled water reservoir consisting of an inverted 1 liter polyethylene bottle is placed near the top of each column. This reservoir has the base cut out for recharging, is stoppered at the neck, and is graduated in approximately 100 mL increments.

Complete saturation of the sample with minimal air spaces can be attained almost instantaneously with this design. Although disaggregation of shale materials may reduce permeability to the point where water addition from the top of a column could be difficult, no permeation problems of this type were encountered. Flow of water into and out of the columns is regulated by thumbscrew hoseclamps.

Leachate collection was accomplished using 250 and 500 mL Erlenmeyer flasks. A

total of 7 columns was assembled and placed on a benchtop rack for stability. Material placed in the columns was crushed by hammer under a leather cover to less than or equal to 1 inch (2.5 centimeters). One kilogram of sample was placed in each column while keeping tension on the perforated tubing to insure that the tube was centered as much as possible and to avoid kinking. Sample material was packed lightly during assembly so that a full kilogram could be placed in each column.

The original experiment using this design determined that aeration times up to seven days between flushings do not affect leachate quality. Therefore, a leaching cycle based on a convenient time schedule was chosen. Columns were charged with deionized water (specific conductance less than 2.0 micromhos/cm³) until all material was covered. The inlet valves were sealed and the input volume recorded. Material was left saturated for 60 hours and then allowed to drain for 24 hours. Effluent was then collected, the volume measured and subsequently analyzed for the previously mentioned parameters. The aeration cycle encompassed five days.

Sampling Methods and Locations

Sample material for the laboratory leaching tests was obtained along four intervals on TNFLH 1-1(14) from which sulfidic rock was excavated for encapsulation. Four columns, one representing each section, were prepared from the samples. Sampling was performed using a weighted interval method based on the exposed percentage of the three lithologic assemblages exposed along each outcrop. An excess of rock was collected from each sampling point, crushed and equal portions by weight blended to form a composite totaling one kilogram. This method insured that the columns contained proportions of lithologies representative of their respective intervals. Three additional columns prepared in a 1986 study were monitored for a duration equal to those prepared for this experiment. These leaching tests had been exposed to a maximum of eight cycles during 1986 and subsequently left to oxidize until the initial recharge during September 1987. Table 4 presents a summary of the leaching columns, sources and approximate percentage of lithotypes in each. HK-1 and HK-2 material was obtained from pyritic outcrops east of TNFLH 1-1(14), and MGQ was obtained from a road base source quarry to the west of the segment. HK-2 was initially charged in 1986 with calcium carbonate saturated water to simulate chemical injection mitigation methods.

Table 4. Input Materials for Laboratory Leaching Tests

Column	Material Source	Percent Lithotype	NNP of Source
HK-1	Exposures along Hemlock Knob	Predominantly argillite	-50 tons CaCO_3 /1,000tons
HK-2	Exposures along Hemlock Knob	Predominantly argillite	-50 tons CaCO_3 /1,000tons
MGQ	Road base source quarry	Meta-sandstone	+50 tons CaCO_3 /1,000 tons
Comp A	959+30 - 969+30	40% meta-sandstone 60% argillite	-8 tons CaCO_3 /1,000 tons
Comp B	988+00 - 990+50	50% meta-sandstone 50% argillite	-35 tons CaCO_3 /1,000 tons
Comp C	996+50 - 998+50	25% meta-sandstone 75% argillite	-43 tons CaCO_3 /1,000 tons
Comp D	1048+00 - 1058+00	80% meta-sandstone 20% argillite	-18 tons CaCO_3 /1,000 tons

Field Leaching Studies

Purpose of Field Tests

Field leaching experiments were constructed to examine the effectiveness of present encapsulation techniques used on TNFLH 1-1(14). Additional objectives of these field studies included the utilization of the leach tests to attempt to develop a more cost effective method for sulfidic material encapsulation and to project chemical trends within present sites. Comparisons of tank leachates to actual encapsulation site effluents were examined to determine the effectiveness of each model in reducing toxicity in relation to untreated waters. Variations in effluent quality due to seasonal changes and rainfall inputs were also examined.

General Design

For the purpose of accurately assessing an encapsulation site, a model was created which simulated the internal roadfill design as closely as possible. Variations were then made in the amounts, chemical composition and position of the representative limestone aggregate layer and in the amount of topsoil cover. Each model was constructed using 30 gallon (100 liter) polyethylene drums and incorporated approximately 350 pounds (160 kilograms) of sulfidic material. This volume was large enough to allow a realistic simulation, yet be constructed within the constraints of time and cost. The dimensions of the drum corresponded to a vertical scale factor of approximately 10 as calculated from an average fill depth of 30 feet determined through measurements and borehole data. The dimensions of each drum were a height of 3.0 feet (0.9 meters) by 1.7 feet (0.5 meters) in diameter. The initial model, therefore, contained limestone aggregate in a basal configuration that was 0.2 foot (6 centimeters) thick between BIDIM-U14 filter fabric. Sulfidic material was placed in 0.2 foot (6 centimeters) thick lifts with agricultural lime application between each layer. Lime application rates used during fill construction were about 200 gm/ft² (6.7 kg/m²). Although this value was not strictly scaled down, lime application utilized in the tank design was roughly equivalent to 20 gm/layer or 9 gm/ft². This rate provided a sufficient cover of the pyritic material. A topsoil cover 0.6 foot (18 centimeters) in thickness capped the model. Drainage was provided by a PVC nozzle installed in the base of the tank. Lids, having a large opening in the center, were fastened on each model with wire. The edge of the lid opening protruded approximately 2 inches (5 centimeters) over the encapsulated model. This design insured that rainfall contacted as much material as possible without merely filtering down the inside wall of the drum (Figure 6). Test effluents were collected in 1.0 gallon polyethylene bottles. All leaching experiments were constructed near TNFLH 1-1(14) and immediately adjacent to a rain gauge in order to monitor the amount of rainfall that the models received.

Variations of the Model

Nine leaching models were constructed for this study. Seven variations of the encapsulation method were designed using similar source material. One tank was left empty to serve as a prototype and to collect rainwater. Another tank incorporated sulfidic material from a nearby source other than TNFLH 1-1(14). The models were designed as follows:

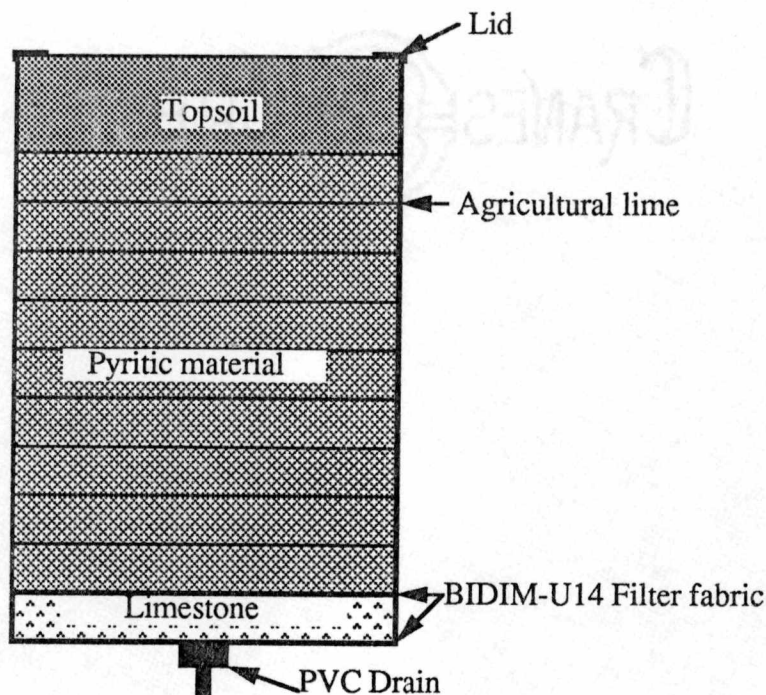


Figure 6. Field Leaching Test Schematic

- FT-0: Prototype and empty tank for the collection of rainwater.
- FT-1: Control model containing only sulfidic material.
- FT-2: Original model based on currently used encapsulation site design, with a full compliment of basal aggregate, agricultural lime and topsoil.
- FT-3: Model containing a full compliment of limestone aggregate and topsoil with the limestone aggregate buffer layer placed at the top of the model.
- FT-4: Model similar to FT-2, but featuring a 30% reduction in the amount of basal limestone aggregate.
- FT-5: Model similar to FT-2, but featuring a 60% reduction in the amount of basal limestone aggregate.

- FT-6: Model similar to FT-2, but featuring a 50% reduction in the amount of topsoil cover, full compliment of basal limestone aggregate.
- FT-7: Model featuring a buffer layer composed of approximately 500 gm (1.1 pounds) of NaCO_3 briquettes and a full compliment of topsoil cover.
- FT-8: Untreated material from a U.S. Forest Service access road containing coarsely crystalline sulfide minerals.

Sampling

Material for each model, except FT-8, was obtained from the same 250 foot (76 meter) roadcut from which laboratory composite B was formed (refer to Table 4). This section was chosen due to the fact that approximately equal percentages of the various lithologies were represented in the section. In addition, NNP values show that this section was one having a high potential for acid production on TNFLH 1-1(14). An estimated 4,000 cubic yards of rock from this cut were encapsulated during road construction. Water samples from the fill containing this material were used for baseline leachate quality comparisons. A weighted interval sampling technique was used to obtain samples with specific points being equal to those used to construct Comp B. Although no accurate assessment of particle size used in actual fill construction was available, sampled rock was crushed by hammer and the size fraction less than or equal to 4 inches (10 centimeters) was retained. Any material which showed signs of weathering was discarded. Retained sample was mixed at random, by hand, during construction of the models.

Field Samples

Purpose and Locations

Surface water samples were collected at several locations along TNFLH 1-1(14). These samples provided baseline water quality measurements for both the lab and field leaching experiments. They also illustrated typical acidic effluent values in true field settings and aided in the evaluation of present FHWA remedial action measures.

Table 5 gives the sampling locations, descriptions of the locations and sampling periodicity for each point examined during the study. Samples F-996+50-UD and HK-SR were the primary field sampling localities. F-996+50-UD represents effluents emitting directly from the encapsulation site chosen for correlation with the field models. This fill was selected due to the accessibility of an underdrain with discharge sufficient

Table 5. Locations and Descriptions of Field Sampling Points

Sample ID	Location	Description	Sampling Periodicity
F-996+50-UD	Encapsulation site at 996+50 on TNFLH 1-1(14)	Mouth of under-drain at base of fill	30 days
HK-SR	Near crest of Hemlock Knob approximately 2 miles east of TNFLH 1-1(14)	Surface drainage ditch along base of roadcut	30 days
A-OR, A-SR	959+30	Surface drainage ditch and outcrop runoff along base of roadcut	Once
C-OR	996+50	Runoff from outcrop face	Twice
D-SR	1052+00	Surface drainage ditch along base of roadcut	Twice

for sampling. In addition, approximately 50% of the pyritic volume encapsulated at this site originated from the interval in which material was obtained for construction of the field tanks. HK-SR, in addition to the other sampling points, provides an indication of water quality resulting from unimpeded sulfide oxidation in a fully aerated environment. A sampling periodicity of 30 days maximum was attempted for F-996+50-UD and HK-SR; however, due to extremely low rainfall amounts during portions of the study period, this criterion could not always be met.

Miscellaneous Studies

Cores

Four boreholes using a hollow-stem power auger and 2 inch split spoon sampler were drilled into encapsulation sites along TNFLH 1-1(14) and at one location east of the project. Boreholes 2, 3 and 4, shown in Figure 2 (refer to page 3), were placed into fills containing the same source materials used for the construction of lab columns Comp A, Comp B, Comp C and all field tanks except FT-8. BH-1 was drilled into a fill approximately 3 miles east of the project. This particular fill contained pyritic material

that was untreated prior to burial and was used as a baseline comparison for the remaining cores.

The purpose of the boreholes was to penetrate the full depth of the encapsulation site through the limestone underblanket. This was only accomplished in BH-3. Pertinent information gathered from the cores included the state of sulfide oxidation and material degradation in encapsulation sites and untreated fills; condition of the limestone buffer layer; and mineralogical assessment of both primary and secondary phases present in the encapsulated material. Borehole logs are presented in Appendix B.

Mineralogical Characterization

A mineralogical characterization using XRD and a binocular microscope was performed on rock samples obtained during leach test sampling and borehole drilling. X-ray diffraction analyses were conducted on composite packmount samples from each borehole in addition to composites from the Hemlock Knob location and each interval from which lab leach tests materials were obtained. Also, upon dismantling of the laboratory leaching columns, sufficient oxidation products were present in HK-1, HK-2 and Comp C to allow examination. The leached material from these column experiments was sampled by cone and quarter method, the sample placed in a polyethylene bottle, and agitated by ultrasound for a minimum of two hours. The liberated portion of the oxidation products was decanted and an elutriated mount was prepared for X-ray analysis.

The mineralogical examination of these samples allowed comparisons to be made between pre- and post-oxidation phases present in both treated and untreated fills, as well as in laboratory tests. The investigation of leaching material mineralogies permitted the identification of secondary phases resulting from oxidation which coat the rock material. These phases are of particular interest in that they serve to armor both pyritic material and, in fills, any limestone buffer blanket that is installed to neutralize acid drainage. The effects of coating can decrease the oxidation of pyrite through reduced O₂ contact, and can decrease the buffer capacity of limestone aggregate. If secondary phases are precipitated in sufficient quantity, they begin to fill interstitial voids within a roadfill. This void filling decreases the infiltration capacity of an encapsulation site and lowers O₂ content available for sulfide oxidation.

Sulfur Speciation Study

A sulfur speciation study was undertaken to determine several parameters in pre- and post-leached materials in the bench scale tests. This procedure allows the calculation of percent sulfur present as sulfide, sulfate and organic forms (Sobek, et al, 1978). All leached rock except that in MGQ and Comp B was examined. The percentage reductions in total sulfur in these columns during the course of the tests was also determined. The amount of sulfur present as these three forms was examined in unleached material from Comp C for comparative purposes.

Analytical Methods and Measured Parameters

Water samples collected for this study were analyzed for volume collected (with the exception of surface stream samples), pH, conductivity, sulfate, acidity, Al, total Fe, Mn, Cu, and Zn.

Standard procedures for field sampling were followed when collecting surface water and fill effluent samples. These samples were collected in 1 liter polyethylene bottles. All effluents were separated into two fractions. The first was left unfiltered for pH, conductivity and acidity measurements. The second fraction was vacuum filtered through a 0.45 micron membrane filter as soon as possible after collection in order to remove all particulates. This fraction was acidified to a pH of less than 2.0 with ultrapure HNO_3 and refrigerated at 4°C for future analysis of dissolved metals.

Volume measurements conducted on field tank effluents and laboratory leachates were done using a graduated polyethylene cylinder. The cylinder was rinsed with deionized water followed by a rinse with dilute HCl and several rinses with deionized water between readings to avoid cross contamination of samples.

Measurements of pH were made using a Beckman Electromate Model 100001 pH meter with an Orion combination electrode. A Hach conductivity meter was used for specific conductance measurements.

Sulfate was determined using a barium sulfate turbidity technique in conjunction with a Hach DR/2 benchtop spectrophotometer (APHA, 1985). This procedure involved the separation of 50 mL of filtered effluent into two 25 mL fractions which were placed into cuvetts. One portion was used as a blank and left untreated. Barium chloride indicator was added to the second cuvet and allowed to react for 5 minutes. After the reaction phase, the blank absorbance was measured on the instrument and calibrated to represent zero. The use of the blank compensated for any absorbance due to coloration of the

effluents. The treated cuvet absorbance was then measured and the sulfate concentration determined from a calibrated scale.

Acidity measurements were made using titrimetric methods (APHA, 1985). A 50 mL aliquot of unfiltered water was used for analysis. The sample was acidified to a pH of less than 4.0 with 0.02 N H_2SO_4 , if the original pH reading was above this value. Samples having pH values less than 4.0 were not acidified. Two to three drops of 30% H_2O_2 were added to each sample and heated to digest organics. Samples were cooled and titrated using 0.1N NaOH and Fisher Scientific automated instrumentation to an inflection endpoint pH of 8.3. Acidity is represented as mg/L CaCO_3 through unit recalculations. Positive acidity values indicate acidic water, whereas a negative acidity indicates excess alkalinity.

Aluminum was measured using two methods. The procedure used for most samples was an absorptiometric technique utilizing pyrocatechol violet as an indicator (Dougan and Wilson, 1974). This wet chemical technique provides rapid turnaround analysis of samples with Al concentrations as low as 42 ug/L. The method has some limitations due to chemical interference by high Fe concentrations. Effluents from FT-1, FT-8, C-OR and some samples at HK-SR exhibited Fe interference too high for effective analysis. Aluminum in these effluents was measured using flameless atomic absorption (AA) via carbon rod analyzer (CRA). CRA avoids many of the chemical interference problems associated with flame AA or colorimetric methods (Culver, 1975). However, the considerable time, cost and rigorous analytical program design requirements precluded the use of a CRA for aluminum analysis in all effluents.

The remaining dissolved metals were determined by flame AA using a Varian 475 double beam spectrophotometer. Analytical program guidelines were established for each specific metal to reduce interferences resulting from chemical or physical interactions between species or the flame and analyte (APHA, 1985 ; Varian, 1979).

An analytical quality assurance (QA) program was followed for each respective parameter measured in the effluents. The program insured that results were as accurate and precise as possible and reduced the chances of contamination. All labware and sample bottles used during the study were cleaned using a standard multi-step washing procedure involving a detergent wash, potable water rinse, deionized water rinse, 10% HCl rinse and several final washes with deionized or distilled-deionized water. Clean sample bottles, prior to use for collection or storage of effluents, were rinsed with sample as a final precaution.

Conductivity and pH equipment was calibrated using standard solutions prior to a battery of analyses. Probes were rinsed with deionized water and wiped dry between readings. Conductivity and pH readings were taken in the field when possible. If samples were frozen or weather conditions unfavorable, these parameters were measured after return to the laboratory.

Sulfate standards were analyzed for QA purposes during each analytical run for that parameter. The dissolved metals analysis incorporated both single and multi-element standards to construct calibration curves and check the accuracy of the calibration equations on a daily basis. During AA runs, two standards were run to every 10 samples to maintain a constant check on accuracy. To examine laboratory QA as a whole, a set of certified, multi-element, commercial water standards were purchased through Environmental Resource Associates of Arvada, Colorado and analyzed. This process allowed inter-laboratory comparisons to be made and served as a final accuracy and precision check for all analytical procedures. A summary of the QA program and precision and accuracy of the methods is provided in Appendix A.

CHAPTER V

RESULTS OF METHODS

Lab Columns

Data Trends in Effluents

The bench scale leaching tests were conducted for 45 cycles. All columns were initially charged on 9-4-87. Testing ended on 7-14-88. Comparisons of the measured parameters over time indicate that leachates from all columns attained a constant chemical quality very rapidly. Effluents generally had high initial values of chemical parameters which decreased until stabilization occurred. The initial stabilization period for most tests was one to five cycles. All columns had reached a restricted range of values after 10 cycles. All of the parameters measured for this study, with the exception of Al, followed this trend. Aluminum values exhibited a reverse trend with concentrations increasing until stabilization further into the experimental program. The parameters showing the least fluctuation over time were pH, conductivity and sulfate (Figures 7 - 12). The consistent drop in conductivity levels seen in HK-1 from cycle 40 to cycle 43 is not representative of the general trend. A plausible explanation for the decrease cannot be determined from experimental records. Acidity values demonstrated moderate variance (Figures 13 and 14). A significant spike in acidity levels was observed at cycle 41 for HK-1. The increase is not consistent with the decrease of conductivity values over the same period and may be attributable to an error in the analysis. Aluminum, iron and zinc concentrations, when above detection levels, had the greatest variance from cycle to cycle (Figures 15 - 18). Aluminum levels in MGQ effluents were consistently below detection and are not included in the data plots. The sharp increase in Zn concentrations for HK-1 at cycle 33 may be attributable to analytical error. Copper concentrations were below detection in all leachates. Manganese values were present above detection levels over time only in Comp B and Comp C. Comp B began with concentrations at 3.7 mg/L which decreased to less than 1.0 mg/L by cycle 33. Comp C began at 4.8 mg/L and by cycle 41 had decreased to below detection levels.

The patterns over time seen with all species except Al are probably due to the rapid oxidation of abundant fine material generated by pulverization of the rock material. The great surface area results in rapid depletion of the sulfide source in the fines during the first few cycles. This depletion causes high initial concentrations of sulfate, acidity and

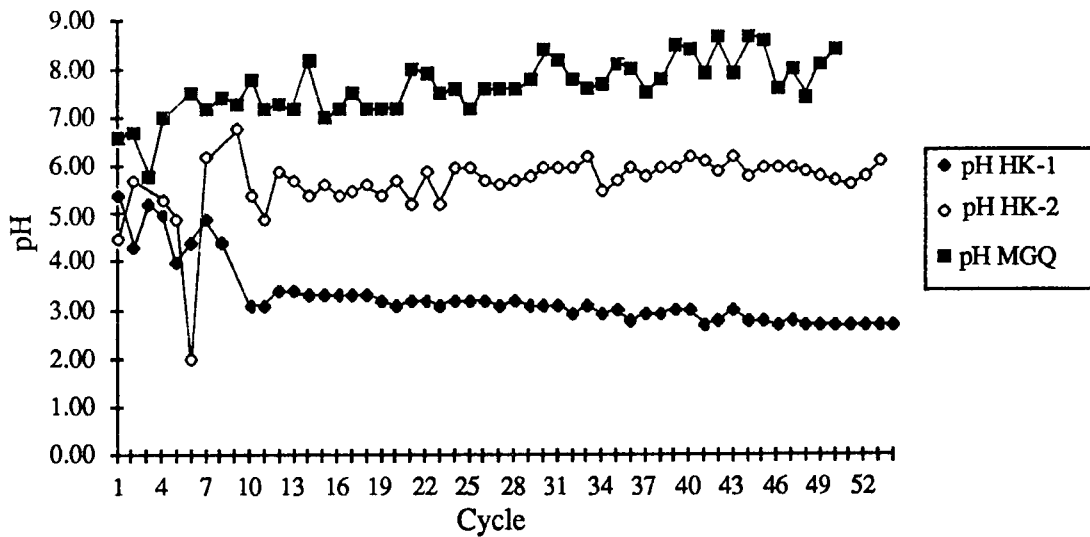


Figure 7. Plot of pH Versus Cycle for Columns HK-1, HK-2 and MGQ

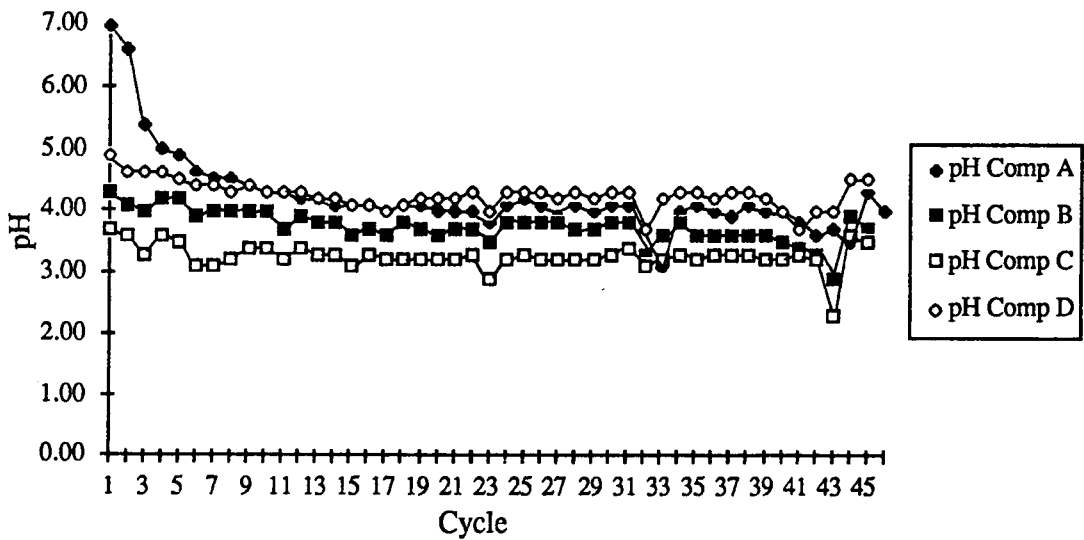


Figure 8. Plot of pH Versus Cycle for Columns Comp A, Comp B, Comp C and Comp D

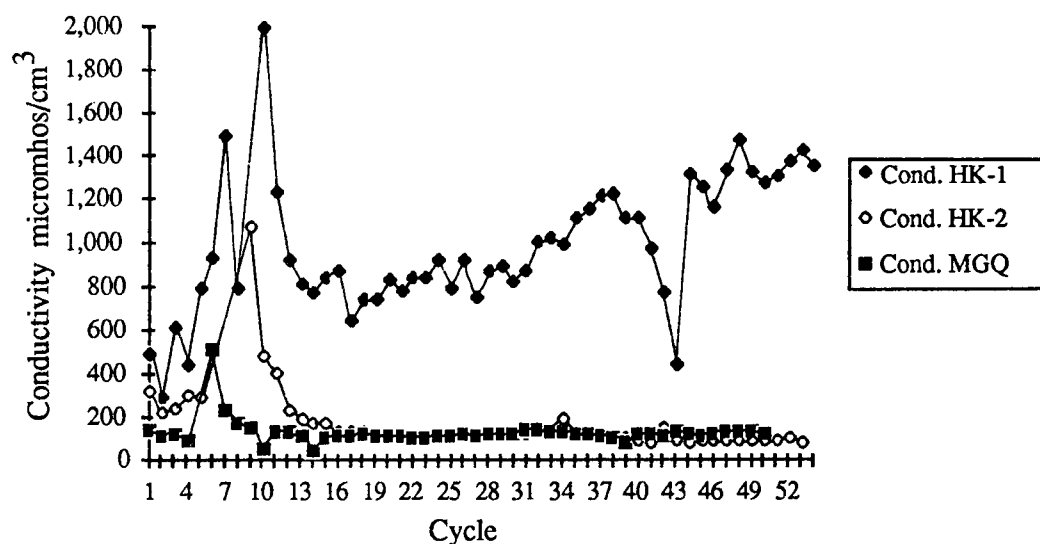


Figure 9. Plot of Conductivity Versus Cycle for Columns HK-1, HK-2 and MGQ

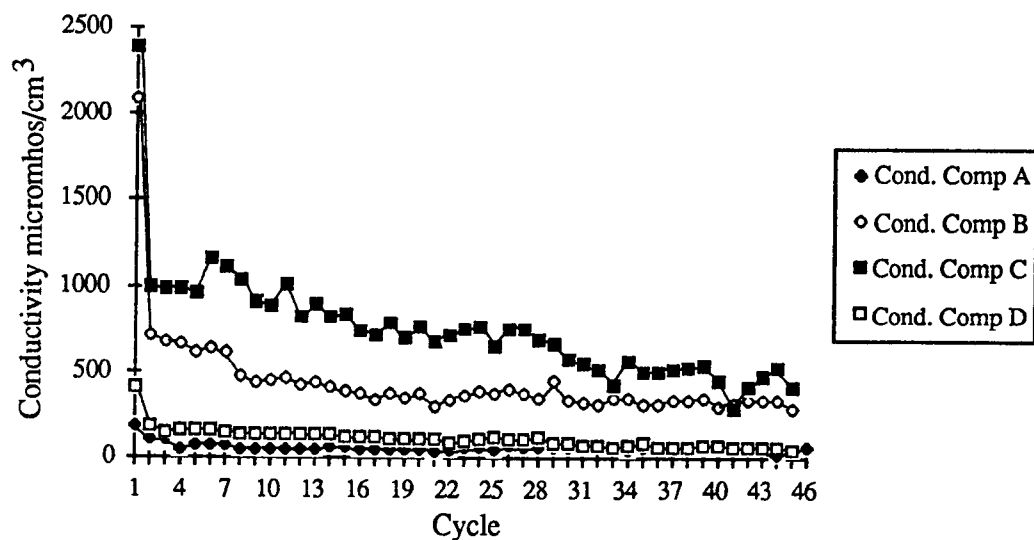


Figure 10. Plot of Conductivity Versus Cycle for Columns Comp A, Comp B, Comp C and Comp D

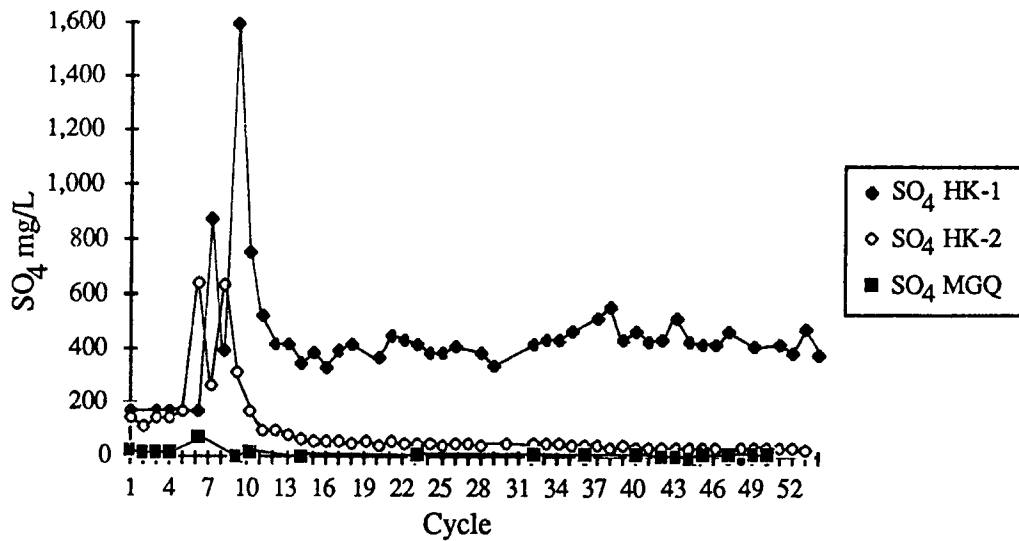


Figure 11. Plot of Sulfate Versus Cycle for Columns HK-1, HK-2 and MGQ

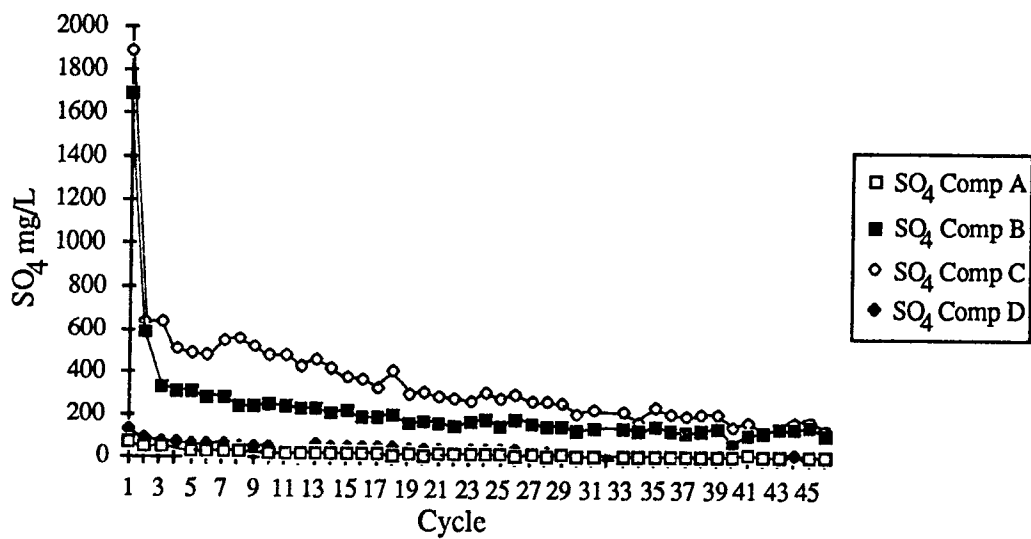


Figure 12. Plot of Sulfate Versus Cycle for Columns Comp A, Comp B, Comp C and Comp D

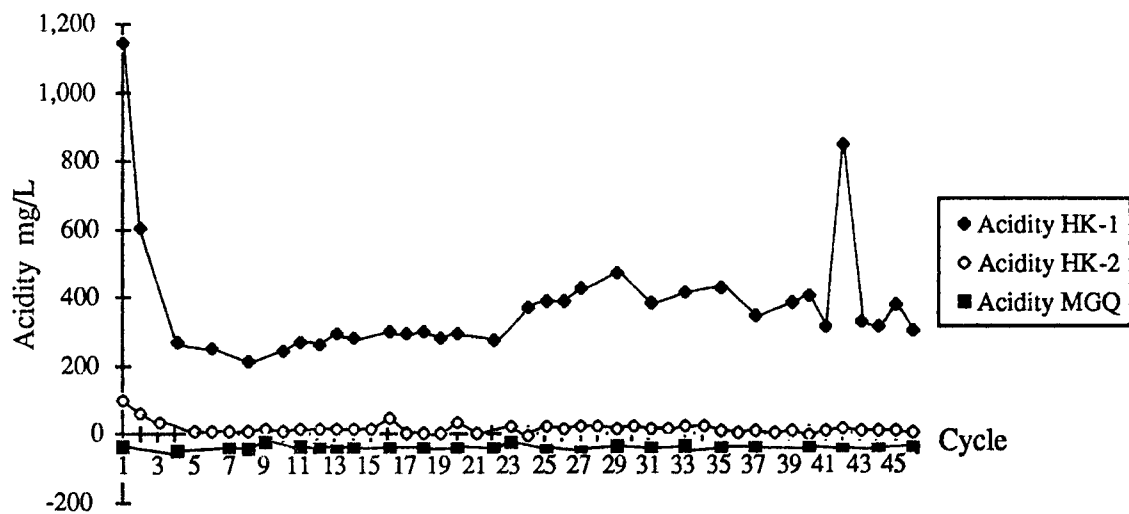


Figure 13. Plot of Acidity Versus Cycle for Columns HK-1, HK-2 and MGQ

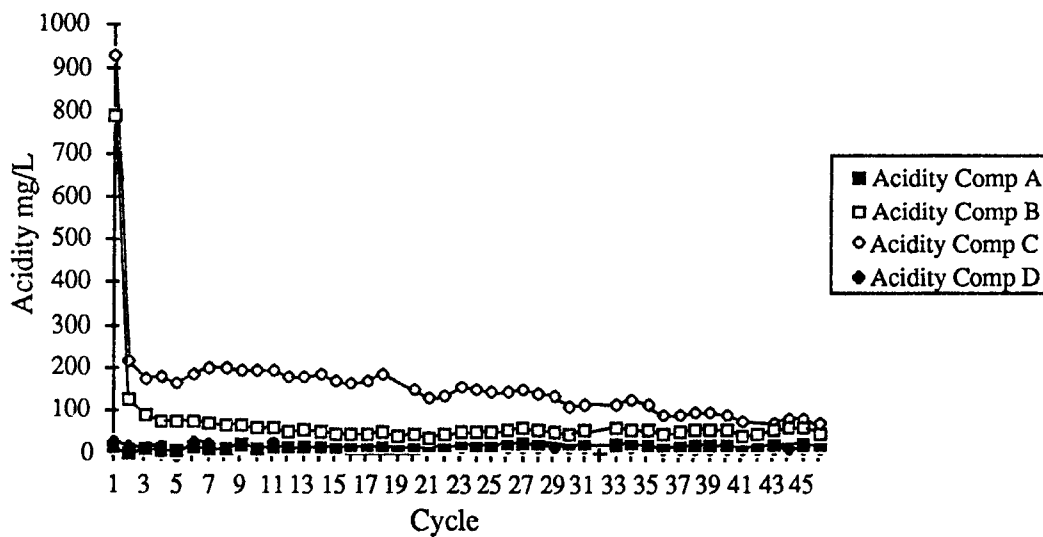


Figure 14. Plot of Acidity Versus Cycle for Columns Comp A, Comp B, Comp C and Comp D

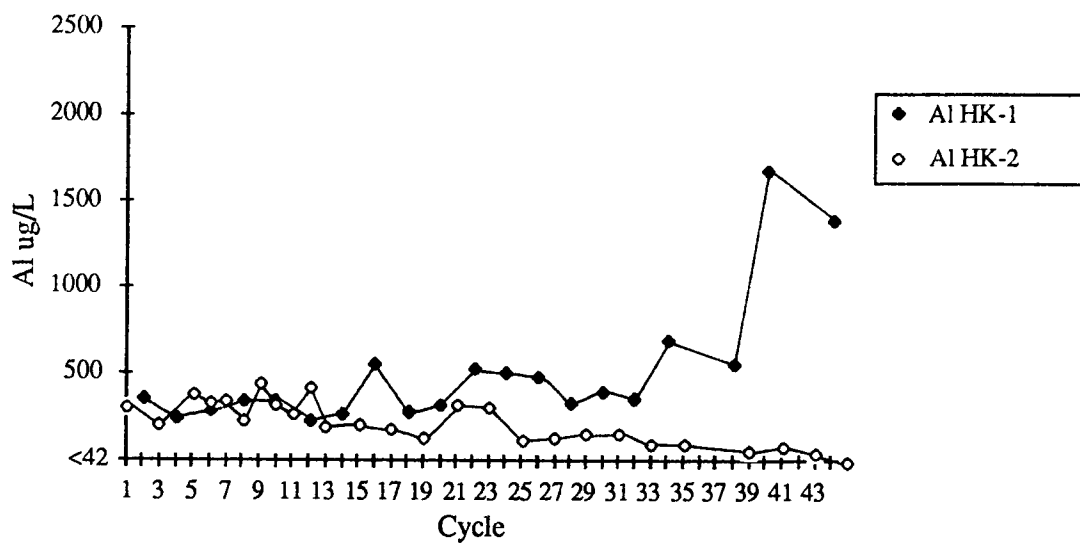
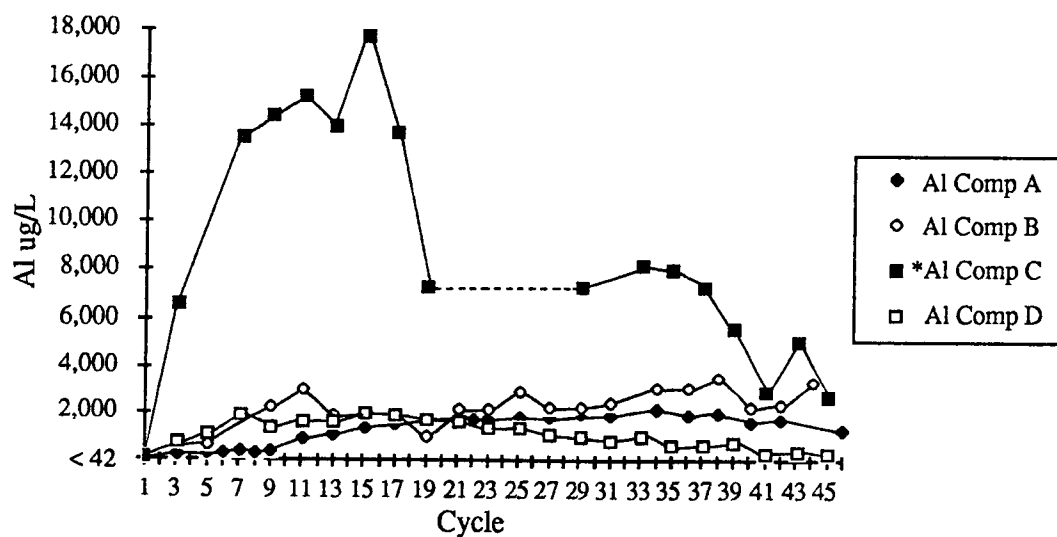


Figure 15. Plot of Aluminum Versus Cycle for Columns HK-1 and HK-2



* - - - = Gap in analytical sequence due to insufficient volume for analysis

Figure 16. Plot of Aluminum Versus Cycle for Columns Comp A, Comp B, Comp C and Comp D

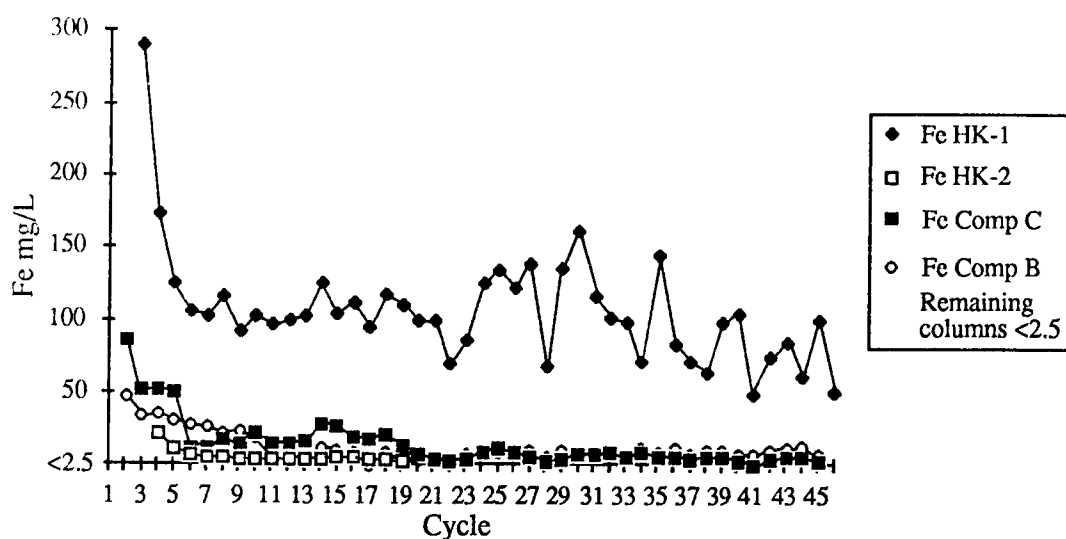


Figure 17. Plot of Iron Versus Cycle for Columns HK-1, HK-2, Comp C and Comp B

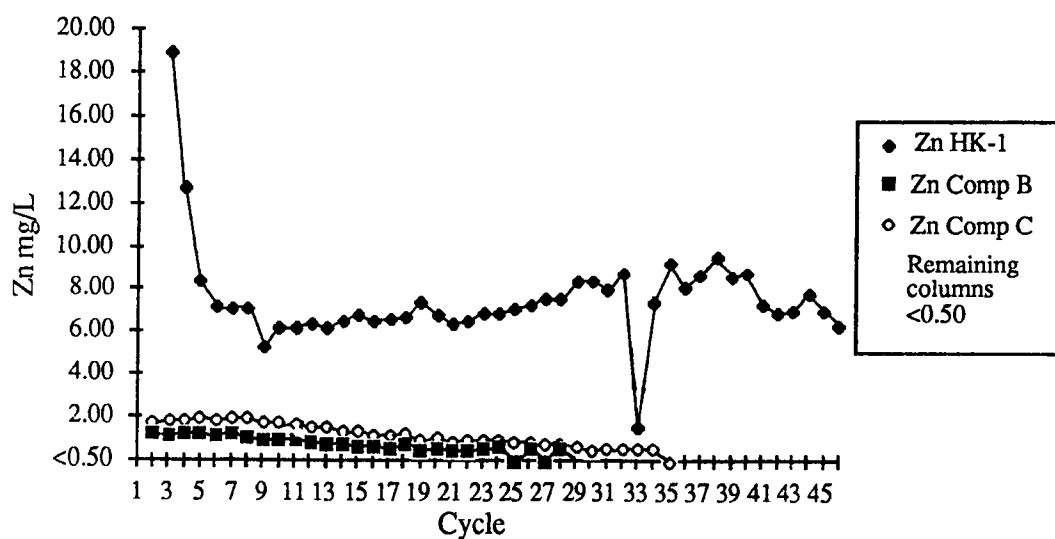


Figure 18. Plot of Zinc Versus Cycle for Columns HK-1, Comp B and Comp C

dissolved metals which decrease in proportion to decreasing amounts of unoxidized silt-to fine-sand sized sulfidic material. The initial oxidation also drives the pH of interstitial water down rapidly during the first few cycles. Aluminum concentrations would not be expected to be high initially. The increase in Al solubility occurs in response to the decrease in pH. Therefore, two to three cycles are required in order for substantial Al to be generated from aluminosilicate minerals which are the primary source.

Sulfur Speciation and Depletion

Following the leaching experiments, sulfur phase distribution was determined for the leached materials from all columns except Comp B and MGQ. MGQ was not analyzed since leaching studies indicated the initial absence of sulfides. Comp B remained on line for continued monitoring at the close of this study and subsequently was not examined. For baseline comparisons, sulfur phase distributions in unleached materials comprising Comp C were calculated. The method used for these experiments allows the calculation of sulfur present as pyritic (sulfide), sulfate and organically-bound phases (Sobek, et al., 1978). A series of acid leaching steps using HCl and HNO₃, with sulfur analysis via a LECO furnace between leachings, was used to determine the distribution. Table 6 summarizes the results of this experiment. The analysis of unleached materials shows that approximately 50% of the total sulfur present is in the form of sulfides. A suprisingly high percentage was bound with organics; however, the value is not unreasonable given that these rocks were 75% argillite and probably had a high initial organic content. Sandstone dominated materials would probably show less of this phase. Substantial reductions in the amount of sulfide sulfur were observed in the leached materials. Columns HK-1 and HK-2 show that nearly all of this phase had oxidized after about two years of oxidation alternating with leaching. The total sulfur content was still quite high and almost all of that which remained was bound with organic materials. Since Comp C materials show that the organic sulfur remains constant in pre- versus post-leaching rock, a valid assumption might be that the high values in HK-1 and HK-2 reflect relative increases, with respect to decreases in the other types, rather than true redistribution into this form. The oxidizing environment within the columns would be expected to preclude formation of significant organic sulfur. Leached materials from the remaining columns indicate that approximately one-half of the total initial sulfur content was leached from the columns over a period of 45 weeks. The significance of these findings in relation to acid production is discussed in chapter VI.

Table 6. Sulfur Phase Distribution in Laboratory Leaching Materials

Source	Total Sulfur	HCl Extraction	HNO ₃ Extraction	Percentage as Sulfide Phases	Percentage as Sulfate Phases	Percentage as Organic Phases	Total Sulfur Reduction
Comp C Unleached	0.606%	0.517%	0.215%	49.8%	14.7%	35.5%	--
Comp C Leached	0.338%	0.177%	0.133%	13.0%	47.7%	39.3%	55.8%
HK-1 Leached	1.50%	1.43%	1.47%	0.0%	4.7%	95.3%	--
HK-2 Leached	1.39%	1.33%	1.25%	4.3%	5.8%	89.9%	--
Comp A Unleached	0.064%	--	--	--	--	--	--
Comp A Leached	0.037%	0.022%	0.011%	29.7%	40.6%	29.7%	57.8%
Comp D Unleached	0.050%	--	--	--	--	--	--
Comp D Leached	0.025%	0.009%	0.005%	16.0%	64.0%	20.0%	50.0%

-- = Not Determined

Mineralogical Changes

Pre-leaching and post-leaching mineralogical characterizations were performed on the Hemlock Knob and Comp C materials. Columns MGQ, Comp A, and Comp D were not analyzed due to the lack of sufficient oxidation products to provide enough sample for elutriated X-ray mounts. Comp B was not analyzed since leaching experiments with this column continued at the close of the study.

HK-1 and HK-2 both contained alteration products sufficient to cement the material together and coat the walls of the leaching tube. Comp C, while not cemented, exhibited widespread particle coatings and material degradation.

The mineral identification was performed using X-ray diffraction and binocular microscope examinations. The variety of phases present in the sample materials resulted in complex X-ray patterns which proved difficult to interpret. Mineral identification was based on five or more d-spacings which matched exactly or within reasonable error tolerances. If between three and five d-spacings were matched, and presence of the potential phase feasible, the identification was assumed to be tentative. Several unidentified lines remained in each pattern after the characterization. All samples were analyzed using Cu K alpha radiation on a Norelco diffractometer. A one degree per minute rotation was used to generate the patterns. Table 7 shows the results of the characterization for unleached and leached materials from Hemlock Knob and Table 8 gives the comparisons for Comp C materials. The post-leaching secondary phases identified are those that generally are expected to form during oxidation of sulfide and feldspar minerals. One unexpected phase prevalent in the leached material was yavapaiite. The abundance of potassium phases such as jarosite and yavapaiite indicates the presence of a significant source for this cation within the rocks used in the leaching systems. A possible potassium source is the dissolution of feldspar minerals and muscovite. Discussion of column geochemistry in detail is presented in chapter VI.

Field Tanks

Data Trends in Effluents

All variations of the encapsulation models, with the exception of FT-0, FT-7 and FT-8, were placed into service within a 60 day period beginning 9-10-87 and ending 11-7-87. FT-0 began service on 8-27-87, FT-1 on 12-23-87 and FT-8 on 1-14-88. All data plots presented in this section represent the same amount of real time within the range outlined above. However, the number of collections varied for each of the models due to

Table 7. Mineralogical Characterization for Hemlock Knob Materials

HK-Unleached	HK-1 Leached	HK-2 Leached	Formula
Identified:	Identified:	Identified:	
Quartz	Quartz	Quartz	SiO_2
Muscovite	Muscovite	Muscovite	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
Albite	--	--	$\text{NaAlSi}_3\text{O}_8$
Marcasite	--	--	FeS_2
--	Kaolinite	Kaolinite	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$
--	Yavapaiite	--	$\text{KFe}(\text{SO}_4)_2$
--	Jarosite	--	$\text{KFe}(\text{SO}_4)_2(\text{OH})_6$
--	--	Copiapite	$\text{Fe}^{2+}\text{Fe}^{3+}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$
Tentative:	Tentative:	Tentative:	
--	Copiapite	--	$\text{Fe}^{2+}\text{Fe}^{3+}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$
--	Melanterite	Melanterite	$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$
--	Ferrihydrite	Ferrihydrite	$\text{Fe}(\text{OH})_3$
--	Illite	Illite	$(\text{H}_3\text{O},\text{K})_y(\text{Al}_4\cdot\text{Fe}_4\cdot\text{Mg}_4\cdot\text{Mg}_6)-$ $(\text{Si}_{8-y}\cdot\text{Al}_y)\text{O}_{22}(\text{OH})_4$
--	--	Jarosite	$\text{KFe}(\text{SO}_4)_2(\text{OH})_6$

slightly different responses to rainfall inputs, overturned or burst collection vessels and one incidence of vandalism. Over time, pH in all variations featuring treatment amendments, with the exception of FT-7 (Na_2CO_3 buffer), tends to approach a common range of 6.8 to 8.0 (Figures 19 and 20). Values of pH in FT-3, containing the limestone aggregate layer at the top of the sulfidic rock volume, were slightly lower and demonstrated more variability. FT-1 and FT-8, both containing untreated material, show a steady decline in pH until stabilization at values from 2.8 to 3.4 and 2.0 to 2.4 respectively.

FT-7 produced highly alkaline effluents unsuitable for most analyses although the amount of buffer material was relatively small (500 gm). Typical pH and conductivity values for this model are 10.0 to 11.0 and 207,000 micromhos respectively. Substantial improvement in conductivity was seen in the most recent samples. No other parameters were measured for this model.

Conductivity, sulfate and acidity show trends similar to that of pH. These parameters demonstrate significant variability in the first few samples collected. Stabilization at a

Table 8. Mineralogical Characterization for Comp C Materials

Comp C Unleached	Comp C Leached	Formula
Identified:	Identified:	
Quartz	--	SiO_2
Clinochlore	Clinochlore	$(\text{Mg}, \text{Fe}^{2+}, \text{Al})_3(\text{Si}, \text{Al})_2\text{O}_5(\text{OH})_4$
Illite	Illite	$(\text{H}_3\text{O}, \text{K})_y(\text{Al}_4 \cdot \text{Fe}_4 \cdot \text{Mg}_4 \cdot \text{Mg}_6) \cdot (\text{Si}_{8-y} \cdot \text{Al}_y)\text{O}_{22}(\text{OH})_4$
Muscovite	--	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$
Augite	--	$(\text{Ca}, \text{Na})(\text{Mg}, \text{Fe}^{2+}, \text{Al})(\text{Si}, \text{Al})_2\text{O}_6$
Albite	--	$\text{NaAlSi}_3\text{O}_8$
--	Yavapaiite	$\text{KFe}(\text{SO}_4)_2$
--	Copiapite	$\text{Fe}^{2+}\text{Fe}^{3+}_4(\text{SO}_4)_6(\text{OH})_2 \cdot 20\text{H}_2\text{O}$
--	Alunite	$\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$
Tentative:	Tentative:	
Pyrite	--	FeS_2
Smythite	--	$(\text{Fe}, \text{Ni})_9\text{S}_{11}$
--	Jarosite	$\text{KFe}(\text{SO}_4)_2(\text{OH})_6$
--	Diaspore	AlOOH
--	Boehmite	AlOOH

restricted range of values occurred after the first few rainfall flushing events. In general, FT-2, the original model, had somewhat lower conductance and sulfate values than the remainder of the tanks. FT-3, having the limestone layer at the top of the pyritic volume, did not exhibit a substantial recovery period with respect to conductance, sulfate and acidity values. FT-2 and FT-6 (50% topsoil reduction) seem to show the most resistance to fluctuations in species concentrations while FT-3, FT-4 (30% aggregate reduction) and FT-5 (60% aggregate reduction) values showed more variability. Figures 21-26 show the patterns of effluent quality, with respect to these variables in the lime-treated models. Rainwater samples collected from FT-0 had conductivity levels between 25 and 100 micromhos, sulfate values below 1 mg/L (except for two samples), and acidity values indicating neutral to only slightly acidic water. FT-1 is not included in the figures, but parameter ranges are 1,400-13,000 micromhos for conductance, 1,100-9,750 mg/L for sulfate and 132-7,487 mg/L for acidity.

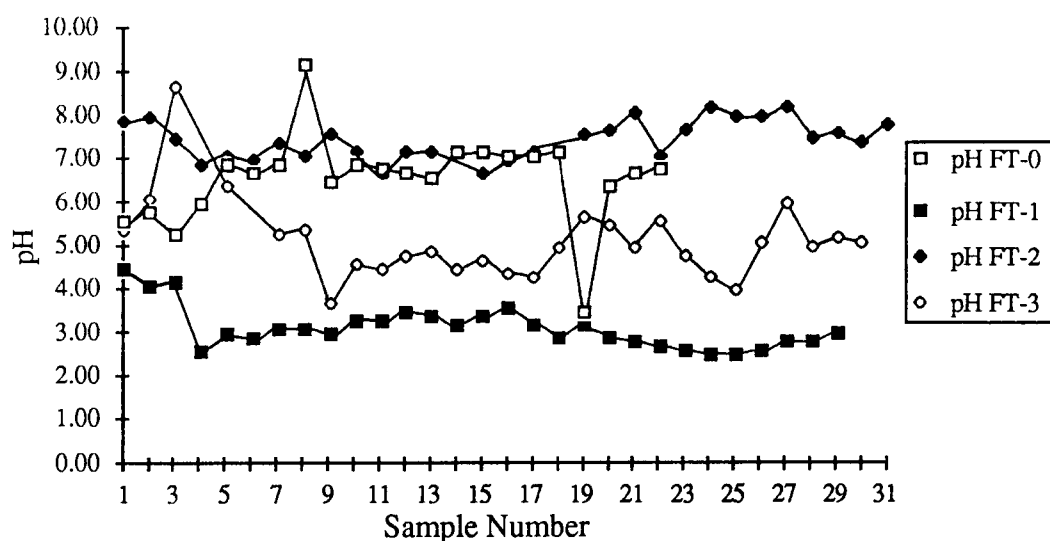


Figure 19. Plot of pH Versus Sample Number for FT-0, FT-1, FT-2 and FT-3

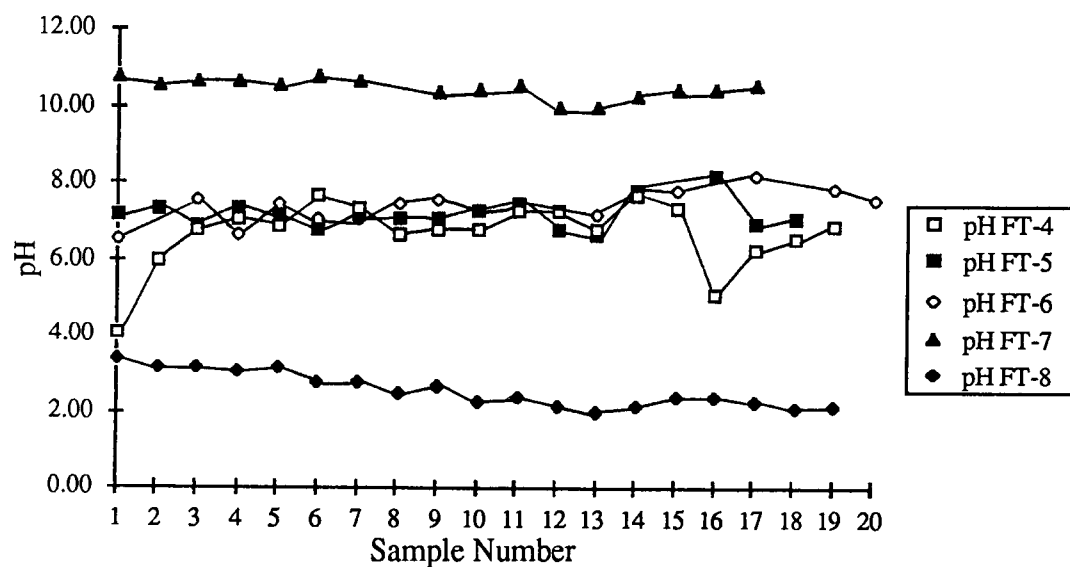


Figure 20. Plot of pH Versus Sample Number for FT-4, FT-5, FT-6, FT-7 and FT-8

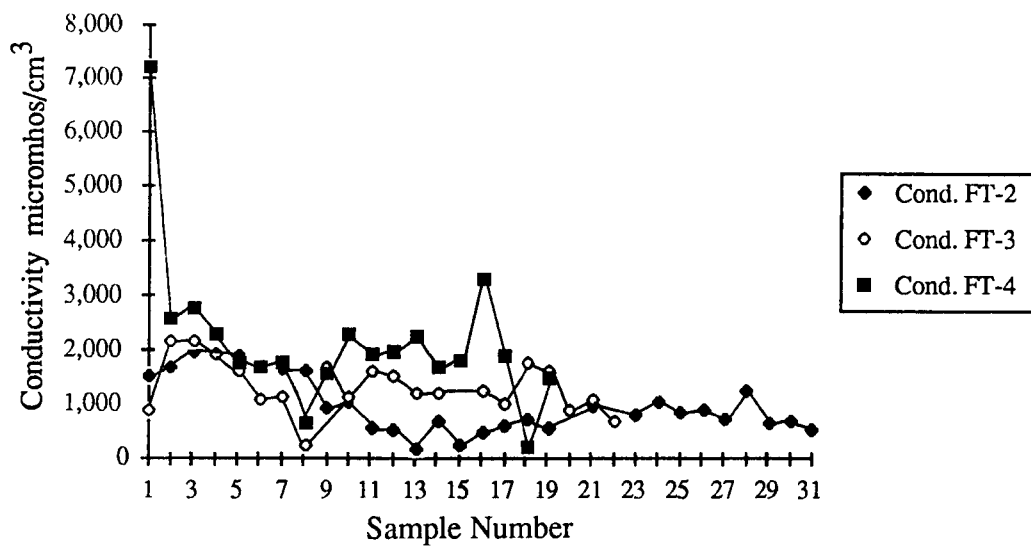


Figure 21. Plot of Conductivity Versus Sample Number for FT-2, FT-3 and FT-4

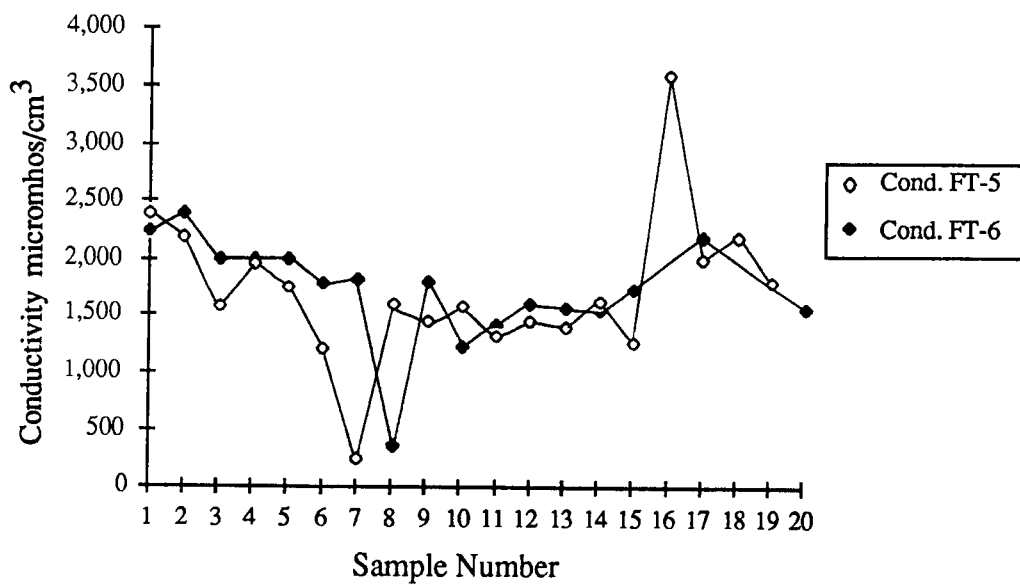


Figure 22. Plot of Conductivity Versus Sample Number for FT-5 and FT-6

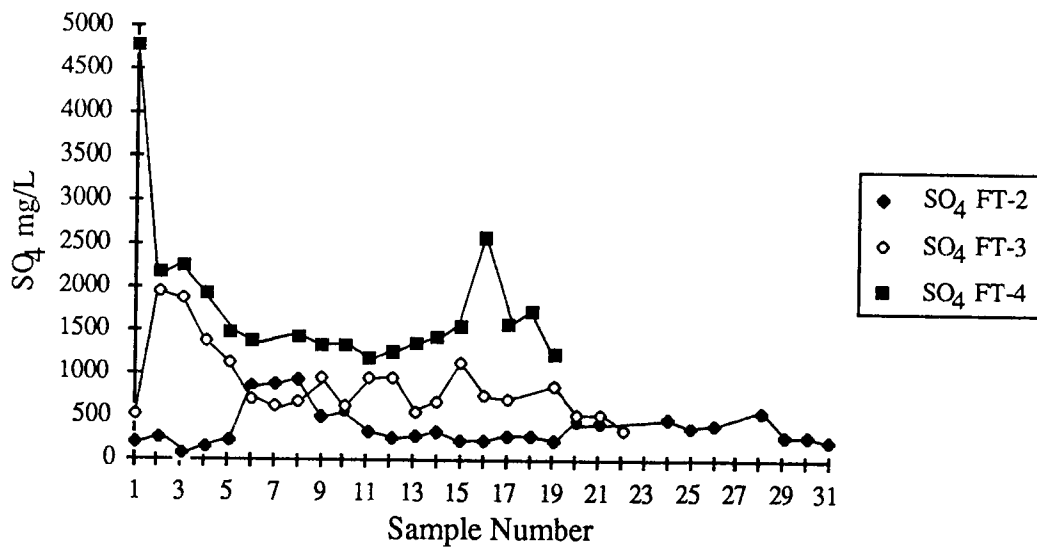


Figure 23. Plot of Sulfate Versus Sample Number for FT-2, FT-3 and FT-4

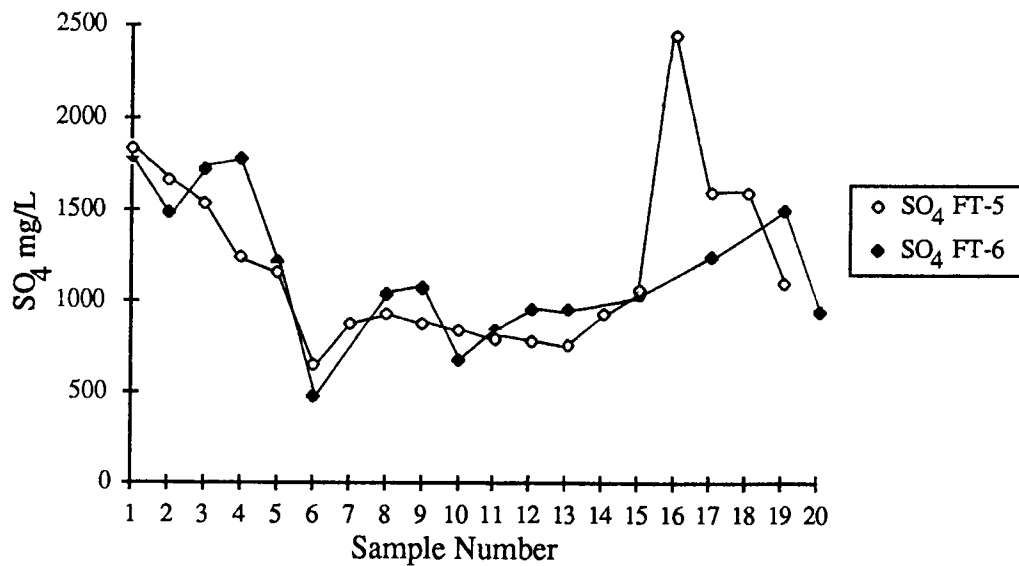


Figure 24. Plot of Sulfate Versus Sample Number for FT-5 and FT-6

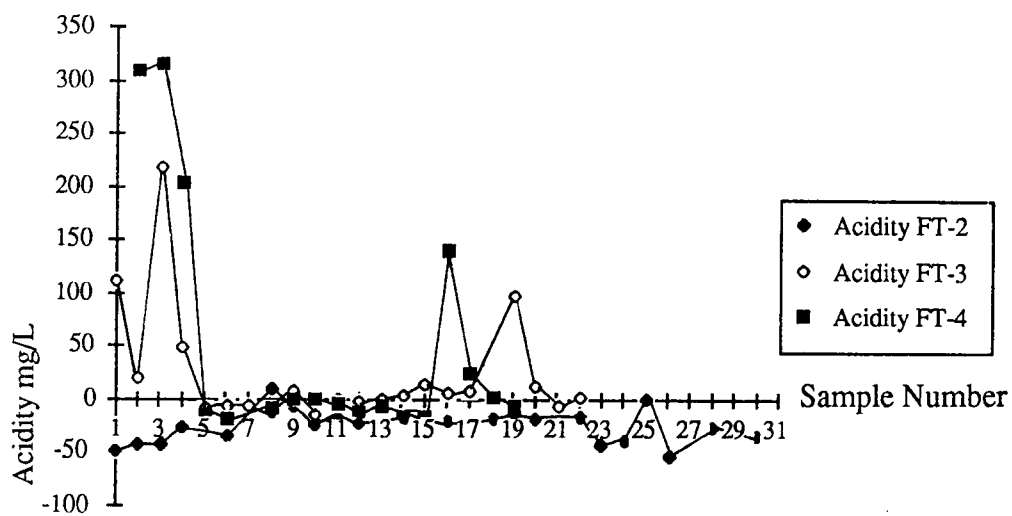


Figure 25. Plot of Acidity Versus Sample Number for FT-2, FT-3 and FT-4

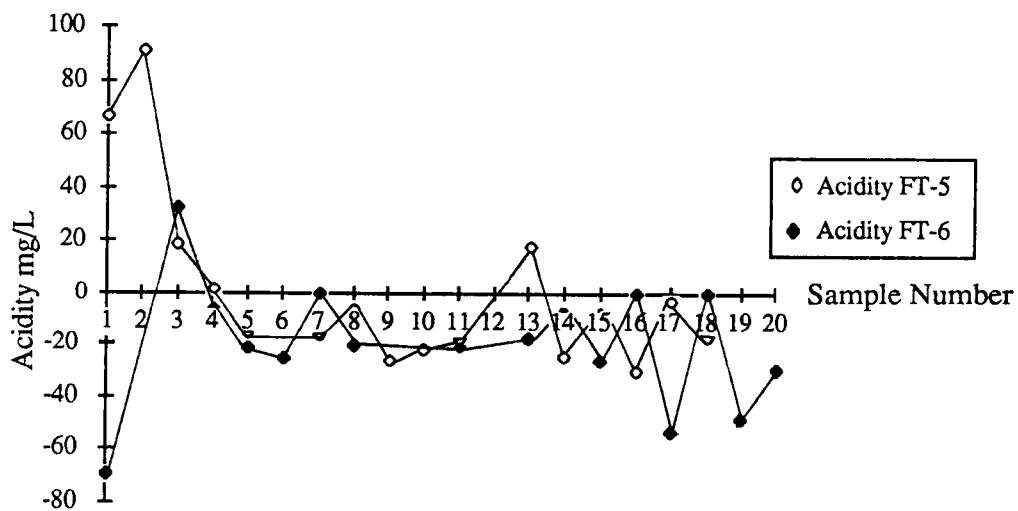


Figure 26. Plot of Acidity Versus Sample Number for FT-5 and FT-6

Dissolved metal concentrations demonstrated the greatest fluctuations. Total Fe, Cu and Zn concentrations were generally below detection limits in the treated models. Aluminum, however, due to the low detection limits of the analytical methods used, was consistently measured in tank effluents. Manganese was also detected in most samples. Figures 27 and 28 show Al concentrations in effluents for the treated models. Manganese values were generally in the range of 1.0 to 50.0 mg/L and exhibited trends similar to Al.

Treated models, notably FT-2, show a resistance to fluctuations in effluent quality due to variations in rainfall input and time between rainfall flushing events. Statistical comparisons of rainfall amounts between sample collection to pH, conductivity, sulfate and iron levels resulted in no correlation coefficient greater than 0.3 for any model. Therefore, rainfall amounts do not affect discharge waters to a significant degree. When the time between collection was correlated to these same four parameters in FT-1 effluents, the highest coefficient that resulted was 0.02. On this basis, the time between collection has no significant influence on water quality.

The primary influential factor affecting leachate quality seems to be seasonal variations of temperature. Figures 19 through 28 were constructed in such a manner as to show effluent quality trends for each tank from the first rainfall and flushing event. The graphs have to have an equivalent starting point specifically, the first collection from each tank, to provide a representative comparison. A representative comparison of leachate quality to rainfall input and seasonal cycles therefore, is difficult with these data plots. Figures 29 through 36 show effluent chemistry plotted against real time to illustrate seasonal patterns.

The untreated models, FT-1 and FT-8, seem to have a significant seasonal dependence on species concentrations, especially dissolved metals. Effluent quality was seen to improve slightly during the colder months when ice filled interstitial pores within the models preventing oxygen recharge and slowing sulfide oxidation rates. Leachate quality worsened considerably during warmer periods when sulfide oxidation rates and microbial activity increased. Figures 29 and 30 illustrate this trend for Fe and Zn concentrations in FT-1 leachates. FT-3, FT-4 and FT-5 effluents also seem to show a similar, but subdued, dependence on seasonal changes in temperature with respect conductivity, sulfate and aluminum (Figures 31 - 36). The significant spike in conductivity and sulfate for these models, seen during July, represents a flushing event on 7-12-88 following a 60 day aeration period due to lack of significant rainfall during the months of May and June (Figures 31, 32, 33 and 34). The flushing event affected metal concentrations which increased sharply. FT-6 also demonstrated increases in Mn and Zn values to above

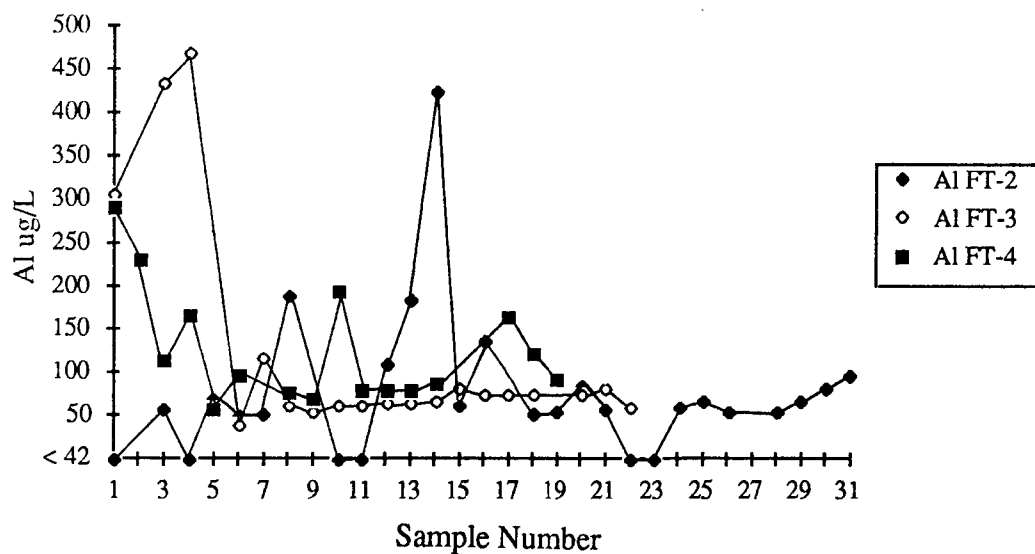


Figure 27. Plot of Aluminum Versus Sample Number for FT-2, FT-3 and FT-4

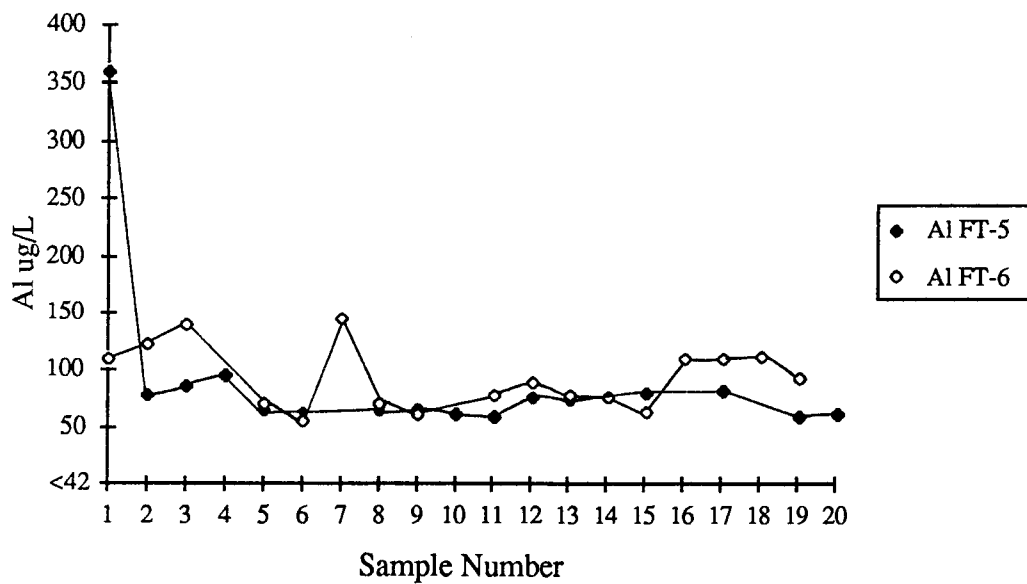


Figure 28. Plot of Aluminum Versus Sample Number for FT-5 and FT-6

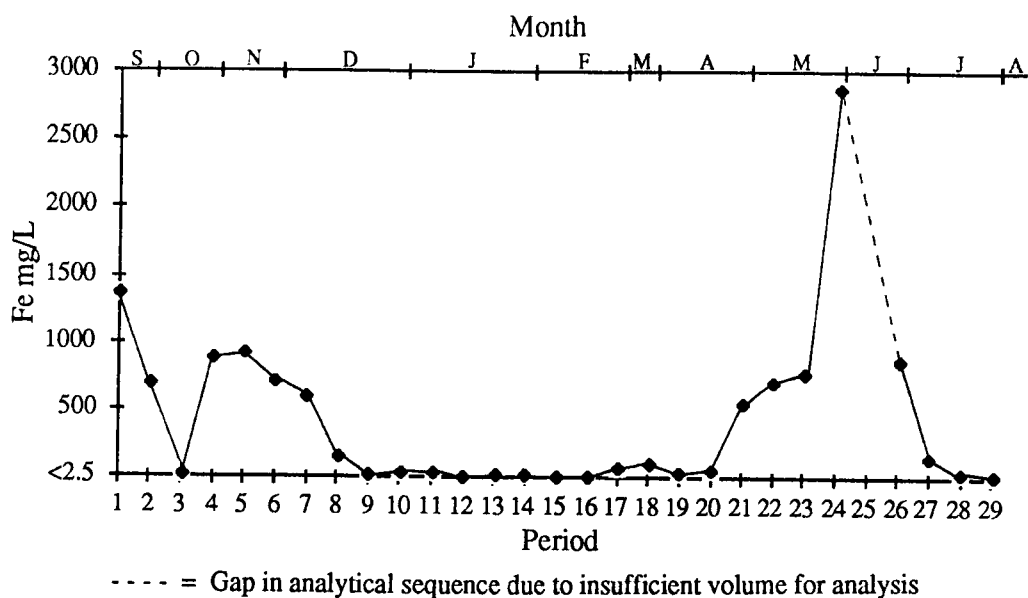


Figure 29. Plot of Iron Versus Time for FT-1

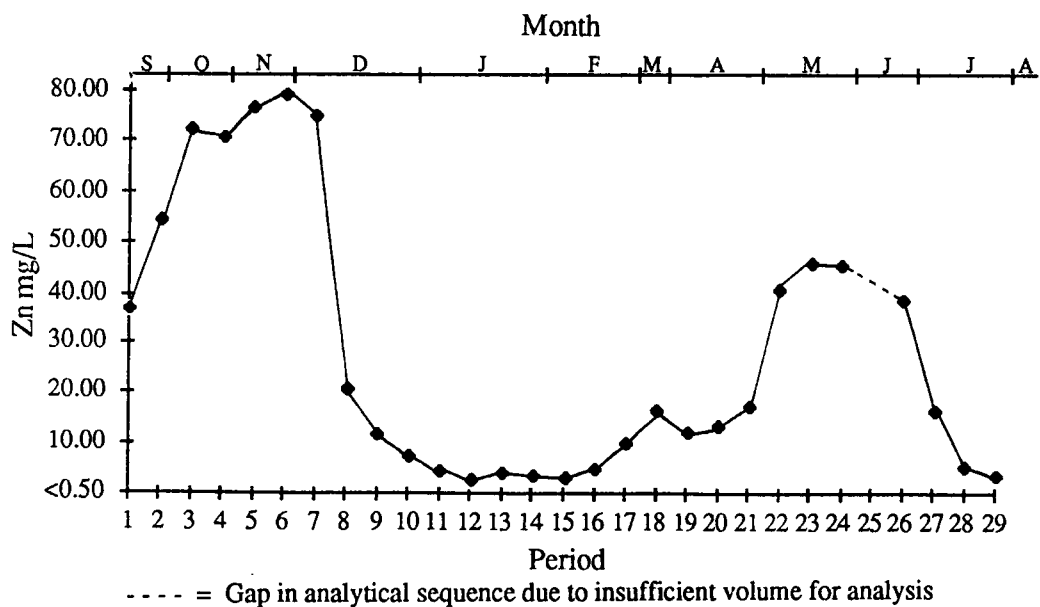


Figure 30. Plot of Zinc Versus Time for FT-1

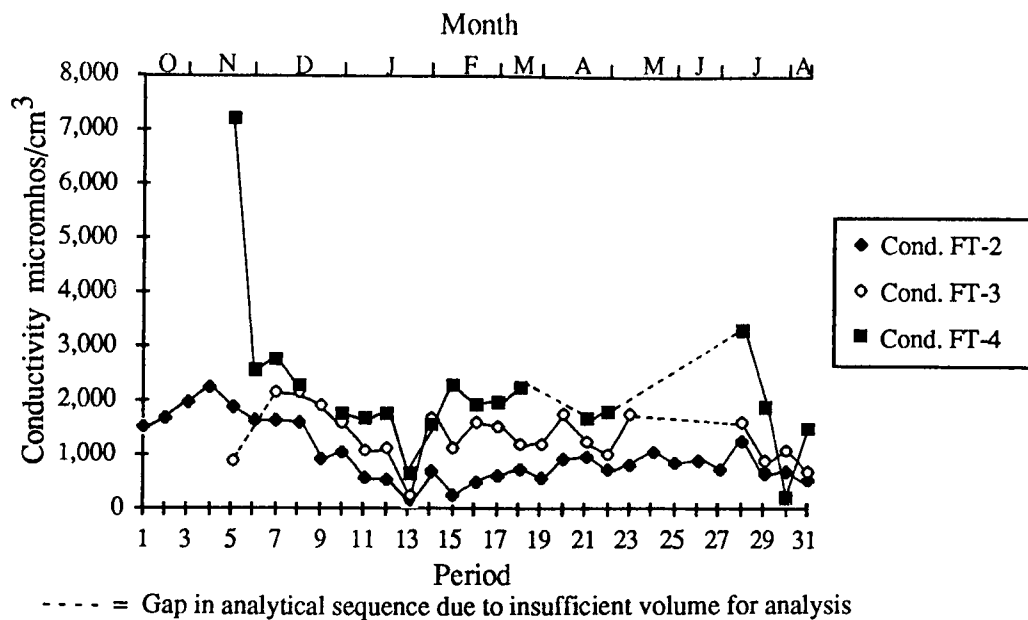


Figure 31. Plot of Conductivity Versus Time for FT-2, FT-3 and FT-4

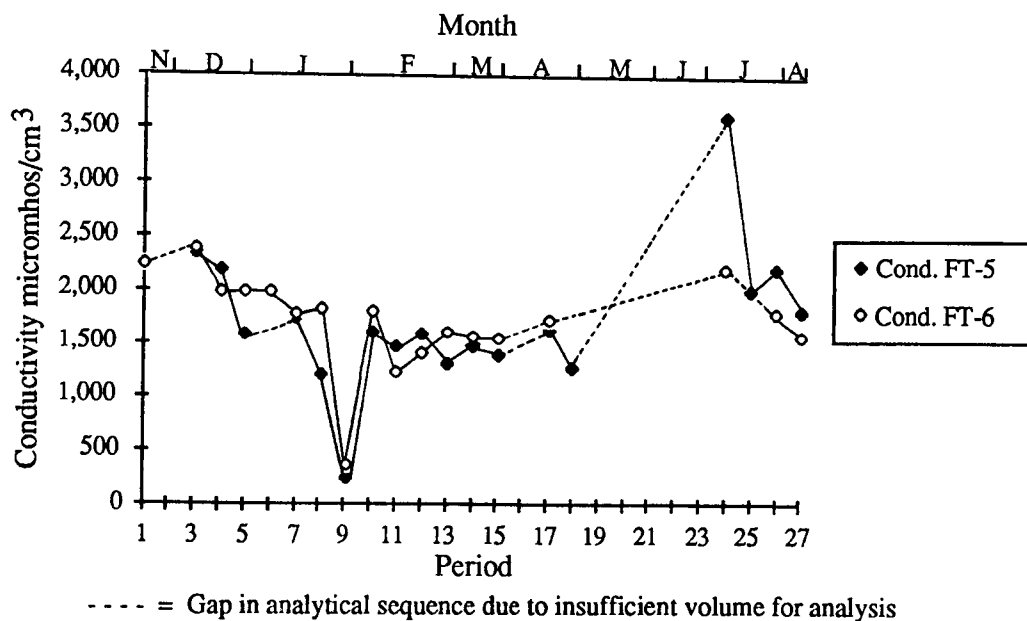


Figure 32. Plot of Conductivity Versus Time for FT-5 and FT-6

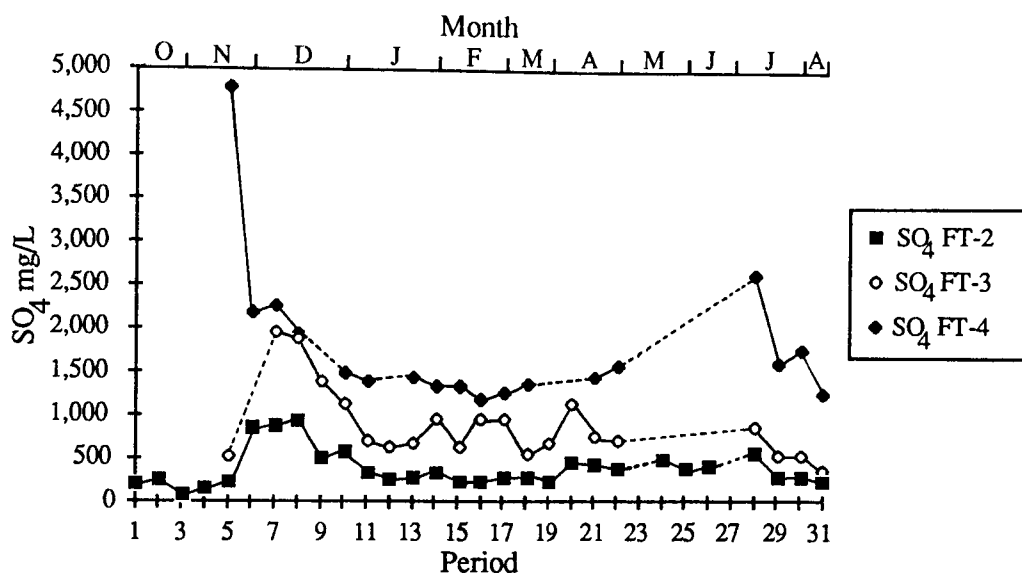


Figure 33. Plot of Sulfate Versus Time for FT-2, FT-3 and FT-4

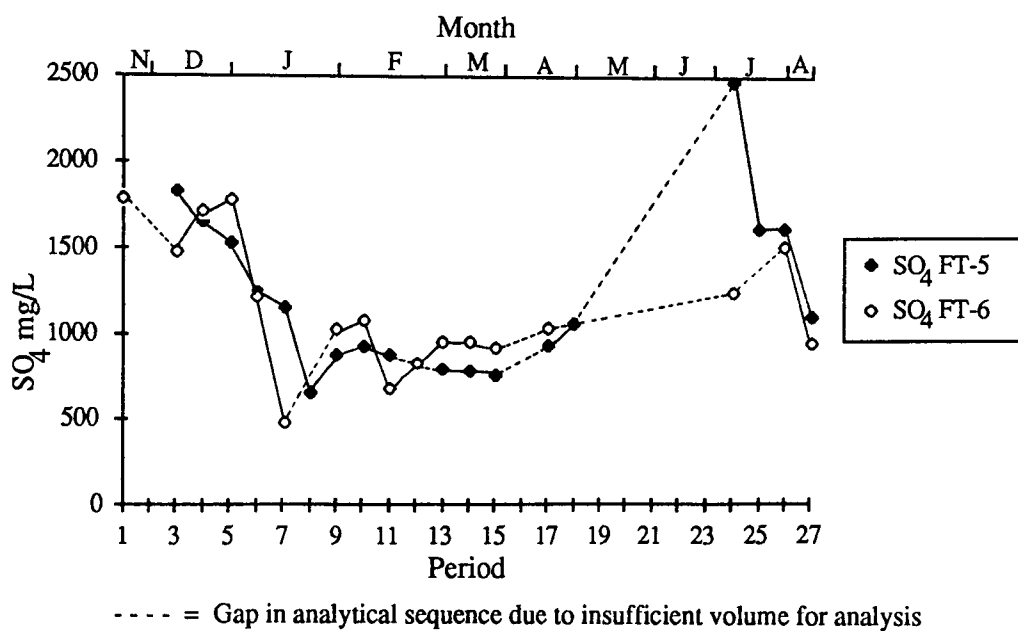


Figure 34. Plot of Sulfate Versus Time for FT-5 and FT-6

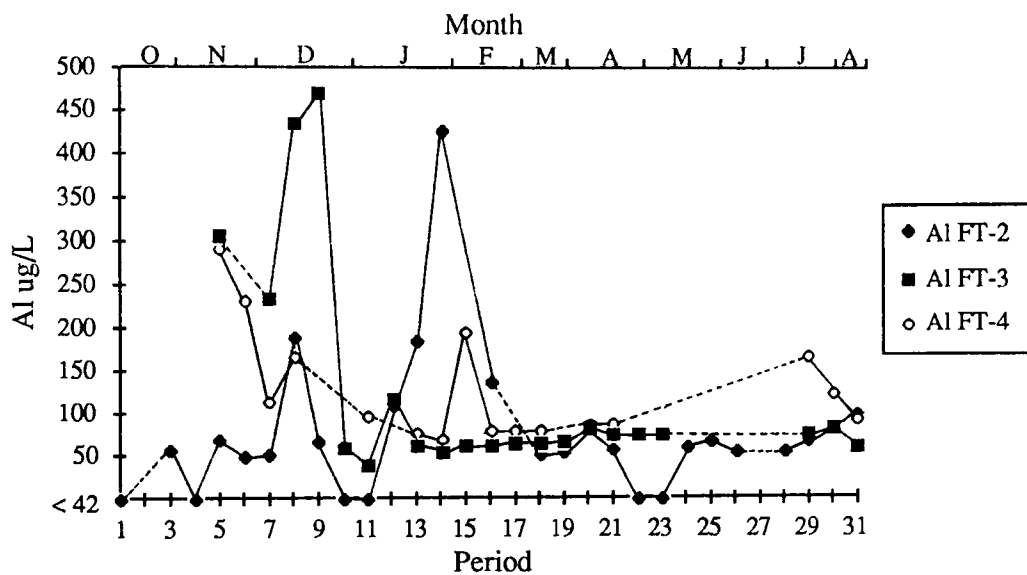


Figure 35. Plot of Aluminum Versus Time for FT-2, FT-3 and FT-4

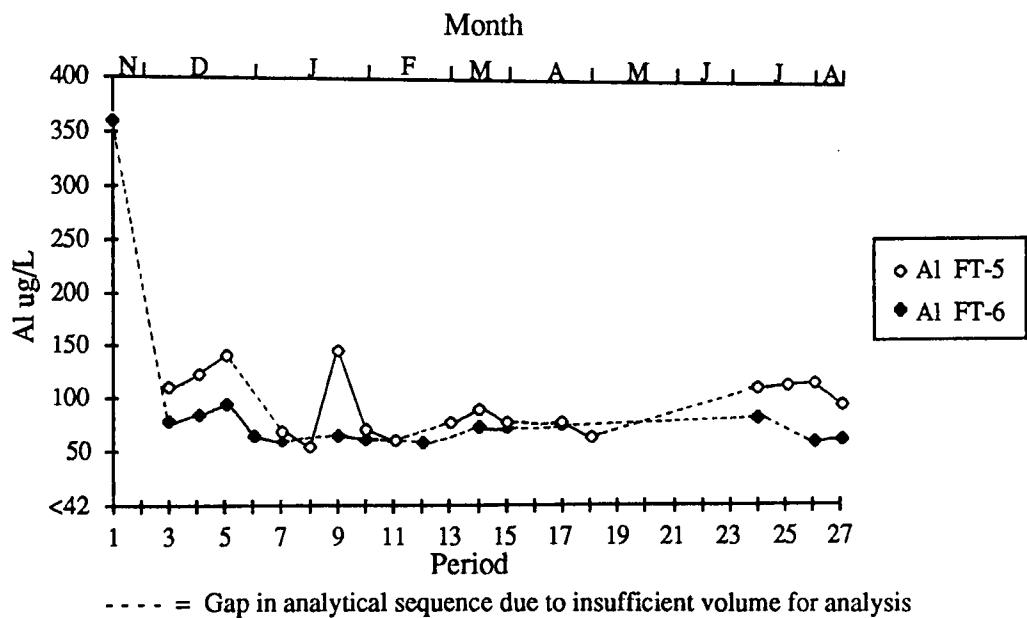


Figure 36. Plot of Aluminum Versus Time for FT-5 and FT-6

detection levels; however, these decreased to near detection levels within 17 days. In general, the treated models had much greater stability in terms of dissolved metals concentrations than models containing untreated material. Effluents from the encapsulation site underdrain (F-996) showed no seasonal variations.

Table 9 summarizes the relationships of pH, conductivity, sulfate, Fe and Mn to monthly rainfall totals and time of year for most of the field leaching tests and the baseline samples collected from F-996+50.

Comparisons to Fill Effluents

Table 10 shows effluent quality over the time span of the study for discharge water emanating from an underdrain at the 996+50 encapsulation site (F-996-UD). These samples were analyzed to provide a baseline water quality comparison for the field models. Leachate quality from models featuring treatment by lime and limestone differs little from that of F-996-UD samples. Especially noteworthy are the small differences between FT-2, the original simulation of a fill, and actual roadfill effluent compositions (Table 9). F-996-UD samples had pH ranges from 6.4 to 7.2 and an average specific conductance of 549 micromhos/cm³. Water from the fill was consistently alkaline, although it contained moderate amounts of sulfate.

Dissolved metals were consistently near or below detection levels, with the exception of manganese which averaged 2.9 mg/L. Effluents from F-996-UD showed no apparent seasonal variations. The constant quality of encapsulation site leachates over time is probably due to the insulation effects of the six-foot thick topsoil layer and paved highway at the upper surface. In addition, there probably is no freezing which could affect effluent quality at depth within the fill.

Field Samples

Data Trends

Surface water samples from points along TNFLH 1-1(14) were collected when possible from 9-12-87 through 7-12-88 (Table 5, page 25). These samples represent water quality resulting from weathering of exposed, untreated outcrops and talus in true field settings. All of these samples were collected either from surface drainage ditches or runoff along outcrop faces. Sufficient flow for sampling usually only occurred during and shortly after a significant rainfall event. The only site which had enough flow volume for consistent sampling according to the monthly criteria was HK-SR. The

Table 9. Comparisons of Average Monthly Values to Rainfall
and Time of Year

Parameter		Month											
		Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
RF Amt.		2.18	1.43	2.10	5.64	4.48	2.82	3.15	3.73	2.99	2.65	7.04	3.35
Avg. pH	FT-1	4.5	3.6	3.0	3.0	3.4	3.4	3.2	3.0	2.7	2.5	2.7	3.0
	FT-2	NIS	7.8	7.0	7.3	7.1	7.0	7.4	7.6	8.0	8.1	7.5	7.8
	FT-3	NIS	NIS	5.6	6.0	7.3	6.8	6.9	7.1	7.2	--	5.5	6.8
	FT-4	NIS	NIS	5.0	6.9	7.2	7.1	6.8	7.6	--	--	6.0	6.9
	FT-5	NIS	NIS	--	7.2	7.1	7.3	6.8	7.6	--	--	7.0	7.0
	FT-6	NIS	NIS	6.6	7.3	7.3	7.4	7.4	7.8	--	--	8.0	7.6
	F-996	6.4	--	--	6.9	6.7	6.7	7.1	6.8	7.0	6.6	7.1	--
Avg. Cond. (micro- mhos)	FT-1	5,500	5,430	4,300	3,720	1,290	1,190	2,400	4,200	4,980	9,725	3,780	1,770
	FT-2	NIS	NIS	2,250	1,800	1,060	510	470	660	890	920	840	880
	FT-3	NIS	NIS	890	2,000	1,060	1,440	1,220	1,360	1,800	--	1,230	720
	FT-4	NIS	NIS	4,925	2,300	1,440	2,080	2,250	1,760	1,800	--	--	1,500
	FT-5	NIS	NIS	--	2,040	2,085	1,460	1,440	1,460	--	--	2,600	1,820
	FT-6	NIS	NIS	2,250	2,100	1,460	1,420	1,560	1,740	--	--	2,000	1,580
	F-996	350	--	--	1,150	62	740	550	560	500	510	570	--
Avg. SO ₄ (mg/L)	FT-1	4,450	5,150	4,800	4,080	1,290	1,190	1,600	1,800	4,980	9,750	3,780	1,100
	FT-2	NIS	190	430	740	300	250	430	260	440	420	380	280
	FT-3	NIS	NIS	540	1,600	760	850	620	870	ND	--	650	360
	FT-4	NIS	NIS	3,500	1,900	1,400	1,270	1,360	1,500	--	--	1,980	1,250
	FT-5	NIS	NIS	--	1,570	910	840	770	1,000	--	--	1,880	1,100
	FT-6	NIS	NIS	1,800	1,550	870	830	940	1,040	--	--	1,370	950
	F-996	61	--	--	520	470	280	180	150	130	110	110	ND
Avg. Fe (mg/L)	FT-1	1,370	542	929	604	27	11	79	70	680	2,780	353	25
	FT-2	NIS	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
	FT-3	NIS	NIS	48	18	<2.5	<2.5	<2.5	<2.5	<2.5	--	<2.5	<2.5
	FT-4	NIS	NIS	380	<2.5	<2.5	<2.5	<2.5	<2.5	--	--	<2.5	<2.5
	FT-5	NIS	NIS	NIS	<2.5	<2.5	<2.5	<2.5	<2.5	--	--	<2.5	<2.5
	FT-6	NIS	NIS	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	--	--	<2.5	<2.5
	F-996	--	--	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Avg. Mn (mg/L)	FT-1	52	89	101	82	11	12	16	40	63	116	50	13
	FT-2	1.3	<1.0	1.6	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1.2	<1.0
	FT-3	NIS	NIS	2.8	29.6	2.4	2.0	1.7	2.5	3.5	--	6.0	2.4
	FT-4	NIS	NIS	4.0	6.3	3.3	2.0	3.1	2.0	--	--	20.5	5.8
	FT-5	NIS	NIS	--	22.4	7.1	3.8	2.0	1.9	--	--	18.2	6.1
	FT-6	NIS	NIS	10.8	7.0	2.0	<1.0	1.2	<1.0	--	--	7.4	1.5
	F-996	--	--	8.4	5.3	2.4	2.2	1.9	1.5	1.6	1.3	<1.0	--

NIS = Not in service

ND = Not determined due to insufficient volume

-- = No sample(s) collected

Table 10. Ranges and Average Values for Chemical Parameters in F-996-UD Effluents

Parameter	Range	Average Value
pH	6.4 - 7.2	6.8
Conductivity (umhos)	62 - 1,150	549
Sulfate (mg/L)	61 - 520	226
Acidity (mg/L)	-92 - -165	-121
Al (ug/L)	59 - 157	86
Fe (mg/L)	<2.5	<2.5
Mn (mg/L)	<1.0 - 8.4	2.9
Cu (mg/L)	<1.5	<1.5
Zn (mg/L)	<0.50	<0.50

remaining sites were checked on the same dates as HK-SR, but often no sample could be obtained. Table 11 summarizes the results of the field sample analyses and gives average parameter values for each of the sites. The dissolved metal concentrations had the most variability in HK-SR and C-OR with levels changing by an order of magnitude or more between sampling dates. The remaining parameters were relatively stable and demonstrated small or only moderate fluctuations. No apparent relationship resulted from comparisons of water quality at HK-SR to rainfall amounts from the five days prior to each collection or time between sampling. No apparent trends were observed with respect to the time of year. The quality of surface runoff obtained was probably dictated mostly by the time of sampling in relation to a specific rainfall event. If samples were collected shortly after the initiation of a storm event then runoff water would be expected

Table 11. Average Composition of Surface Drainage Waters on TNFLH 1-1(14)

Sample	N	pH	Cond.(umhos)	SO ₄ (mg/L)	Acid.(mg/L)	Al(ug/L)	Fe	Mn	Cu	Zn
HK-SR	6	3.3	700	227	130	5267	12.4	10.5	<1.5	0.84
A-OR	1	2.7	1875	224	701	126	ND	ND	ND	ND
A-SR	1	6.1	160	57	1	331	ND	ND	ND	ND
C-OR	2	3.0	1380	1020	990	101.6*	242.6	8.2	1.8	3.86
D-SR	2	8.4	1135	54	-114	119	<2.5	<1.0	<1.5	<0.50

N = Sample population

ND = Not determined

* = Value is in mg/L

Fe, Mn, Cu and Zn values are in mg/L

to have high concentrations of chemical species due to initial flushing or washing of oxidized material surfaces. The dilution effects of rainfall further into the event reduce species concentrations. Most surface water samples were usually collected within a day after a period of rainfall. C-OR on 12-28-87 (Table A-26, page 104) was collected soon after the beginning of significant rainfall. Parameter values for that sample are much higher than those of any other samples which were all taken at some point after a storm.

These samples show that water quality from untreated rock exposed along these roadcuts can be highly acidic and contain toxic quantities of dissolved metals. The water quality generated along such intervals generally is that which should be expected given the acid-base accounting data characterizing these materials. Only surface water along section D, from which Comp D (NNP= -8) was obtained, proved to be of consistently better quality than expected.

Mineralogical Characterization of Encapsulation Sites

A mineralogical characterization of materials obtained from the fills by borehole was made to further evaluate the chemical environment within encapsulation sites. Three encapsulation sites on TNFLH 1-1(14) were drilled for this study using a power auger and split spoon sampler. One untreated fill (BH-1) west of this segment was augered to provide a baseline comparison. Composite samples were obtained from a split spoon core by scraping materials at points where coatings and precipitated phases were most prevalent. The composite was ground by mortar and pestle and a packmount prepared for X-ray analysis. An identical analytical program and the same identification criteria used for X-ray analysis of laboratory composites was used for borehole samples. Binocular microscope examinations of were also conducted on uncrushed samples. Results of the mineralogical characterization are presented in Table 12.

Phases present in these boreholes were similar to those found in the lab columns. Ferrihydrite was prevalent in the core material, but this was expected since pH conditions are higher within the fill than in the laboratory columns or untreated fill materials. The potassium iron sulfate, yavapaiite, was also observed in materials from two of the fills.

Table 12. Mineralogical Characterization for Roadfill Materials

BH-1 Phases Identified:	Formula	BH-2 Phases Identified:	Formula	BH-3 Phases Identified:	Formula	BH-4 Phases Identified:	Formula
Quartz	SiO ₂	Quartz	SiO ₂	Quartz	SiO ₂	Quartz	SiO ₂
Clinchlore	Refer to BH-4	Clinchlore	Refer to BH-4	Clinchlore	Refer to BH-4	Clinchlore	(Mg,Fe ²⁺ ,Al) ₃ (Si,Al) ₂ O ₅ (OH) ₄
Muscovite	KAl ₂ (AlSi ₃ O ₈)(OH) ₂	Muscovite	KAl ₂ (AlSi ₃ O ₈)(OH) ₂	Muscovite	KAl ₂ (AlSi ₃ O ₈)(OH) ₂	Muscovite	KAl ₂ (AlSi ₃ O ₈)(OH) ₂
Gypsum	CaSO ₄ ·2H ₂ O	Pyrite	FeS ₂	Illite	Refer to BH-4	Calcite	CaCO ₃
Jarosite	KFe(SO ₄) ₂ (OH) ₆	Albite	NaAlSi ₃ O ₈	Albite	NaAlSi ₃ O ₈	Albite	NaAlSi ₃ O ₈
				Yavapaiite	KFe(SO ₄) ₂	Illite	(H ₃ O,K) _y (Al ₄ Fe ₄ Mg ₄ Mg ₆)(Si _{8-y} Al _y) -O ₂₂ (OH) ₄
Tentative:							
Ferrhydrite	Fe(OH) ₃	Ferrhydrite	Fe(OH) ₃	Ferrhydrite	Fe(OH) ₃	Siderite	FeCO ₃
Illite	Refer to BH-4	Alunite	(K,Na)Al ₃ (SO ₄) ₂ (OH) ₆	Gypsum	CaSO ₄ ·2H ₂ O	Melanterite	FeSO ₄ ·7H ₂ O
Yavapaiite	KFe(SO ₄) ₂			Copiapite	Fe ²⁺ Fe ³⁺ ₄ (SO ₄) ₆ (OH) ₂ ·20H ₂ O		
Albite	NaAlSi ₃ O ₈						

CHAPTER VI

DISCUSSION

Lab Column Trends

Acid Production Rates

The long-term laboratory leaching tests indicate that the effluent composition from each particular column seems to be dependent on the nature of the input rock. Specifically, pH and acidity levels appear to be related to the NNP of the source. Acid production in the lab column leachates, as indicated by these two parameters, rapidly reaches a constant level. This level was different for each of the columns. At the end of the 45 leaching cycles, acidity levels demonstrated no sign of improvement. Considering the small volume and average particle size of the composite samples, this trend suggests that the pyritic materials used in this study are capable of producing acid drainage for long periods of time. Hood and Oertel (1984) studied conductivity and Na/Ca ratios of actual field effluents from cast piles over time and estimated that each leaching cycle in their study represented approximately three years of natural weathering. The style of comparison used in that study was not possible for the present leaching experiments since large cast piles of overburden are not exposed on TNFLH 1-1(14). However, the assumption may be made that the columns do represent an accelerated rate of acid production due to the frequency of flushing, volume of input rock and small particle size factors mentioned previously. On this basis, the leaching studies suggest that significant acid production from untreated, sulfidic Ocoee rocks may occur for at least several decades in the field. Further evidence is provided by the poor quality of surface water samples collected from the base of 10 year old roadcut exposures on TNFLH 1-1(14) and Hemlock Knob.

Theoretically, acid production from these sources should cease when the available supply of pyrite is depleted through oxidation. The sulfur speciation study on HK-1 and HK-2 indicates that nearly all of the sulfide sulfur phases and hence, the sulfide source, was oxidized after approximately two years of leaching alternating with aeration. Despite the fact that pH and acidity values were still low at the end of the leaching experiments, the possibility exists that these two columns may have been close to a point where improvements in leachate quality begin to occur.

In HK-2, the initial inundation of the source material with CaCO_3 -saturated water in 1986 seemed to have long-term effects on the amount of acidity produced. Despite the

better effluent quality, the total amount of sulfide sulfur phases present at the end of the experiments was essentially equal to HK-1. Apparently enough residual carbonate remained in the column to buffer the leachate but not to slow the oxidation of sulfides. In the remaining columns examined for sulfur distribution, approximately one-half of the original total sulfur percentage had been depleted after 45 weeks of leaching. These columns seem to follow a trend consistent with that of HK-1 and HK-2 and therefore, about half of the significant acid-production life of the material remained after the experiments.

Column Geochemistry and Mineralogy

When the laboratory leaching columns were initially charged, the extremely fine sulfidic material generated by the pulverization process oxidized rapidly. The first few cycles reflected this oxidation by showing high concentrations of dissolved metals, (except Al). In addition, high sulfate, acidity, pH and conductivity levels were observed, which subsequently decreased rapidly. As the pH dropped, dissolution of primary phases other than sulfides increased. Once acidity and pH values decreased to a point where a propagation cycle was established, all parameters began to stabilize. *Thiobacillus ferrooxidans* is assumed to have catalyzed sulfide oxidation since this strain of bacteria is ubiquitous in natural materials. However, specific identification tests were not conducted to confirm bacteria presence or absence.

Once the acid production cycle was established, many geochemical changes appeared to have occurred over time. Sulfur present as sulfide phases was either redistributed as sulfate phases or was rendered into a dissolved state and exited the columns with effluents. Sulfur bound with organic materials is highly resistant to leaching and tends to remain in a system (Sobek et al, 1987). The oxidizing environment within the columns is not conducive to the formation of any additional organically-bound sulfur; however, examination of HK-1 and HK-2 show that approximately 98% of the total sulfur in post-leaching materials is bound with organics. Since additional organic sulfur was probably not forming within the columns, the interpretation is that it remained the same in relation to decreases in the relative proportions of the other two forms. The remaining columns showed that approximately 50% of the total post-leaching sulfur was present as sulfate phases.

Alteration and dissolution of primary phases, especially albite, seems to occur over time within the columns. In addition, micaceous minerals such as muscovite and clinocllore (chlorite) probably experience significant alteration. The dissolution of

these minerals provides a source for major cations, in addition to Al, and allows the formation of secondary phases such as jarosite, yavapaiite and alunite. The high iron and sulfate concentrations further aid in the formation of jarosite seen in HK-1 and Comp C (Tables 7 and 8, pages 40 and 41). The probable presence of jarosite in HK-2 was unexpected since pH conditions within this column were ordinarily higher than 4.8. This phase may have formed in HK-2 in residual water left in the column after draining or directly along sulfide mineral surfaces where localized pH was probably much lower than the effluent as a whole. The presence of melanterite in HK-1 and HK-2 indicates that evaporation during the aeration stage of each leaching cycle was sufficient to allow for formation of this phase. The oxidation of melanterite during the innundation stages of each cycle would be expected to produce copiapite. Copiapite was observed in all three columns examined for the mineralogical characterization; however, melanterite was not observed in Comp C. All of the available melanterite may have been oxidized during each recharge. The presence of ferrihydrite in HK-2 was not unexpected; yet this phase also seemed to be present in HK-1 where pH conditions were well below the ideal range for formation. Since ferrihydrite does not precipitate directly from a saturated media when pH values are less than 4.8, the source for this mineral is apparently the dissolution of copiapite and/or the decomposition of jarosite. Other phases identified in the columns include diasporite and boehmite in Comp C. These minerals are not unexpected given the relatively high Al concentrations seen in leachates from this column.

Comparisons to Field Methods and FHWA Predictive Measures

Laboratory composite B and field leaching model FT-1 incorporated untreated sulfidic material from the same source interval to establish a comparative base between lab and field leaching programs. Hood and Oertel (1984) determined that chemical species concentrations in leachates from laboratory experiments similar to those used in the present study were approximately 4.5 times less than actual mine drainage concentrations. Similar general trends in chemical composition were observed between Comp B and FT-1; however, FT-1 effluents were far more concentrated. Comparisons of average conductivity, sulfate and acidity over the entire FT-1 leaching program to the same parameters, averaged over the last five cycles in Comp B, were done to establish specific ratios. Conductivity in FT-1 was 11 times higher, on average, than stabilized values of the Comp B leachates. Sulfate and acidity were 24 and 32 times greater, respectively, in FT-1 effluents. Therefore, with the source materials used in this study, the longer

oxidation periods and higher temperatures during warmer months generates significantly more acidic waters in the field tests than those from the laboratory columns.

Relationships of the lab results to predictive methods used by the FHWA were examined to determine the effectiveness of current evaluation procedures. Specifically, the acid-base accounting results shown in Table 4 (page 21) were compared to effluent quality. Good correlation appears to exist between the NNP estimates and all column leachates except Comp D. NNP values for the Hemlock Knob, Comp B and Comp C materials indicate significant potential for acid drainage. These columns, with the exception of HK-2, show highly acidic leachates. MGQ acid-base accounting indicates that alkaline, or at least neutral, water would result from contact with these rocks. The MGQ column had the best water quality of all of the leaching tests. Comp A NNP values show that the input material was only marginally deleterious, and effluent quality substantiates the estimate. Comp D NNP estimates indicate a moderate potential for acid production, yet effluents from this test were comparable to Comp A leachates. The possibility exists that discrepancies in the sampling methods used in this study and those utilized by the FHWA resulted in the lack of correlation for Comp D. The acid-base accounting procedure used by the FHWA provides a worst-case assessment of acid production characteristics since sulfide dissolution is forced by acid digestion and all sulfur is assumed to occur as sulfide phases which have a tendency to leach easily. However, the NNP estimates are good general AD predictors when applied to sulfide-bearing, meta-sedimentary rocks in the study area.

Field Leaching Studies

Relative Effectiveness of the Model Variations

Variations in effluent quality were generally small among models featuring treated material, FT-7 excluded (refer to Table 9, page 53). Comparisons of treated to untreated effluents show that metal concentrations, with the exception of copper, are up to an order of magnitude greater in untreated leachates. FT-2, the original model, had slightly better water quality than the other tanks. The increases in conductivity, sulfate, iron and manganese in FT-4, FT-5 and FT-6 may be due to the increased volume of pyritic material incorporated into these models as compared to FT-2. FT-3 leachates improved to levels similar to the original model, although the recovery period was substantial, and acidity never attained levels commensurate with the degree of limestone addition. FT-4 seemed to have consistently higher values of conductivity and sulfate than expected, in

consideration of the 30% limestone reduction. This aberration may be due to higher initial sulfide concentrations in the source material. Despite precautions to avoid significant sampling variability, natural variations in sulfide mineralization, within the stratigraphic unit, make exact duplication of the large volume of rock incorporated into the models impossible.

The small differences seen in effluent chemistry from the treated field tanks indicate that water quality representative of encapsulation site effluents may be attained, despite reductions in the basal limestone aggregate layer of up to 60%. Topsoil reductions by 50% do not appear to affect the character of leachate. Placement of the buffer layer at the top of the pyritic volume was not immediately effective in improving leachate quality.

These findings suggest that the addition of interlayer lime and a basal position of the limestone aggregate layer are the influential factors in improving leachate composition. Since reductions in the thickness of limestone aggregate did not appear to seriously alter effluent chemistry, the lime treatment is probably the single most critical amendment in improving discharge waters. The addition of interlayer lime is assumed to have maintained moderately alkaline conditions within the pyritic material volume. The pH increase drives metal solubilities downward (Wilmoth, 1977) and reduces the values of acidity, sulfate and conductivity prior to interception by the limestone blanket. Concentrations of chemical species that are in a dissolved state are further decreased by the formation of oxide, hydroxide and sulfate phases in stable environments within interstices of the sulfidic mass or along the surfaces of acid-producing particles. The formation of secondary phases at these sites reduces their formation along particle-solution interfaces within the limestone blanket. This, in turn, allows the aggregate layer to remain mostly free of mineral coatings and can serve effectively to induce additional alkalinity to discharge waters. The field tanks were not dismantled to examine the nature and distribution of precipitated phases; however, visual inspection, of basal limestone aggregate obtained from the encapsulation site penetrated by BH-3, indicated no appreciable coating of the buffer material approximately 10 years post closure.

Comparisons to Baseline Water Quality

Baseline water quality data was provided by samples from a fill underdrain at station 996+50. The data trends indicate that the models featuring lime and limestone treatment provide an accurate assessment of fill leachate chemistry. Especially noteworthy are the small differences between FT-2 and F-996-UD effluent chemistry (Table 9, page 53). FT-2 effluents contained only slightly higher amounts of dissolved sulfate and were

slightly less alkaline. The remaining parameters show nearly identical ranges. Untreated material in FT-1 produced leachates having average conductivity, sulfate and acidity levels which were 7, 15, and 16 times higher, respectively, than average fill discharge values. The remaining model variations, with the exception of FT-7, had pH and dissolved metal ranges comparable to F-996-UD. Stabilized values of conductivity and sulfate were approximately 3 to 10 times greater than fill effluents depending on the particular model. Acidity values for these models were comparable to FT-2 leachates, which, as previously mentioned, were 16 times greater than baseline. Despite the moderate variations in conductivity, sulfate and acidity, the FT-3, 4, 5, and 6 models produce general leachate quality comparable to encapsulation site discharges.

Fill Geochemistry and Mineralogy

The results of the bench and field scale leaching studies and mineralogical characterization of borehole materials allow some inferences to be made about chemical conditions within an encapsulation site. Mineral phases generated in the encapsulation sites by sulfide weathering are similar to those found in the lab leaching tests. The presence of secondary potassium iron sulfate minerals, such as jarosite and yavapaiite, indicates that dissolution of primary phases occurs which, in turn, supplies major cations to interstitial waters. Calcium minerals, such as gypsum, and carbonate minerals, such as calcite and siderite, were more prevalent in the the encapsulation sites than in the lab columns due to fill lime treatment.

In untreated fill materials taken from BH-1, no unoxidized sulfides were found either by visual inspection or X-ray analysis. Material was extensively degraded and cemented by secondary phases in many places. Fresh, unaltered sulfides were identified by one or both methods in BH-2, BH-3 and BH-4.

Each length of core was tested for the presence of alkaline zones by reacting the entire length with 10% HCl applied by a wash bottle. This test indicates that significant alkaline zones, consistent with the frequency of lime application during construction, are still present within the encapsulation sites on TNFLH 1-1(14). Mineral precipitates and clay materials appeared to be more prevalent in these zones. Limestone underblanket samples taken from BH-3 show no significant coating of the particles.

The nature and distribution of secondary mineralization and the good effluent quality at F-996-UD indicates that the internal chemical conditions suggested for the field models also applies to the encapsulation sites. The addition of interlayer lime seems to encourage

the development of alkaline conditions within the body of the fill. The increase in pH has several effects. First, *Thiobacillus ferrooxidans* does not have the opportunity to catalyze sulfide oxidation. Secondly, the increased pH values lower metal solubilities and help to further decrease species concentrations by promoting the formation of phases in interstices and along sulfidic material surfaces. Lastly, the formation of mineral phases at these sites serves to armor acid-producing particles from further oxidation, helps to reduce fill porosity and permeability, and reduces mineral phase formation along particle-solution boundaries within the limestone underblanket.

Effectiveness of Current FHWA Technology

Alkaline effluents and presence of abundant fresh sulfides in encapsulated materials demonstrates that the fill design used on TNFLH 1-1(14) is effective in retarding significant sulfide oxidation. Water quality representative of area surface streams from the encapsulation site at 996+50, approximately 10 years post closure, indicates that the current encapsulation method represents a long-term solution to AD in a highway construction setting. However, the results from the field-scale models show that significant reductions in the amount of basal limestone aggregate do not seriously degrade effluent quality. Since the field leaching tests represent accurate models of the fills, analogous reductions of limestone aggregate in the encapsulation sites may be assumed to produce similar results.

Comparisons of the laboratory leaching tests to acid-base accounting measures used by the FHWA show that the current predictive measures are adequate for assessing the disposition of materials that are encountered during construction. This method, as used by the FHWA, may be considered as a worst-case prediction technique for reasons stated earlier.

CHAPTER VII

CONCLUSIONS

Interpretation of the results of the study produced several conclusions as related to the laboratory leaching experiments. These conclusions include:

1. Differences in leachate quality among a series of laboratory leaching experiments incorporating different source materials of various lithologies indicate that the chemical composition of acidic effluents is dependent upon the mineralogical, chemical and NNP characteristics of the source material.
2. Sulfur phase distribution studies of materials from bench-scale leaching tests show that almost all sulfur bound as sulfide phases is either redistributed into sulfate phases or flushed from the system after two years of weekly flushing alternating with aeration. Organic sulfur appears to remain relatively constant during long-term oxidation. On this basis, the presence of substantial sulfide sources and hence, the acid-production life of sulfidic Ocoee rocks in laboratory leaching studies, such as used in this study, seems to be approximately two years.
3. The results of the sulfur redistribution studies, along with the fact that a previous study determined that each laboratory leaching cycle represents approximately three years of natural weathering (Hood and Oertel, 1984), suggest that sulfidic Ocoee rocks are capable of significant acid production for several decades in the field.
4. The oxidation of sulfides, along with leaching and hydration of other primary minerals such as albite, muscovite and chlorite, in acidic water, provides a source for species which result in abundant secondary mineral formation. Mineral phases resulting from the weathering of Ocoee rocks include jarosite, copiapite, ferrihydrite, aluminum oxides and hydroxides, and kaolinite.
5. Comparisons of average conductivity, sulfate and acidity values in laboratory leachates with the same parameters in field leaching test effluents show that the field models have values that are 11, 24 and 32 times higher respectively, than those of the lab columns. On this basis, no specific ratio provides a consistent, quantitative measure of the difference in effluent quality between laboratory and field tests.
6. FHWA acid-production predictive measures (acid-base accounting) generally have good correlation with the characteristics of effluents obtained from the leaching of

similar source material. Therefore, these measures are adequate predictors of AD when applied to sulfide-bearing Ocoee rocks in the study area.

Conclusions resulting from the field leaching tanks and encapsulation site investigation are as follows:

1. Field leaching models featuring lime and limestone treatment variations have leachate compositions similar to actual encapsulation site effluents.
2. Field-scale models featuring variations of present encapsulation techniques show that separate reductions in the quantity of the limestone aggregate layer by 60% and topsoil cover by 50% do not substantially degrade water quality.
3. A basal position of the limestone aggregate layer within a roadfill model is critical for establishing rapid recovery of effluents to acceptable quality.
4. Statistical modeling indicates that variations in rainfall amounts or length of time between flushings do not significantly affect leachate quality.
5. Seasonal temperature variations seemed to have a significant effect on field leaching test effluent quality, especially unencapsulated materials.
6. The addition of interlayer agricultural lime between layers of sulfidic material is the single most influential factor affecting leachate quality.
7. The addition of interlayer lime promotes the development of neutral conditions within the the body of a fill. These conditions allow the formation of secondary minerals to occur within the fill body rather than along particle-solution boundaries within the limestone underblanket. This, in turn, allows the limestone aggregate layer to remain uncoated and intact and can serve effectively to induce additional alkalinity to discharge waters.
8. The quality of surface water obtained from the base of sulfidic roadcuts on TNFLH 1-1(14) and Hemlock Knob indicates that these exposures continue to generate substantial AD after approximately 10 years.
9. Current FHWA encapsulation technology seems to be a long-term method to prevent AD in highway construction settings. A more economical variation, however, might include reductions in the limestone underblanket and/or amount of topsoil cover.

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LIST OF REFERENCES

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APPENDICES

APPENDIX A

ANALYTICAL DATA FILES

Table A-1. FHWA Project Sampling Point Summary

Item	Description
Lab Leaching Tests:	
HK-1:	Constructed from materials from crest of Hemlock Knob approximately two miles east of TNFLH 1-1(14).
HK-1:	Constructed from materials from crest of Hemlock Knob approximately two miles east of TNFLH 1-1(14).
MGQ:	Constructed from materials from road base source quarry approximately one mile west of TNFLH 1-1(14).
Comp A:	Constructed from materials along 959+30 - 969+30 interval on TNFLH 1-1(14).
Comp B:	Constructed from materials along 988+00 - 990+50 interval on TNFLH 1-1(14).
Comp C:	Constructed from materials along 996+50 - 998+50 interval on TNFLH 1-1(14).
Comp D:	Constructed from materials along 1048+00 - 1058+00 interval on TNFLH 1-1(14).
Field Leaching Tests:	
FT-0:	Empty tank for the collection of rainwater
FT-1:	Control model containing untreated material from 998+00 - 990+50.
FT-2:	Original model based on encapsulation site design, full compliment of basal aggregate and topsoil.
FT-3:	Model containing a full compliment of limestone aggregate and topsoil, with the buffer layer placed at the top of the model.
FT-4:	Model featuring a 30% reduction in the amount of basal limestone aggregate.
FT-5:	Model featuring a 50% reduction in the amount of basal limestone aggregate.
FT-6:	Model featuring a 50% reduction in the amount of topsoil cover, full compliment of basal limestone aggregate.
FT-7:	Model featuring a buffer layer composed of approximately 500 gm of NaCO ₃ briquettes and a full compliment of topsoil.
FT-8:	Untreated material from a U.S. Forest Service access road containing coarsely crystalline pyrite. Source outcrop was upgradient from STB-3.

Table A-1 (Continued)

Item	Description
Surface Water Points on TNFLH 1-1(14):	
F-996+50-UD:	Mouth of fill underdrain at 996+50.
HK-SR:	Surface drainage ditch near crest of Hemlock Knob approximately two miles east of TNFLH 1-1(14).
A-OR:	Outcrop runoff along roadcut face at 960+00 on TNFLH 1-1(14).
A-SR:	Surface drainage ditch along base of roadcut at 996+00 on TNFLH 1-1(14).
C-OR:	Outcrop runoff along roadcut face at 996+50 on TNFLH 1-1(14).
D-SR:	Surface drainage ditch along base of roadcut at 1052+00 on TNFLH 1-1(14).

Table A-2. Detection Limit Summary and Key for Data Files

Item	Description
*Detection Limits:	
Sulfate	1.0 mg/L
Total iron	2.5 mg/L
Manganese	1.0 mg/L
Copper	1.5 mg/L
Zinc	0.50 mg/L
Aluminum	42 ug/L
Key:	
ND	Not Determined.
Input (mL)	Input volume into lab leaching columns.
Effluent (mL)	Effluent volume from lab leaching columns after 24 hours of drainage.
Vol (mL)	Volume of effluent collected from field tanks.
RF Amt. (in.)	Rainfall amount that the field tanks received between collections or, pertaining to field samples, the amount of rainfall five days prior to the collection date.

* Sources:
 Varian Techtron Pty. Ltd., 1979
 Experimental Determinations

Table A-3. QA Summary and Accuracy of Analytical Methods

Parameter	Avg. Absolute Deviation	Max. Absolute Deviation	Comments
pH	--	--	Instruments calibrated with standards prior to each set of analyses. Refer to Table A-4 for a comparison to commercial standards.
Conductivity	--	--	Instrument calibrated with standards if necessary prior to each set of analyses. Refer to Table A-4 for comparison to commercial standards.
Sulfate	-2.4% to +6.4%	-4.0% to +15%	Accuracy based on values of 33 standard analyses. One standard run during each set of analyses.
Acidity	--	--	Refer to Table A-4 for comparison to commercial water standards.
Aluminum: Colorimetric Method	-3.5% to +5.4%	-16% to +28%	Accuracy based on 33 standard analyses. One to two standards run with each analytical batch. Calibration curve checked and recalculated, if necessary, on a daily basis. Standards used to recalculate calibration curves are not included in the accuracy estimates.
CRA Method	-3.2% to +2.6%	-12% to +10%	Accuracy based on 37 standard analyses. One standard run to every five samples. See comments for colorimetric method pertaining to calibration standards.
Iron	-4.0% to +2.8%	-12% to +9%	Based on first 100 standards analyzed during AA runs. One standard run to every five samples. See comments for Al colorimetric method pertaining to calibration standards.

Table A-3. (Continued)

Parameter	Avg. Absolute Deviation	Max. Absolute Deviation	Comments
Manganese	-5.4% to +3.7%	-14% to +12%	Based on first 100 standards analyzed during AA runs. One standard run to every samples. See comments for Al colorimetric method pertaining to calibration standards.
Copper	-9.9% to +5.7%	-28% to +12%	Accuracy based on a population of 91 standards. One standard run to every five samples. See comments for Al colorimetric method pertaining to calibration standards.
Zinc	-2.7% to +4.2%	-8% to +8%	Accuracy based on a population of 86 standard analyses. One standard run to every five samples. See comments for Al colorimetric method pertaining to calibration standards.

Table A-4. Analytical Results of the Present Study for Environmental Resource Associates (ERA) Multi-Element Water Standards

Parameter	Value	ERA Value	ERA Advisory Range
pH	9.0	9.1	8.9 - 9.3
Conductivity (Micromhos)	1680	1680	1580 - 1780
Sulfate (mg/L)	172	164	147 - 181
Acidity (mg/L)	-179	-165	-155 - -175
Al (ug/L) Colorimetric Method	119	119	89 - 149
CRA Method	112	119	89 - 149
Iron (mg/L)	14.1	13.1	9.8 - 16.4
Manganese (mg/L)	16.8	16.1	12.1 - 20.1
Copper (mg/L)	10.5	11.0	8.2 - 13.8
Zinc (mg/L)	13.9	18.3	13.7 - 22.9

Table A-5. Precipitation Summary, Stratton Gap Station

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Total	1987	1988	
1987																																			
AUG	ND	ND	ND	ND	0.45	0.13	0.00	1.40	0.70	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.10	0.05	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	3.35	3.35	
SEPT	0.00	0.00	0.00	0.00	0.02	0.58	0.25	0.00	0.00	0.00	0.20	1.50	0.20	0.05	0.00	0.00	0.17	0.00	0.45	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.52	0.02	4.98	4.98	
OCT	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.15	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.08	0.00	0.02	1.43	1.43	
NOV	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.36	0.00	0.12	0.00	0.00	0.05	0.00	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.05	0.02	0.01	2.10	2.10		
DEC	0.00	0.00	0.18	0.00	0.00	0.23	0.00	0.00	0.05	0.03	0.37	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.07	0.00	0.00	0.00	1.06	0.09	0.65	1.27	0.89	0.00	0.16	0.05	5.64	5.64	
1988																															TOTAL	17.50	17.50		
JAN	0.55	0.00	0.06	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.18	0.05	0.33	0.32	0.09	0.41	0.62	0.03	0.90	0.32	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.07	0.43	0.00	0.00	4.48		
FEB	0.00	1.07	0.00	0.85	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.35	0.22	0.15	0.00	0.00	0.05	0.01	0.00	0.02	0.01	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	2.82		
MAR	0.00	0.00	0.00	0.20	0.05	0.00	0.00	0.00	0.00	0.17	0.83	0.22	0.69	0.01	0.00	0.13	0.00	0.00	0.09	0.07	0.00	0.00	0.00	0.00	0.00	0.29	0.05	0.00	0.00	0.35	0.00	0.00	3.15		
APR	0.64	0.00	0.34	0.05	0.00	0.66	0.01	0.13	0.00	0.00	0.00	0.50	0.02	0.00	0.18	0.00	0.00	0.62	0.48	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.73		
MAY	0.00	0.00	0.11	1.19	0.04	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.10	0.05	0.76	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.99		
JUN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.55	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.65		
JUL	0.00	0.15	1.10	0.08	0.08	0.00	0.00	0.00	0.00	0.00	0.20	0.28	0.80	0.36	0.00	0.74	0.00	0.10	0.00	0.00	2.45	0.25	0.00	0.00	0.00	0.00	0.40	0.00	0.00	0.00	0.00	0.00	7.04		
AUG	0.02	0.18	0.00	2.37	0.78	0.04	0.00	0.00	0.32	0.63	0.50	0.00	0.00	0.00	0.00	0.00	0.00	1.65	0.60	0.00	0.35	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.06	1.58	9.62	3.35		
SEPT	0.02	0.00	0.65	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.08	1.52	0.00	0.10	0.00	0.00	0.00	0.71	0.01	0.03	0.00	0.00	0.00	0.00	0.00	5.52	4.98		
OCT	0.82	0.92	0.02	0.05	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.05	0.15	0.01	0.05	0.01	0.00	0.00	0.00	0.20	0.00	0.00	0.03	0.27	3.13	1.43	
NOV	0.05	0.00	0.00	1.58	1.20	0.35	0.39	0.00	0.37	0.00	0.07	0.15	0.03	0.00	1.50	0.00	0.00	0.14	0.81	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	1.87	0.00	0.00	0.06	8.76	2.10		
DEC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00	1.40	0.00	0.40	0.16	0.01	0.00	0.03	0.61	0.00	1.20	0.63	4.61	5.64		
1989																															TOTAL	58.50	17.50		
JAN	0.07	0.05	0.29	0.00	0.00	0.22	0.00	1.13	0.03	0.62	0.62	0.84	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.36	0.00	0.00	0.00	0.00	5.47	4.48		
FEB																																0.00	2.82	0.00	
MAR																																0.00	3.15	0.00	
APR																																0.00	3.73	0.00	
MAY																																0.00	2.99	0.00	
JUN																																0.00	2.65	0.00	
JUL																																0.00	7.04	0.00	
AUG																																0.00	3.35	0.00	
SEP																																0.00	4.98	0.00	
OCT																																0.00	5.52	0.00	
NOV																																0.00	8.76	0.00	
DEC																																0.00	2.10	0.00	
																																TOTAL	5.47	5.47	

Table A-6. Analytical Data File for HK-1

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	ND	ND	5.40	500	170	ND	ND	ND	ND	ND	ND
2	ND	ND	4.30	300	120	ND	ND	ND	ND	ND	ND
3	ND	ND	5.20	620	175	ND	ND	ND	ND	ND	ND
4	ND	ND	5.00	450	175	ND	ND	ND	ND	ND	ND
5	ND	ND	4.00	800	175	ND	ND	ND	ND	ND	ND
6	ND	ND	4.40	940	175	ND	ND	ND	ND	ND	ND
7	ND	ND	4.90	1,500	875	ND	ND	ND	ND	ND	ND
8	ND	ND	4.40	800	400	ND	ND	ND	ND	ND	ND
9	175	181	3.10	2,000	1,600	1,147	ND	ND	ND	ND	ND
10	175	195	3.10	1,240	760	609	ND	291.5	1.4	<1.5	19.00
11	175	170	3.40	925	530	ND	360	173.8	<1.0	<1.5	12.80
12	175	184	3.40	820	420	270	ND	125.4	<1.0	<1.5	8.38
13	185	185	3.30	775	420	ND	242	106.6	<1.0	<1.5	7.17
14	180	178	3.30	850	350	251	ND	102.7	<1.0	<1.5	7.10
15	175	177	3.30	875	390	ND	301	117.2	<1.0	<1.5	7.04
16	185	183	3.30	650	330	217	ND	92.8	<1.0	<1.5	5.25
17	180	178	3.30	750	400	ND	349	103.9	<1.0	<1.5	6.19
18	175	175	3.20	750	420	246	ND	96.8	<1.0	<1.5	6.15
19	175	175	3.10	840	ND	273	351	99.6	<1.0	<1.5	6.40
20	175	170	3.20	790	370	264	ND	102.8	<1.0	<1.5	6.16
21	180	175	3.20	850	450	300	236	125.7	<1.0	<1.5	6.50
22	180	176	3.10	850	440	286	ND	104.7	<1.0	<1.5	6.74
23	180	175	3.20	925	420	ND	271	112.8	<1.0	<1.5	6.44
24	170	170	3.20	800	390	302	ND	96.2	<1.0	<1.5	6.62
25	180	176	3.20	925	390	299	562	118.8	<1.0	<1.5	6.63
26	175	176	3.10	760	410	302	ND	110	<1.0	<1.5	7.33
27	175	172	3.20	880	ND	282	286	99.4	<1.0	<1.5	6.80
28	175	163	3.10	900	390	298	ND	100.4	<1.0	<1.5	6.35
29	175	170	3.10	825	340	ND	327	70.3	<1.0	<1.5	6.43
30	180	180	3.10	880	ND	278	ND	86	<1.0	<1.5	6.92

Table A-6. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/l	Al ug/L	Fe mg/L	Mn mg/l	Cu mg/L	Zn mg/L
31	180	167	2.90	1,010	420	376	528	125	<1.0	<1.5	6.92
32	175	164	3.10	1,025	440	394	ND	134.7	<1.0	<1.5	7.12
33	180	167	2.90	1,000	440	390	512	123.3	<1.0	<1.5	7.24
34	180	177	3.00	1,120	470	430	ND	139	<1.0	<1.5	7.55
35	180	61	2.80	1,160	ND	ND	486	69.3	<1.0	<1.5	7.58
36	180	170	2.90	1,220	520	474	ND	136.4	<1.0	<1.5	8.40
37	180	173	2.90	1,230	560	ND	335	162.4	<1.0	<1.5	8.38
38	180	161	3.00	1,115	440	388	ND	116.6	<1.0	<1.5	7.99
39	170	159	3.00	1,120	470	ND	398	101.9	<1.0	<1.5	8.74
40	175	171	2.70	980	430	416	ND	99.3	<1.0	<1.5	1.53
41	180	142	2.80	780	440	ND	355	72	<1.0	<1.5	7.40
42	175	153	3.00	450	520	431	ND	145.5	<1.0	<1.5	9.31
43	175	155	2.80	1,320	430	ND	694	83.1	<1.0	<1.5	8.07
44	180	167	2.80	1,260	420	345	ND	70.9	<1.0	<1.5	8.66
45	180	168	2.70	1,170	420	ND	ND	63.7	<1.0	<1.5	9.63
46	175	164	2.80	1,335	470	388	ND	98.4	<1.0	<1.5	8.55
47	175	162	2.70	1,475	ND	406	565	104.4	<1.0	<1.5	8.77
48	180	162	2.70	1,325	410	319	ND	49.7	<1.0	<1.5	7.26
49	180	175	2.70	1,275	ND	851	1683	74.5	<1.0	<1.5	6.83
50	175	186	2.70	1,310	420	328	ND	85.8	<1.0	<1.5	6.97
51	180	170	2.70	1,375	390	314	15712	60.4	<1.0	<1.5	7.77
52	160	177	2.70	1,425	480	380	ND	100.4	<1.0	<1.5	7.00
53	190	176	2.70	1,360	380	305	1395	50.5	<1.0	<1.5	6.23

Table A-7. Analytical Data File for HK-2

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	ND	ND	4.50	325	150	ND	ND	ND	ND	ND	ND
2	ND	ND	5.70	230	115	ND	ND	ND	ND	ND	ND
3	ND	ND	5.80	250	150	ND	ND	ND	ND	ND	ND
4	ND	ND	5.30	310	150	ND	ND	ND	ND	ND	ND
5	ND	ND	4.90	300	175	ND	ND	ND	ND	ND	ND
6	ND	ND	2.00	7,000	650	ND	ND	ND	ND	ND	ND
7	ND	ND	6.20	7,250	270	ND	ND	ND	ND	ND	ND
8	325	330	6.80	1,075	640	103	308	ND	ND	ND	ND
9	300	323	5.40	490	320	60	ND	ND	ND	<1.5	2.03
10	305	320	4.90	410	170	39	208	21.6	<1.0	<1.5	1.31
11	300	314	5.90	240	102	ND	ND	11.5	<1.0	<1.5	<0.74
12	300	330	5.70	200	98	13	387	6.7	<1.0	<1.5	0.62
13	310	316	5.40	180	86	12	335	4.9	<1.0	<1.5	<0.50
14	305	312	5.60	173	70	12	350	5.5	<1.0	<1.5	<0.50
15	300	312	5.40	140	64	8	234	4.3	<1.0	<1.5	<0.50
16	310	308	5.50	138	64	14	442	4.5	<1.0	<1.5	<0.50
17	310	307	5.60	135	64	10	319	4.3	<1.0	<1.5	<0.50
18	305	318	5.40	125	56	15	275	3.3	<1.0	<1.5	<0.50
19	305	305	5.70	121	65	15	422	4	<1.0	<1.5	<0.50
20	305	311	5.20	125	48	16	199	4.5	<1.0	<1.5	<0.50
21	300	296	5.90	121	60	15	ND	4.9	<1.0	<1.5	<0.50
22	300	306	5.20	107	52	14	212	5	<1.0	<1.5	<0.50
23	300	297	6.00	104	52	49	ND	3.9	<1.0	<1.5	<0.50
24	300	304	6.00	110	56	4	188	4.2	<1.0	<1.5	<0.50
25	305	306	5.70	114	48	6	ND	3	<1.0	<1.5	<0.50
26	305	310	5.60	112	50	6	131	<2.5	<1.0	<1.5	<0.50
27	305	310	5.70	128	50	39	ND	<2.5	<1.0	<1.5	<0.50
28	310	315	5.80	119	44	4	320	<2.5	<1.0	<1.5	<0.50
29	305	313	6.00	116	ND	0	ND	<2.5	<1.0	<1.5	<0.50
30	300	311	6.00	122	54	22	304	<2.5	<1.0	<1.5	<0.50

Table A-7. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
31	305	315	6.00	133	53	22	ND	<2.5	<1.0	<1.5	<0.50
32	300	310	6.20	123	50	16	122	<2.5	<1.0	<1.5	<0.50
33	300	317	5.50	200	52	22	ND	<2.5	<1.0	<1.5	<0.50
34	305	313	5.70	128	48	24	135	<2.5	<1.0	<1.5	<0.50
35	305	315	6.00	121	46	18	ND	<2.5	<1.0	<1.5	<0.50
36	305	203	5.80	121	44	21	158	<2.5	<1.0	<1.5	<0.50
37	305	311	6.00	105	40	18	ND	<2.5	<1.0	<1.5	<0.50
38	305	301	6.00	107	44	18	161	<2.5	<1.0	<1.5	<0.50
39	305	306	6.20	94	37	22	ND	<2.5	<1.0	<1.5	<0.50
40	305	304	6.10	82	36	24	91	<2.5	<1.0	<1.5	<0.50
41	305	301	5.90	153	39	10	ND	<2.5	<1.0	<1.5	<0.50
42	290	289	6.20	94	38	7	91	<2.5	<1.0	<1.5	<0.50
43	305	310	5.80	90	34	10	ND	<2.5	<1.0	<1.5	<0.50
44	310	302	6.00	93	35	7	ND	<2.5	<1.0	<1.5	<0.50
45	330	324	6.00	101	38	12	ND	<2.5	<1.0	<1.5	<0.50
46	325	167	6.00	99	ND	ND	54	<2.5	<1.0	<1.5	<0.50
47	310	287	5.90	95	38	9	ND	<2.5	<1.0	<1.5	<0.50
48	300	305	5.80	96	37	16	89	<2.5	<1.0	<1.5	<0.50
49	300	324	5.70	97	39	8	ND	<2.5	<1.0	<1.5	<0.50
50	305	305	5.60	98	34	10	51	<2.5	<1.0	<1.5	<0.50
51	300	301	5.80	105	41	10	ND	3.5	<1.0	<1.5	<0.50
52	300	304	6.10	88	33	7	<42	<2.5	<1.0	<1.5	<0.50

Table A-8. Analytical Data File for MGQ

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	ND	ND	6.60	150	30	ND	ND	ND	ND	ND	ND
2	ND	ND	6.70	118	18	ND	ND	ND	ND	ND	ND
3	ND	ND	5.80	123	18	ND	ND	ND	ND	ND	ND
4	ND	ND	7.00	100	19	ND	ND	ND	ND	ND	ND
5	200	196	7.50	520	ND	-32	ND	ND	ND	ND	ND
6	195	190	7.20	240	78	ND	ND	<2.5	<1.0	<1.5	<0.50
7	175	170	7.40	180	ND	ND	ND	<2.5	<1.0	<1.5	<0.50
8	175	160	7.30	155	ND	-47	ND	<2.5	<1.0	<1.5	<0.50
9	170	290	7.80	60	2	ND	ND	<2.5	<1.0	<1.5	<0.50
10	200	186	7.20	138	20	ND	ND	<2.5	<1.0	<1.5	<0.50
11	150	204	7.30	132	ND	-42	ND	<2.5	<1.0	<1.5	<0.50
12	180	193	7.20	115	ND	-42	ND	<2.5	<1.0	<1.5	<0.50
13	180	>250	8.20	50	ND	-19	ND	<2.5	<1.0	<1.5	<0.50
14	185	177	7.00	108	3	ND	ND	<2.5	<1.0	<1.5	<0.50
15	180	185	7.20	116	ND	-33	ND	<2.5	<1.0	<1.5	<0.50
16	180	177	7.50	113	ND	-41	ND	<2.5	<1.0	<1.5	<0.50
17	180	184	7.20	123	ND	-44	ND	<2.5	<1.0	<1.5	<0.50
18	175	188	7.20	116	ND	-42	ND	<2.5	<1.0	<1.5	<0.50
19	185	183	7.20	115	ND	ND	ND	<2.5	<1.0	<1.5	<0.50
20	180	182	8.00	113	ND	-37	ND	<2.5	<1.0	<1.5	<0.50
21	185	210	7.90	107	ND	ND	54	<2.5	<1.0	<1.5	<0.50
22	180	181	7.50	108	ND	-40	ND	<2.5	<1.0	<1.5	<0.50
23	185	188	7.60	117	12	ND	ND	<2.5	<1.0	<1.5	<0.50
24	190	183	7.20	117	ND	-37	ND	<2.5	<1.0	<1.5	<0.50
25	180	184	7.60	130	ND	ND	49	<2.5	<1.0	<1.5	<0.50
26	185	181	7.60	117	ND	-42	ND	<2.5	<1.0	<1.5	<0.50
27	180	181	7.60	127	ND	-34	137	<2.5	<1.0	<1.5	<0.50
28	185	182	7.80	129	ND	-10	<42	<2.5	<1.0	<1.5	<0.50
29	185	181	8.40	125	ND	-48	<42	<2.5	<1.0	<1.5	<0.50

Table A-8. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
30	185	190	8.20	142	ND	-50	ND	<2.5	<1.0	<1.5	<0.50
31	180	183	7.80	142	11	ND	<42	<2.5	<1.0	<1.5	<0.50
32	180	178	7.60	135	ND	-36	ND	<2.5	<1.0	<1.5	<0.50
33	180	167	7.70	140	BD	ND	66	<2.5	<1.0	<1.5	<0.50
34	190	179	8.10	126	ND	-40	ND	<2.5	<1.0	<1.5	<0.50
35	180	180	8.00	124	12	ND	60	<2.5	<1.0	<1.5	<0.50
36	180	208	7.50	112	BD	-36	ND	<2.5	<1.0	<1.5	<0.50
37	180	180	7.80	107	ND	ND	60	<2.5	<1.0	<1.5	<0.50
38	200	160	8.50	89	ND	-43	ND	<2.5	<1.0	<1.5	<0.50
39	180	187	8.40	125	14	ND	<42	<2.5	<1.0	<1.5	<0.50
40	180	177	7.90	125	ND	-43	ND	<2.5	<1.0	<1.5	<0.50
41	195	179	8.70	120	9	ND	<42	<2.5	<1.0	<1.5	<0.50
42	175	180	7.90	132	3	-45	ND	<2.5	<1.0	<1.5	<0.50
43	190	170	8.70	130	ND	-39	<42	<2.5	<1.0	<1.5	<0.50
44	180	171	8.60	120	11	ND	ND	<2.5	<1.0	<1.5	<0.50
45	175	171	7.60	129	ND	-46	<42	<2.5	<1.0	<1.5	<0.50
46	170	174	8.00	132	12	ND	ND	<2.5	<1.0	<1.5	<0.50
47	180	178	7.40	132	ND	-46	<42	<2.5	<1.0	<1.5	<0.50
48	175	182	8.10	132	12	ND	ND	<2.5	<1.0	<1.5	<0.50
49	180	185	8.40	123	11	-43	65	<2.5	<1.0	<1.5	<0.50

Table A-9. Analytical Data File for Comp A

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	310	290	7.00	200	76	16	181	<2.5	1.3	<1.5	<0.50
2	310	310	6.60	120	56	5	ND	<2.5	<1.0	<1.5	<0.50
3	325	324	5.40	115	52	11	256	<2.5	<1.0	<1.5	<0.50
4	300	>500	5.00	55	<1.0	10	ND	<2.5	<1.0	<1.5	<0.50
5	300	310	4.90	80	34	10	291	<2.5	<1.0	<1.5	<0.50
6	310	308	4.60	82	36	16	289	<2.5	<1.0	<1.5	<0.50
7	300	312	4.50	80	32	14	394	<2.5	<1.0	<1.5	<0.50
8	305	308	4.50	64	34	13	294	<2.5	<1.0	<1.5	<0.50
9	300	304	4.40	62	ND	22	434	<2.5	<1.0	<1.5	<0.50
10	310	307	4.30	63	26	14	ND	<2.5	<1.0	<1.5	<0.50
11	305	313	4.30	62	26	19	998	<2.5	<1.0	<1.5	<0.50
12	305	308	4.20	58	26	17	ND	<2.5	<1.0	<1.5	<0.50
13	310	316	4.20	62	26	17	1,166	<2.5	<1.0	<1.5	<0.50
14	310	316	4.10	66	26	19	ND	<2.5	<1.0	<1.5	<0.50
15	325	308	4.10	65	26	20	1,383	<2.5	<1.0	<1.5	<0.50
16	310	296	4.10	62	26	23	ND	<2.5	<1.0	<1.5	<0.50
17	310	308	4.00	60	22	21	1,628	<2.5	<1.0	<1.5	<0.50
18	300	315	4.10	61	21	22	ND	<2.5	<1.0	<1.5	<0.50
19	310	318	4.10	63	26	22	1,678	<2.5	<1.0	<1.5	<0.50
20	310	321	4.00	62	19	22	ND	<2.5	<1.0	<1.5	<0.50
21	330	317	4.00	48	24	22	1,852	<2.5	<1.0	<1.5	<0.50
22	325	321	4.00	63	24	24	1,810	<2.5	<1.0	<1.5	<0.50
23	310	319	3.80	67	24	26	1,700	<2.5	<1.0	<1.5	<0.50
24	325	313	4.10	65	26	24	ND	<2.5	<1.0	<1.5	<0.50
25	320	317	4.20	58	24	24	1,904	<2.5	<1.0	<1.5	<0.50
26	325	315	4.10	79	21	26	ND	<2.5	<1.0	<1.5	<0.50
27	325	319	3.90	74	26	28	1,901	<2.5	<1.0	<1.5	<0.50
28	325	323	4.10	72	21	26	ND	<2.5	<1.0	<1.5	<0.50
29	320	309	4.00	77	22	ND	2,044	<2.5	<1.0	<1.5	<0.50
30	325	335	4.10	70	21	26	ND	<2.5	<1.0	<1.5	<0.50
31	310	307	4.10	71	21	26	1,914	<2.5	<1.0	<1.5	<0.50

Table A-9. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
32	325	307	3.10	67	18	24	ND	<2.5	<1.0	<1.5	<0.50
33	325	311	4.00	63	20	28	2,248	<2.5	<1.0	<1.5	<0.50
34	300	310	4.10	69	21	22	ND	<2.5	<1.0	<1.5	<0.50
35	325	316	4.00	68	19	23	1,933	<2.5	<1.0	<1.5	<0.50
36	320	312	3.90	67	19	24	ND	<2.5	<1.0	<1.5	<0.50
37	310	318	4.10	68	21	22	2,017	<2.5	<1.0	<1.5	<0.50
38	320	320	4.00	71	20	22	ND	<2.5	<1.0	<1.5	<0.50
39	320	296	4.00	71	21	22	1,697	<2.5	<1.0	<1.5	<0.50
40	300	296	3.80	71	22	22	ND	<2.5	<1.0	<1.5	<0.50
41	300	307	3.60	70	19	23	1,757	<2.5	<1.0	<1.5	<0.50
42	310	324	3.70	73	21	22	ND	<2.5	<1.0	<1.5	<0.50
43	305	>500	3.50	30	ND	ND	ND	ND	ND	ND	ND
44	300	295	4.30	63	19	21	ND	<2.5	<1.0	<1.5	<0.50
45	300	300	4.00	66	19	21	1,302	<2.5	<1.0	<1.5	<0.50

Table A-10. Analytical Data File for Comp B

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	280	290	4.30	2,100	1,700	796	131	ND	ND	ND	ND
2	275	285	4.10	725	600	126	ND	47.3	3.7	<1.5	1.28
3	275	246	4.00	690	340	93	881	34.7	2.9	<1.5	1.15
4	275	279	4.20	675	320	79	ND	35.6	2.7	<1.5	1.23
5	260	284	4.20	625	320	80	645	31.4	2.6	<1.5	1.24
6	275	288	3.90	650	290	80	ND	28.1	2.5	<1.5	1.20
7	280	284	4.00	625	292	73	2,028	27.1	2.5	<1.5	1.22
8	280	290	4.00	490	245	67	ND	22.7	2.2	<1.5	1.10
9	ND	284	4.00	450	251	68	2,314	23.4	2.1	<1.5	1.00
10	280	270	4.00	460	256	62	ND	18.6	2.1	<1.5	0.95
11	280	284	3.70	475	248	61	3,044	12.7	2	<1.5	0.92
12	275	276	3.90	430	240	52	ND	12.8	1.9	<1.5	0.84
13	280	284	3.80	450	236	58	1,935	13.1	1.9	<1.5	0.81
14	275	284	3.80	425	220	54	ND	11.2	1.9	<1.5	0.81
15	280	286	3.60	400	228	50	2,059	10.7	1.7	<1.5	0.71
16	275	266	3.70	390	196	49	ND	9.2	1.6	<1.5	0.65
17	275	290	3.60	350	192	46	1,997	<2.5	1.6	<1.5	0.61
18	280	288	3.80	390	208	52	ND	9.2	1.6	<1.5	0.73
19	290	285	3.70	360	168	44	1,022	6.8	1.3	<1.5	0.51
20	275	287	3.60	380	172	47	ND	6.7	1.4	<1.5	0.55
21	275	286	3.70	310	166	40	2,218	4.6	1.3	<1.5	0.50
22	275	285	3.70	350	160	46	ND	2.8	1.2	<1.5	0.51
23	280	285	3.50	375	172	52	2,205	7.3	1.3	<1.5	0.56
24	290	287	3.80	400	188	54	ND	10.2	1.4	<1.5	0.66
25	275	287	3.80	380	160	54	2,977	8.7	1.3	<1.5	<0.50
26	290	291	3.80	410	184	60	ND	9.4	1.2	<1.5	0.58
27	ND	285	3.80	390	168	62	2,329	9.3	1.3	<1.5	<0.50
28	290	280	3.70	360	160	56	ND	5.4	1.2	<1.5	0.56
29	290	276	3.70	465	156	53	2,293	9.3	1	<1.5	<0.50
30	290	291	3.80	340	140	50	ND	7.6	1	<1.5	<0.50
31	280	283	3.80	330	148	56	2,454	8.8	1	<1.5	<0.50

Table A-10. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
32	280	287	3.30	315	148	62	ND	8.6	1	<1.5	<0.50
33	300	306	3.60	360	136	60	3,125	6.8	<1.0	<1.5	<0.50
34	300	278	3.80	355	160	60	ND	11.5	1.1	<1.5	<0.50
35	290	293	3.60	320	136	48	3,104	8.2	<1.0	<1.5	<0.50
36	ND	283	3.60	320	128	53	ND	11.3	<1.0	<1.5	<0.50
37	280	288	3.60	340	132	56	3,533	7.6	<1.0	<1.5	<0.50
38	280	290	3.60	350	144	60	ND	9.6	<1.0	<1.5	<0.50
39	280	297	3.60	360	68	58	2,294	10.6	<1.0	<1.5	<0.50
40	310	311	3.50	305	120	45	ND	6.6	<1.0	<1.5	<0.50
41	260	275	3.40	325	128	50	2,402	7.5	<1.0	<1.5	<0.50
42	275	288	3.30	350	148	56	ND	9.7	<1.0	<1.5	<0.50
43	310	287	2.90	350	148	62	3,380	11.1	<1.0	<1.5	<0.50
44	275	293	3.90	340	156	63	ND	13.6	<1.0	<1.5	<0.50
45	305	302	3.70	300	112	50	2,242	7.4	<1.0	<1.5	<0.50

Table A-11. Analytical Data File for Comp C

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	310	325	3.70	2,400	1,900		934	194	ND	ND	ND
2	310	325	3.60	1,010	650		217	ND	87.2	4.8	<1.5
3	305	320	3.30	1,000	650		181	6,654	52.4	4.7	<1.5
4	300	315	3.60	1,000	520		185	ND	52.3	4.8	<1.5
5	300	318	3.50	975	500		171	ND	50.1	4.8	<1.5
6	315	316	3.10	1,175	490		190	ND	11.9	4.7	<1.5
7	310	320	3.10	1,120	560		206	13,619	11.3	4.9	<1.5
8	300	318	3.20	1,050	570		202	ND	18	4.7	<1.5
9	310	312	3.40	920	530		201	14,495	14.5	4.4	<1.5
10	310	306	3.40	900	490		200	ND	21.9	4.3	<1.5
11	310	320	3.20	1,025	490		198	15,306	14.5	4.1	<1.5
12	315	313	3.40	830	440		182	ND	13.9	3.7	<1.5
13	310	312	3.30	910	470		183	14,041	15.6	3.6	<1.5
14	310	318	3.30	840	430		187	ND	27.4	3.7	<1.5
15	320	312	3.10	850	390		176	17,804	27	3.2	<1.5
16	ND	304	3.30	750	380		171	ND	19.7	2.9	<1.5
17	310	314	3.20	720	340		175	13,782	18	2.8	<1.5
18	320	313	3.20	800	420		190	ND	21	3	<1.5
19	320	326	3.20	710	310		ND	7,386	13.6	2.3	<1.5
20	310	307	3.20	770	320		156	ND	7	2.4	<1.5
21	310	310	3.20	690	300		134	ND	3.6	2.2	<1.5
22	325	323	3.30	720	290		136	ND	2.2	2.2	<1.5
23	320	319	2.90	760	280		158	ND	4.3	2.3	<1.5
24	310	319	3.20	770	320		156	ND	8.1	2.3	<1.5
25	325	305	3.30	660	290		150	ND	11.6	2.2	<1.5
26	320	319	3.20	760	310		150	ND	8.5	2.3	<1.5
27	340	319	3.20	760	280		154	ND	6	2.1	<1.5
28	325	320	3.20	700	280		142	ND	3.1	2	<1.5
29	320	315	3.20	670	270		138	7,386	3.6	1.9	<1.5
30	325	319	3.30	590	220		114	ND	6.6	1.5	<1.5
31	325	313	3.40	560	240		118	ND	7.2	1.5	<1.5

Table A-11. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
32	310	316	3.10	520	228	120	ND	7.9	1.5	<1.5	0.55
33	320	318	3.20	430	180	128	8,271	5.2	1.4	<1.5	0.52
34	285	315	3.30	570	250	119	ND	8.7	1.6	<1.5	0.58
35	300	305	3.20	510	220	95	8,118	5.6	1.4	<1.5	<0.50
36	315	314	3.30	510	210	93	ND	5	1.3	<1.5	<0.50
37	320	316	3.30	520	220	97	7,326	4.6	1.3	<1.5	<0.50
38	320	324	3.30	540	220	99	ND	5.8	1.3	<1.5	<0.50
39	310	312	3.20	550	160	95	5,618	6	1.3	<1.5	<0.50
40	310	314	3.20	460	180	78	ND	2.8	1	<1.5	<0.50
41	280	309	3.30	300	130	49	2,945	<2.5	<1.0	<1.5	<0.50
42	310	324	3.20	420	156	73	ND	4.2	<1.0	<1.5	<0.50
43	320	328	2.30	480	172	84	5,096	4.8	1	<1.5	<0.50
44	305	311	3.60	530	172	84	ND	6	1.1	<1.5	<0.50
45	325	323	3.50	420	140	71	2,760	2.9	<1.0	<1.5	<0.50

Table A-12. Analytical Data File for Comp D

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1	320	>500	4.90	425	135		26	ND	ND	ND	ND
2	310	335	4.60	200	98		20	ND	3.3	1.7	<0.50
3	310	320	4.60	155	72		ND	814	<2.5	<1.0	<0.50
4	320	324	4.60	174	76		19	ND	<2.5	<1.0	<0.50
5	320	323	4.50	165	68		ND	1,170	<2.5	<1.0	<0.50
6	320	322	4.40	165	64		26	ND	<2.5	<1.0	<0.50
7	320	326	4.40	164	62		22	1,942	<2.5	<1.0	<0.50
8	320	324	4.30	150	56		19	ND	<2.5	<1.0	<0.50
9	325	322	4.40	144	60		19	1,442	<2.5	<1.0	<0.50
10	320	323	4.30	142	60		20	ND	<2.5	<1.0	<0.50
11	320	325	4.30	145	ND		21	1,640	<2.5	<1.0	<0.50
12	320	319	4.30	142	14		23	ND	<2.5	<1.0	<0.50
13	325	318	4.20	146	62		21	1,718	<2.5	<1.0	<0.50
14	320	322	4.20	144	56		24	ND	<2.5	<1.0	<0.50
15	320	325	4.10	136	56		27	2,035	<2.5	<1.0	<0.50
16	325	310	4.10	132	54		25	ND	<2.5	<1.0	<0.50
17	320	326	4.00	128	54		24	1,979	<2.5	<1.0	<0.50
18	>316	316	4.10	127	54		24	ND	<2.5	<1.0	<0.50
19	320	326	4.20	124	46		22	1,734	<2.5	<1.0	<0.50
20	315	327	4.20	121	46		23	ND	<2.5	<1.0	<0.50
21	325	327	4.20	120	44		20	1,713	<2.5	<1.0	<0.50
22	325	327	4.30	100	36		18	ND	<2.5	<1.0	<0.50
23	320	323	4.00	113	44		20	1,411	<2.5	<1.0	<0.50
24	325	321	4.30	117	44		20	ND	<2.5	<1.0	<0.50
25	330	327	4.30	128	42		18	1,383	<2.5	<1.0	<0.50
26	330	325	4.30	115	44		20	ND	<2.5	<1.0	<0.50
27	320	321	4.20	115	40		20	1,144	<2.5	<1.0	<0.50
28	310	320	4.30	135	32		18	ND	<2.5	<1.0	<0.50
29	320	323	4.20	102	36		16	1,060	<2.5	<1.0	<0.50
30	325	327	4.30	90	28		16	ND	<2.5	<1.0	<0.50
31	325	318	4.30	84	28		16	905	<2.5	<1.0	<0.50

Table A-12. (Continued)

Cycle	Input (mL)	Effluent (mL)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
32	325	316	3.70	78	27	18	ND	<2.5	<1.0	<1.5	<0.50
33	330	322	4.20	73	26	18	1,037	<2.5	<1.0	<1.5	<0.50
34	306	325	4.30	85	27	18	ND	<2.5	<1.0	<1.5	<0.50
35	325	319	4.30	90	27	14	729	<2.5	<1.0	<1.5	<0.50
36	325	320	4.20	74	24	15	ND	<2.5	<1.0	<1.5	<0.50
37	325	327	4.30	73	24	14	645	<2.5	<1.0	<1.5	<0.50
38	325	330	4.30	75	24	14	ND	<2.5	<1.0	<1.5	<0.50
39	325	316	4.20	78	24	13	801	<2.5	<1.0	<1.5	<0.50
40	325	316	4.00	79	24	12	ND	<2.5	<1.0	<1.5	<0.50
41	310	321	3.70	69	23	12	353	<2.5	<1.0	<1.5	<0.50
42	305	306	4.00	70	23	12	ND	<2.5	<1.0	<1.5	<0.50
43	325	348	4.00	67	23	11	454	<2.5	<1.0	<1.5	<0.50
44	325	331	4.50	65	23	12	ND	<2.5	<1.0	<1.5	<0.50
45	325	327	4.50	62	21	11	304	<2.5	<1.0	<1.5	<0.50

Table A-13. Analytical Data File for FT-0

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
9/16/87	>750	2.95	5.40	16.00	ND	ND	ND	ND	ND	ND	ND
10/3/87	>750	2.18	6.10	16.00	ND	ND	ND	ND	ND	ND	ND
10/17/87	18	0.08	8.70	ND	ND	ND	ND	ND	ND	ND	ND
10/29/87	3,090	1.33	ND	ND	ND	ND	ND	ND	ND	ND	ND
11/14/87	976	0.62	6.40	86.00	ND	ND	ND	ND	ND	ND	ND
11/21/87	>4,100	1.35	6.70	18.00	ND	ND	ND	ND	ND	ND	ND
12/16/87	1,704	1.36	5.30	22.00	<1.0	36	64	<2.5	<1.0	<1.5	<0.50
12/23/87	289	0.26	5.40	24.00	<1.0	15	ND	<2.5	<1.0	<1.5	<0.50
12/28/87	>4,100	3.89	3.70	82.00	<1.0	8	48	<2.5	<1.0	<1.5	<0.50
12/31/87	295	0.21	4.60	9.90	<1.0	9	ND	ND	ND	ND	ND
1/14/88	3,838	1.53	4.50	14.00	ND	12	BD	<2.5	<1.0	<1.5	<0.50
1/18/88	3,845	1.15	4.80	9.80	<1.0	7	45	ND	ND	ND	ND
1/21/88	1,466	1.22	4.90	86.00	<1.0	8	53	<2.5	<1.0	<1.5	<0.50
1/31/88	1,695	1.80	4.50	16.00	<1.0	8	ND	<2.5	<1.0	<1.5	<0.50
2/6/88	4,065	1.92	4.70	10.80	<1.0	8	<42	<2.5	<1.0	<1.5	<0.50
2/16/88	955	0.76	4.40	25.00	<1.0	8	142	<2.5	<1.0	<1.5	<0.50
2/26/88	1,545	0.29	4.30	20.00	<1.0	10	ND	<2.5	<1.0	<1.5	<0.50
3/13/88	>4,100	2.17	5.00	183.00	<1.0	22	49	<2.5	<1.0	<1.5	<0.50
4/5/88	965	2.01	5.70	14.00	<1.0	18	<42	<2.5	<1.0	<1.5	<0.50
4/12/88	2,565	1.30	5.50	18.00	<1.0	21	ND	<2.5	<1.0	<1.5	<0.50
4/21/88	4,000	1.30	5.00	16.50	<1.0	24	<42	<2.5	<1.0	<1.5	<0.50
5/5/88	3,105	1.44	5.60	8.00	<1.0	7	ND	<2.5	<1.0	<1.5	<0.50
5/17/88	121	0.56	4.80	25.00	ND	ND	<42	<2.5	<1.0	<1.5	<0.50
5/26/88	2,135	1.09	4.30	53.00	<1.0	15	ND	<2.5	<1.0	<1.5	<0.50
6/21/88	ND	1.30	4.00	44.00	12	14	106	<2.5	<1.0	<1.5	<0.50
6/29/88	92	0.00	5.10	52.00	ND	ND	ND	ND	ND	ND	ND
7/12/88	>4,100	3.24	6.00	50.00	13	5	ND	<2.5	<1.0	<1.5	<0.50
7/22/88	>1,000	4.70	5.00	18.00	<1.0	8	<42	<2.5	<1.0	<1.5	<0.50
7/29/88	2,560	0.40	5.20	15.00	<1.0	7	ND	<2.5	<1.0	<1.5	<0.50
8/5/88	>4,100	3.40	5.10	23.00	<1.0	7	52	<2.5	<1.0	<1.5	<0.50

Table A-14. Analytical Data File for FT-1

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al mg/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
9/16/87	2,079	1.05	4.50	5,500	4,450	3,185	142.3	1372.7	51.8	4.4	37.01
10/3/87	>750	2.18	4.10	6,000	6,000	3,497	189.2	697.8	97.3	5.9	54.71
10/17/87	39	0.08	4.20	5,434	5,150	3,468	166.9	31	99.4	3.5	72.58
10/29/87	2,472	1.33	2.60	4,868	4,300	3,440	101.6	897.5	69.7	6.4	70.71
11/14/87	222	0.62	3.00	4,300	4,800	3,150	103.1	929.1	101.2	3.7	77.05
12/16/87	2,160	2.71	2.90	4,600	5,400	3,463	186.7	719.2	98.3	3.1	79.61
12/23/87	365	0.26	3.10	5,600	6,400	4,356	180.9	594.9	171.9	2.8	75.05
12/28/87	>4,100	3.89	3.10	2,500	2,300	1,100	66.2	150.7	31.5	<1.5	20.83
12/31/87	658	0.21	3.00	2,200	2,200	394	15.1	23.2	25.9	<1.5	11.72
1/14/88	3,850	1.53	3.30	1,220	1,730	284	17.5	35.6	19.6	<1.5	7.36
1/18/88	3,995	1.15	3.30	1,800	1,260	221	15.4	36.2	10.2	<1.5	4.68
1/21/88	3,985	1.22	3.50	1,650	1,040	132	6.7	7.6	2.5	<1.5	2.67
1/31/88	355	1.80	3.40	1,910	1,150	194	ND	27.5	10.6	<1.5	3.95
2/6/88	>4,100	1.92	3.20	1,410	1,100	148	9	18	9	<1.5	3.52
2/16/88	163	0.76	3.40	1,800	1,200	136	7.6	9.4	10.1	<1.5	3.15
2/26/88	895	0.29	3.60	2,010	1,280	206	14.8	5.5	15.5	<1.5	5.02
3/13/88	>4,100	2.17	3.20	2,400	1,600	596	19.3	78.6	16.2	<1.5	10.18
4/5/88	229	2.01	2.90	3,000	2,050	933	27.5	108.1	48	<1.5	16.42
4/12/88	1,910	1.30	3.20	2,000	1,550	601	27.5	43.8	35.8	<1.5	12.15
4/21/88	1,470	1.30	2.90	1,600	1,800	734	33.9	57.8	36.4	<1.5	13.37
5/5/88	2,530	1.44	2.80	3500	3250	2033	95.1	557.6	29.7	5.3	17.48
5/17/88	73	0.56	2.70	6,200	ND	ND	122.3	707.8	69.9	6.6	40.99
5/26/88	2,225	1.09	2.60	4,900	6,700	3,825	214.5	774.4	89.2	5.9	46.02
6/21/88	ND	1.30	2.50	6,300	9,750	7,487	479.6	2874	116	7.4	45.76
6/29/88	54	0.00	2.50	13,150	ND	ND	ND	ND	ND	ND	ND
7/12/88	>4,100	3.24	2.60	5,700	6,750	4,075	248.1	872	90.2	4.5	38.65
7/22/88	>4,100	4.70	2.80	3,600	3,000	1,518	136.6	151.3	42.6	<1.5	16.59
7/29/88	>4,100	0.40	2.80	1,800	1,600	469	55	35.9	18.4	<1.5	5.54
8/5/88	>4,100	3.40	3.00	1,770	1,100	330	24.9	25.4	12.6	<1.5	3.80

Table A-15. Analytical Data File for FT-2

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
10/3/87	>750	2.18	7.90	1,550	220	-49	<42	<2.5	1.9	<1.5	<0.50
10/17/87	180	0.08	8.00	1,700	260	-42	ND	<2.5	<1.0	<1.5	<0.50
10/29/87	898	1.33	7.50	1,995	91	-43	56	<2.5	<1.0	<1.5	<0.50
11/14/87	80	0.62	6.90	2,250	171	-26	<42	<2.5	<1.0	<1.5	<0.50
11/21/87	2,310	1.35	7.10	1,920	250	-9	68	<2.5	2	<1.5	<0.50
11/28/87	1,084	0.12	7.00	1,680	860	-35	48	<2.5	1.1	<1.5	<0.50
12/16/87	1,718	1.36	7.40	1,650	900	-21	52	<2.5	1	<1.5	<0.50
12/23/87	612	0.26	7.10	1,625	950	10	189	<2.5	<1.0	<1.5	<0.50
12/28/87	>4,100	3.89	7.60	955	510	-5	66	<2.5	<1.0	<1.5	<0.50
12/31/87	985	0.21	7.20	1,075	580	-24	<42	<2.5	<1.0	<1.5	<0.50
1/14/88	3,145	1.53	6.70	590	330	-17	<42	<2.5	<1.0	<1.5	<0.50
1/18/88	3,965	1.15	7.20	540	260	-23	110	<2.5	<1.0	<1.5	<0.50
1/21/88	4,012	1.22	7.20	200	290	-28	185	<2.5	<1.0	<1.5	<0.50
1/31/88	1,380	1.80	7.20	710	330	-18	426	<2.5	<1.0	<1.5	<0.50
2/6/88	3,990	1.92	6.70	275	240	-22	61	<2.5	<1.0	<1.5	<0.50
2/16/88	1,085	0.76	7.00	510	230	-20	138	<2.5	<1.0	<1.5	<0.50
2/26/88	1,405	0.29	7.20	620	280	-26	76	<2.5	<1.0	<1.5	<0.50
3/13/88	>4,100	2.17	7.20	750	300	-18	52	<2.5	<1.0	<1.5	<0.50
3/29/88	275	0.98	7.60	580	230	-18	54	<2.5	<1.0	<1.5	<0.50
4/5/88	945	1.03	7.70	950	470	-18	84	<2.5	<1.0	<1.5	<0.50
4/12/88	1,285	1.30	8.10	990	430	-18	56	<2.5	<1.0	<1.5	<0.50
4/21/88	1,285	1.30	7.10	740	380	-16	<42	<2.5	<1.0	<1.5	<0.50
5/5/88	175	1.44	7.70	840	ND	-43	<42	<2.5	<1.0	<1.5	<0.50
5/17/88	186	0.56	8.20	1,060	490	-38	60	<2.5	<1.0	<1.5	<0.50
5/26/88	129	1.09	8.00	870	390	ND	67	<2.5	<1.0	<1.5	<0.50
6/21/88	ND	1.30	8.00	910	420	-53	55	<2.5	<1.0	<1.5	<0.50
6/29/88	140	0.00	8.20	760	ND	ND	ND	ND	ND	ND	ND
7/12/88	>4,100	3.24	7.50	1,270	570	-26	55	<2.5	1.6	<1.5	<0.50
7/22/88	>4,100	4.70	7.60	660	290	-26	67	<2.5	<1.0	<1.5	<0.50
7/29/88	3,050	0.40	7.40	700	290	-34	83	<2.5	<1.0	<1.5	<0.50
8/5/88	>4,100	3.40	7.80	530	230	-29	96	<2.5	<1.0	<1.5	<0.50

Table A-16. Analytical Data File for FT-3

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
11/21/87	691	3.38	5.60	890	540	112	306	48.5	2.8	<1.5	1.57
12/16/87	1,727	2.17	5.80	2,200	1,980	20	235	39.2	51.9	<1.5	4.17
12/23/87	354	0.26	5.30	2,200	1,900	219	434	25.9	51.9	<1.5	3.98
12/28/87	>4,100	3.89	6.00	1,960	1,400	50	471	4.2	10.6	<1.5	0.76
12/31/87	387	0.21	6.90	1,640	1,150	-7	59	<2.5	3.9	<1.5	<0.50
1/14/88	2,355	1.53	6.70	1,120	720	-5	39	<2.5	2.9	<1.5	<0.50
1/18/88	3,905	1.15	6.90	1,160	640	-5	118	<2.5	2.2	<1.5	<0.50
1/21/88	4,050	1.22	9.20	250	680	-12	62	<2.5	1.7	<1.5	<0.50
1/31/88	1,745	1.80	6.50	1,700	980	9	55	<2.5	2.9	<1.5	<0.50
2/6/88	4,020	1.92	6.90	1,130	640	-13	62	<2.5	1.4	<1.5	<0.50
2/16/88	1,123	0.76	6.80	1,640	960	0	61	<2.5	2.1	<1.5	<0.50
2/26/88	1,220	0.29	6.70	1,560	960	-1	65	<2.5	2.6	<1.5	<0.50
3/13/88	>4,100	2.17	6.60	1,225	560	0	63	<2.5	1.8	<1.5	<0.50
3/29/88	1,605	0.98	7.20	1,225	680	4	66	<2.5	1.6	<1.5	<0.50
4/5/88	665	1.03	7.20	1,800	1,140	14	82	<2.5	3.3	<1.5	<0.50
4/12/88	1,475	1.30	7.10	1,250	760	6	75	<2.5	2.2	<1.5	<0.50
4/21/88	1,690	1.30	7.10	1,030	720	8	74	<2.5	2	<1.5	<0.50
5/5/88	80	1.44	7.20	1,800	ND	ND	75	<2.5	3.5	<1.5	<0.50
7/12/88	3,775	3.24	3.50	1,640	880	98	7370	<2.5	9.3	<1.5	6.13
7/22/88	>4,100	4.70	6.40	920	540	12	74	<2.5	4.8	<1.5	1.56
7/29/88	3,320	0.40	6.70	1,120	540	-5	81	<2.5	3.8	<1.5	0.85
8/5/88	>4,100	3.40	6.80	720	360	2	60	<2.5	2.4	<1.5	0.58

Table A-17. Analytical Data File for FT-4

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
11/21/87	440	2.30	4.10	7,250	4,800		293	721.6	62.3	<1.5	34.70
11/28/87	254	0.12	6.00	2,600	2,200	312	231	39	18.1	<1.5	1.66
12/16/87	674	2.59	6.80	2,800	2,260	318	114	<2.5	7.2	<1.5	<0.50
12/23/87	324	0.26	7.10	2,300	1,950	204	167	<2.5	7.2	<1.5	<0.50
12/31/87	371	4.10	6.90	1,800	1,500	-14	57	<2.5	4.5	<1.5	<0.50
1/14/88	374	1.53	7.70	1,700	1,400	-18	96	<2.5	3.1	<1.5	<0.50
1/18/88	64	1.15	7.40	1,800	ND	ND	ND	ND	ND	ND	ND
1/21/88	3,580	1.22	6.70	650	1,450	-8	78	<2.5	3.8	<1.5	<0.50
1/31/88	1,054	1.80	6.80	1,600	1,350	0	68	<2.5	3	<1.5	<0.50
2/6/88	230	1.92	6.80	2,300	1,350	0	195	<2.5	2.4	<1.5	<0.50
2/16/88	300	0.76	7.30	1,950	1,200	-4	80	<2.5	1.5	<1.5	<0.50
2/26/88	495	0.29	7.30	2,005	1,260	-12	80	<2.5	2	<1.5	<0.50
3/13/88	1,630	2.17	6.80	2,250	1,360	-6	79	<2.5	3.1	<1.5	<0.50
4/12/88	425	3.31	7.70	1,700	1,440	-16	86	<2.5	1.6	<1.5	<0.50
4/21/88	920	1.30	7.40	1,810	1,560	-16	<42	<2.5	2.5	<1.5	<0.50
7/12/88	3,845	3.24	5.10	3300	2,600	141	1672	<2.5	30.6	<1.5	25.58
7/22/88	>4,100	4.70	6.30	1900	1,600	26	165	<2.5	15.9	<1.5	8.78
7/29/88	2,250	0.40	6.60	230	1,750	2	123	<2.5	14.9	<1.5	6.19
8/5/88	>4,100	3.40	6.90	1,500	1,250	-6	93	<2.5	5.8	<1.5	3.76

Table A-18. Analytical Data File for FT-5

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
12/16/87	918	3.33	7.20	2,400	1,840	67	111	<2.5	36	<1.5	<0.50
12/23/87	158	0.26	7.40	2,200	1,660	92	124	<2.5	27.1	<1.5	<0.50
12/28/87	>4,100	3.89	6.90	1,600	1,540	19	141	<2.5	4	<1.5	<0.50
12/31/87	52	0.21	7.40	1,975	1,246	2	ND	ND	ND	ND	ND
1/14/88	950	1.53	7.20	1,760	1,160	-15	70	<2.5	2.8	<1.5	<0.50
1/18/88	2,777	1.15	6.80	1,210	660	-13	55	<2.5	3.1	<1.5	<0.50
1/21/88	930	1.22	7.20	260	880	-16	146	<2.5	15.4	<1.5	<0.50
1/31/88	1,450	1.80	7.10	1,620	940	-6	71	<2.5	2.5	<1.5	<0.50
2/6/88	2,655	1.92	7.10	1,470	880	-26	62	<2.5	2.7	<1.5	<0.50
2/16/88	30	0.76	7.30	1,600	840	-22	ND	ND	ND	ND	ND
2/26/88	1,425	0.29	7.50	1,320	800	-18	78	<2.5	2.2	<1.5	<0.50
3/13/88	3,165	2.17	6.80	1,470	780	-12	90	<2.5	2.1	<1.5	<0.50
3/29/88	185	0.98	6.70	1,400	760	18	78	<2.5	1.8	<1.5	<0.50
4/12/88	520	1.33	7.80	1,630	940	-24	77	<2.5	1.9	<1.5	<0.50
4/21/88	1,280	1.30	7.30	1,280	1,060	-8	64	<2.5	1.9	<1.5	<0.50
7/12/88	1,255	3.24	8.20	3,600	2450	-30	110	<2.5	26	<1.5	5.34
7/22/88	>4,100	4.70	7.00	2,000	1,600	-3	111	<2.5	15.7	<1.5	7.52
7/29/88	2,540	0.40	7.10	2,200	1,600	-17	113	<2.5	12.8	<1.5	3.87
8/5/88	>4,100	3.40	7.00	1,820	1,100	-11	93	<2.5	6.1	<1.5	1.55

Table A-19. Analytical Data File for FT-6

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
11/21/87	832	1.90	6.60	2,250	1,800	-69	361	<2.5	10.8	<1.5	0.54
12/16/87	628	2.71	7.30	2,400	1,490	-10	79	<2.5	5.8	<1.5	<0.50
12/23/87	198	0.26	7.60	2,000	1,720	33	85	<2.5	11	<1.5	<0.50
12/28/87	>4,100	3.89	6.70	2,000	1,780	-6	95	ND	ND	ND	ND
12/31/87	433	0.21	7.50	2,000	1,220	-21	65	<2.5	4.2	<1.5	<0.50
1/14/88	2,413	1.53	7.10	1,800	480	-25	62	<2.5	2.9	<1.5	<0.50
1/18/88	4,025	1.15	7.10	1,830	ND	ND	ND	ND	ND	ND	ND
1/21/88	4,037	1.22	7.50	370	1,040	-20	65	<2.5	1.8	<1.5	<0.50
1/31/88	1,248	1.80	7.60	1,825	1,080	-10	66	<2.5	1.3	<1.5	<0.50
2/6/88	3,260	1.92	7.40	1,240	680	-10	62	<2.5	<1.0	<1.5	<0.50
2/16/88	438	0.76	7.30	1,425	840	-20	59	<2.5	<1.0	<1.5	<0.50
2/26/88	615	0.29	7.40	1,610	960	-14	76	<2.5	1	<1.5	<0.50
3/13/88	3,075	2.17	7.20	1,580	960	-16	74	<2.5	1.4	<1.5	<0.50
3/29/88	905	0.98	7.70	1,550	920	-8	74	<2.5	1.1	<1.5	<0.50
4/12/88	865	1.33	7.80	1,740	1,040	-26	80	<2.5	<1.0	<1.5	<0.50
4/21/88	No Sample	1.30	ND	ND	ND	ND	ND	ND	ND	ND	ND
7/12/88	3650	3.24	8.20	2,200	1240	-53	82	<2.5	12.6	<1.5	6.07
7/22/88	No Sample	4.70	ND	ND	ND	ND	ND	ND	ND	ND	ND
7/29/88	1,650	0.40	7.90	1,800	1,500	-48	59	<2.5	2.3	<1.5	1.46
8/5/88	>4,100	3.40	7.60	1,580	950	-29	62	<2.5	1.5	<1.5	0.88

Table A-20. Analytical Data File for FT-7

Date	Vol. (mL)	RF Amt (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L
12/28/87	>3,875	3.89	10.80	142,000	ND	ND
1/14/88	ND	1.53	10.60	65,000	ND	ND
1/18/88	3,570	1.15	10.70	950,000	ND	ND
1/21/88	4,010	1.22	10.70	920,000	ND	ND
1/31/88	270	1.80	10.60	128,000	ND	ND
2/6/88	4,100	1.92	10.80	410,000	ND	ND
2/16/88	170	0.76	10.70	125,000	ND	ND
2/26/88	NO SAMPLE	0.29	ND	ND	ND	ND
3/13/88	3,540	2.17	10.40	3,000	ND	ND
3/29/88	600	0.98	10.50	101,000	ND	ND
4/12/88	885	1.33	10.60	70,000	ND	ND
4/21/88	450	1.30	10.00	9,000	ND	ND
5/17/88	63	0.56	10.00	170,000	ND	ND
7/12/88	>4,100	3.24	10.30	105,000	ND	ND
7/22/88	>4,100	4.70	10.50	52,500	ND	ND
7/29/88	1,940	0.40	10.50	42,500	ND	ND
8/5/88	>4,100	3.40	10.60	34,000	ND	ND

Table A-21. Analytical Data File for FT-8

Date	Vol. (mL)	RF Amt (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al mg/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
1/21/88	857	1.22	3.40	350	600	430	33.2	81	27.5	<1.5	1.94
1/31/88	440	1.80	3.20	3,100	2,700	738	41.3	18	37.3	<1.5	4.48
2/6/88	2,765	1.92	3.20	2,100	2,450	998	57.6	84	29.2	3.9	4.97
2/16/88	528	0.76	3.10	2,800	2,400	1,114	88.9	32	31	3.9	5.75
2/26/88	400	0.29	3.20	3,400	3,200	1,386	87.8	60	46.5	4.6	8.20
3/13/88	3,030	2.17	2.80	2,500	5,000	2,988	124.2	463	62.1	7.8	13.49
3/29/88	350	0.98	2.80	4,900	4,400	2,852	131.4	390	58.3	7.5	10.92
4/5/88	885	1.03	2.50	6,100	8,500	6,828	222.6	1,385	89.8	12.8	24.11
4/12/88	1,165	1.30	2.70	7,300	9,750	7,740	269.4	1,784	93.5	13.4	27.06
4/21/88	2,190	1.30	2.30	4,300	8,750	7,623	261	1,843	69.8	11.4	23.75
5/5/88	1,310	1.44	2.40	6,000	7,000	6,196	259.9	1,839	51.5	8.9	19.71
5/17/88	401	0.56	2.20	8,100	12,000	10,128	333.2	3,254	93	14.2	32.40
5/26/88	690	1.09	2.00	8,300	19,500	13,778	354.2	5,832	159.3	12.7	29.97
6/21/88	ND	1.30	2.20	8,100	18,500	17,554	459	7,150	112.8	6.9	43.16
6/29/88	272	0.00	2.40	13,300	28,000	ND	472.6	9,509	162.6	8.7	55.34
7/12/88	1,420	3.24	2.40	10,700	21,500	20,750	426.5	7,899	105.8	7.1	32.07
7/22/88	1,065	4.70	2.30	8,600	14,500	11,921	324.9	5,068	57	7	22.50
7/29/88	2,700	0.40	2.10	6,500	8,000	7,333	230.6	2,881	33.5	4.5	8.42
8/5/88	>4,100	3.40	2.20	5,600	7,250	6,085	280.9	2,443	22.5	3.6	6.80

Table A-22. Analytical Data File for F-996+50-UD

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
9/12/87		1.70	6.40	350	61	-133	157	ND	ND	ND	ND
12/28/87		3.96	6.90	1150	520	-165	92	<2.5	8.4	<1.5	<0.50
1/18/88		1.47	6.70	62	470	-96	112	<2.5	5.3	<1.5	<0.50
2/16/88		0.72	6.70	740	280	-108	77	<2.5	2.4	<1.5	<0.50
3/4/88		0.20	7.10	550	180	-108	65	<2.5	2.2	<1.5	<0.50
4/5/88		1.03	6.80	560	152	-118	62	<2.5	1.9	<1.5	<0.50
5/5/88		1.34	7.20	550	156	-114	59	<2.5	1.5	<1.5	<0.50
5/17/88		0.20	6.80	450	108	-120	87	<2.5	1.8	<1.5	<0.50
6/21/88		1.18	6.60	510	108	-159	67	<2.5	1.3	<1.5	<0.50
7/12/88		0.48	7.10	570	ND	-92	81	<2.5	<1.0	<1.5	<0.50

Table A-23. Analytical Data File for HK-SR

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
12/28/87		3.96	3.20	490	158	123	430	7.6	<1.0	<1.5	0.61
3/4/88		0.20	3.30	1060	192	90	4,870	<2.5	1.4	<1.5	0.50
4/5/88		1.03	3.30	900	340	172	910	10.8	3.4	<1.5	1.58
5/5/88		1.34	3.20	630	230	127	10,222	14.9	1.7	<1.5	0.99
5/17/88		0.20	3.50	540	220	ND	5,522	15.6	1.7	<1.5	0.74
7/12/88		0.48	3.40	600	220	139	9,649	23.1	1.3	<1.5	0.59

Table A-24. Analytical Data File for A-OR

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/l	Cu mg/l	Zn mg/L
9/12/87		1.70	2.70	1875	224	701	126	ND	ND	ND	ND

Table A-25. Analytical Data File for A-SR

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
9/12/87		1.70	6.10	160	57	1	331	ND	ND	ND	ND

Table A-26. Analytical Data File for C-OR

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
12/28/87		3.96	2.80	2,100	1,780	1,799	202,400	478	15.1	2.2	6.62
4/12/88		0.63	3.10	660	260	182	783	14.4	1.3	<1.5	1.11

Table A-27. Analytical Data File for D-SR

Date	Vol. (mL)	RF Amt. (in.)	pH	Cond. umhos	SO4 mg/L	Acidity mg/L	Al ug/L	Fe mg/L	Mn mg/L	Cu mg/L	Zn mg/L
3/4/88		0.20	8.10	1,900	55	-114	130	<2.5	1.3	<1.5	<0.50
7/12/88		0.48	8.60	370	53	ND(pH>8)	108	<2.5	<1.0	<1.5	<0.50

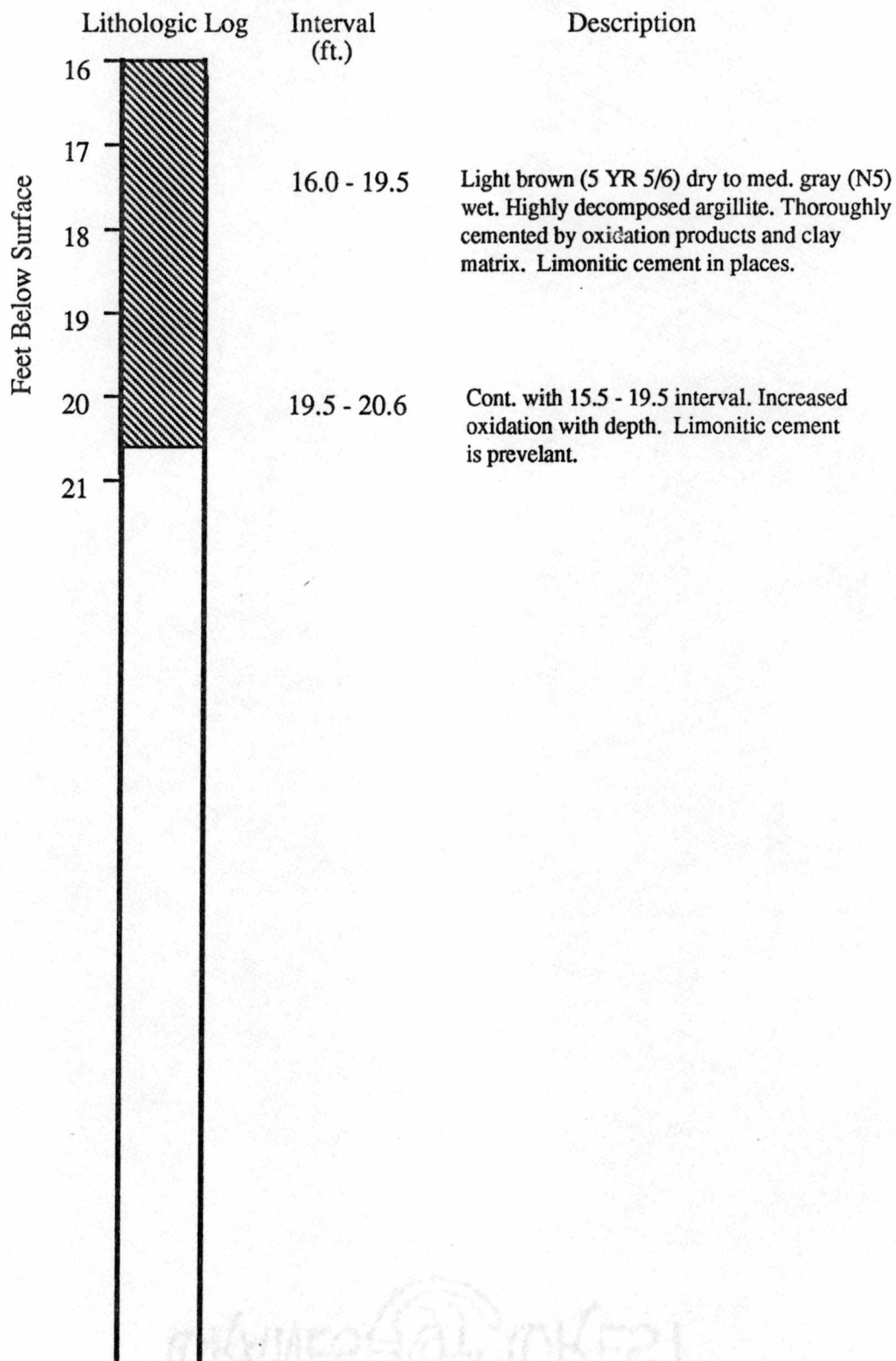
APPENDIX B

BOREHOLE LOGS

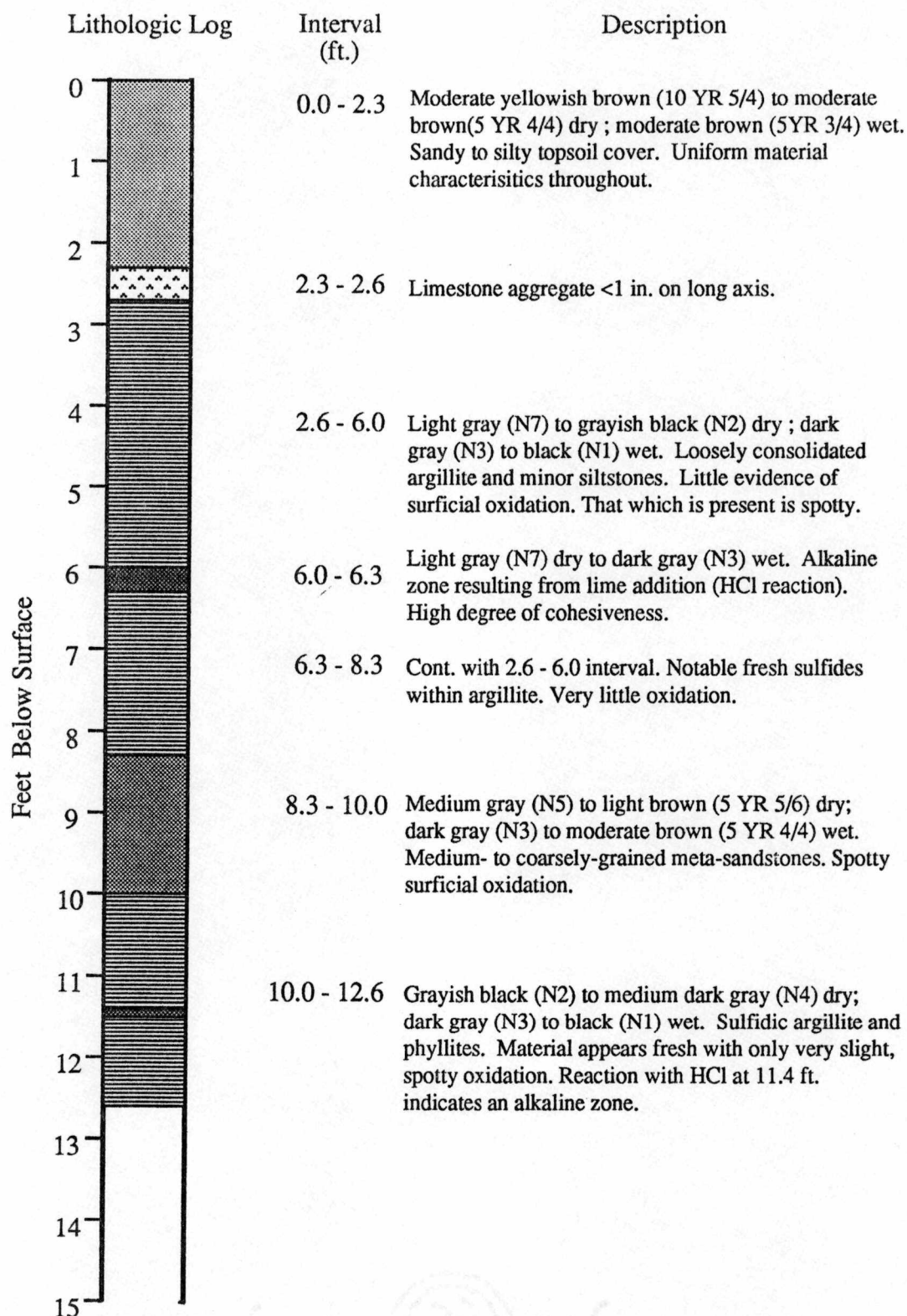
BH-1 and BH-1 Ext. Auger Boring Log

Lithologic Log	Interval (ft.)	Description
0	0.0 - 0.1	Vegetation Mat: Partially to completely decomposed vegetation.
1	0.1 - 2.8	Moderate brown (5YR4/5) to dark yellowish brown (10YR 4/2) dry; 10 YR 4/2 to dark greenish gray (5 YG 4/1) wet. Sandy, non-oxidized topsoil matrix with small argillite chips.
2	2.8 - 3.0	Dark yellowish brown (10 YR 6/6) dry . Friable siltstone fragments.
3	3.0 - 4.6	Medium dark gray (N4) dry to grayish black (N2) wet. Sulfidic argillite fragments. Moderately oxidized surfaces.
4	4.6 - 4.8	Moderate yellowish brown (10YR 5/4) dry to moderate brown (5YR 3/4) wet. Friable, highly weathered meta-sandstone fragments.
5	4.8 - 9.2	Moderate yellowish brown (10YR 5/4) to grayish black (N2) dry; grayish black to brownish black (5YR 2/1) wet. Argillite fragments with minor siltstones. Highly oxidized,, small particles are cemented by secondary products.
6	9.2 - 10.5	Absent interval, hole refusal at 9.2. Begin BH-1 Extention at 10.5.
7	10.5 - 11.0	Cont. with 4.8 - 9.2 interval.
8	11.0 - 11.6	Med. dark gray (N4) dry to greenish black (5 G 2/1) wet. Highly oxidized argillite. Marked increase in cohesiveness. Some unoxidized sulfides at base of interval within argillite clasts.
9	11.6 - 15.5	Absent interval .
10	15.5 - 16.0	Cont. with 11.0 - 11.6 interval. Some increased oxidation. Selenite found at 16.5 ft.

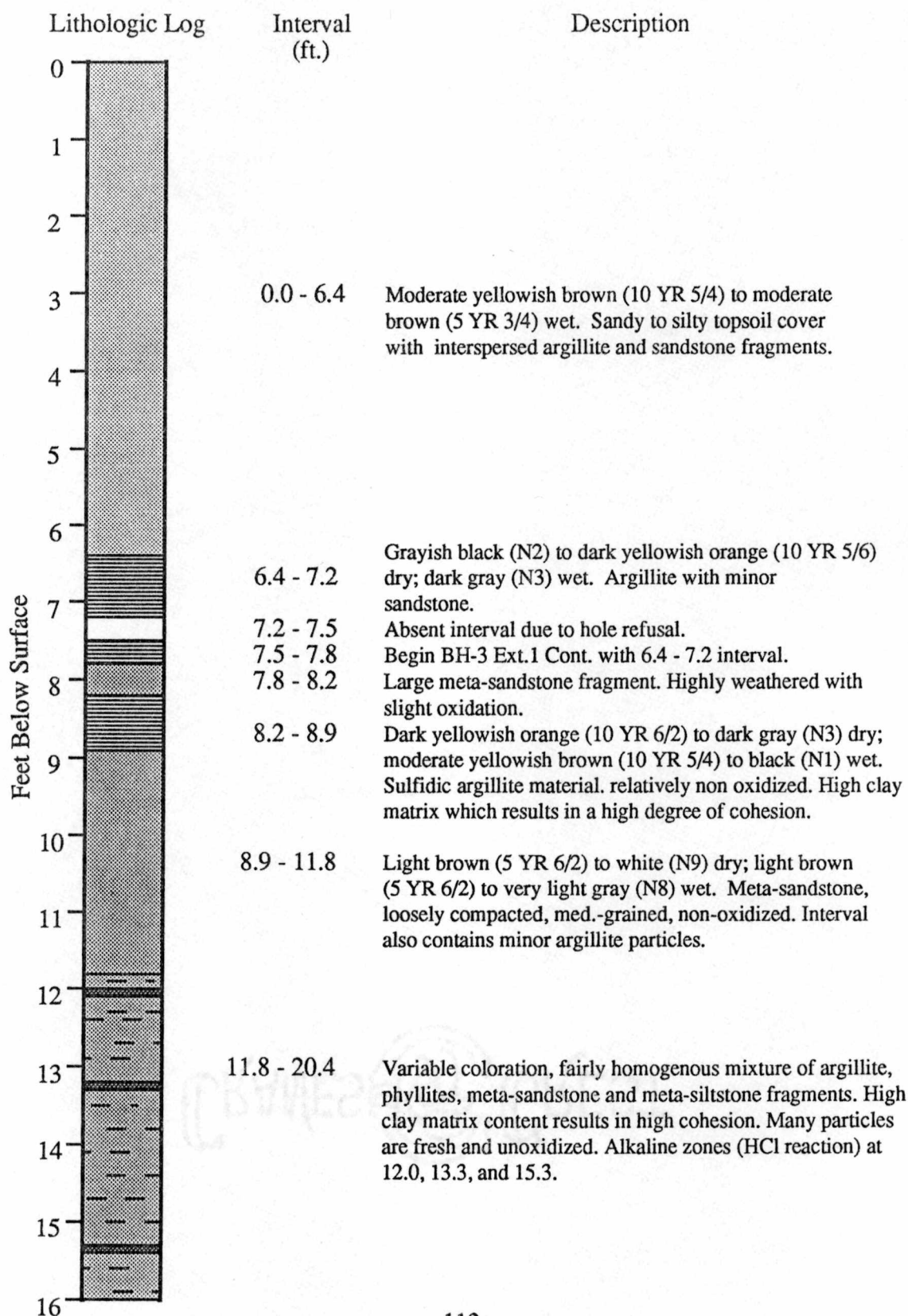
BH-1 and BH-1 Ext. Auger Boring Log (Continued)



BH-2 Auger Boring Log



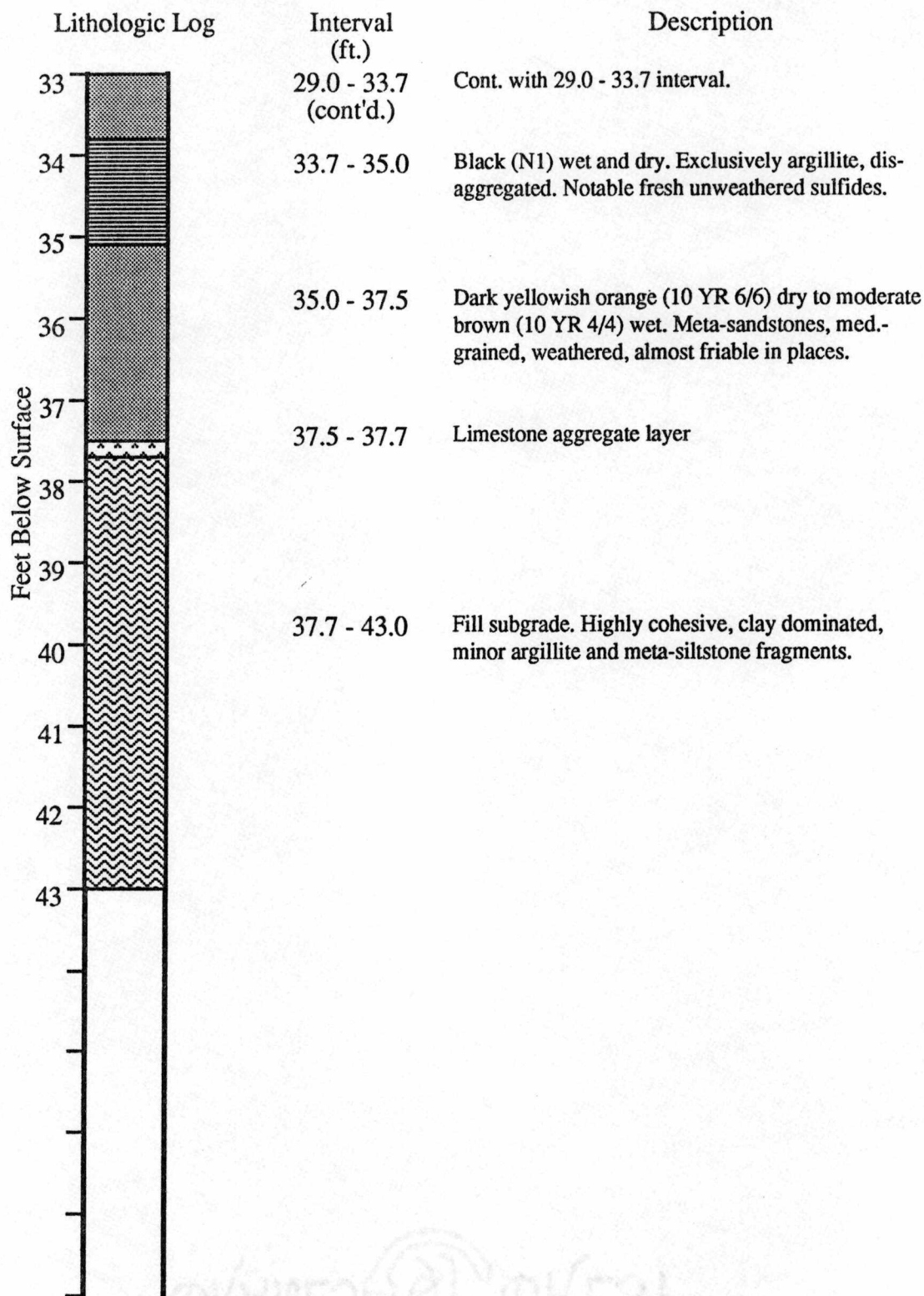
BH-3, BH-3 Ext.1 and BH-3 Ext.2 Auger Boring Log



BH-3, BH-3 Ext.1 and BH-3 Ext.2 Auger Boring Log (Continued)

Lithologic Log	Interval (ft.)	Description
17		
18		
19	11.8 - 20.4 (cont'd.)	Variable coloration, fairly homogenous mixture of argillite, phyllites, meta-sandstone and meta-siltstone fragments. High clay matrix content results in high cohesion. Many particles are fresh and unoxidized.
20		
21	20.4 - 21.5	Interval as same material characteristics as 11.8 - 20.4. Oxidation is more evident. Notable white mineral precipitate in alkaline zone (HCl reaction) at 20.5.
22	21.5 - 22.4	Light olive gray (5 YR 5/2) dry to moderate brown (5 YR 5/4) wet. Small argillite particles. Highly cohesive due to clay matrix. Aklaline zone at 22.3.
23	22.4 - 23.7	Material character same as 11.8 - 20.4. Slight increase in oxidation coatings. Selenite found at 23.0.
24		
25	23.7 - 26.3	Black (N1) to med. gray (N5) to dark yellowish orange (10 YR 6/6) where oxidized both wet and dry. Mostly argillite and meta-siltstones. Material is slightly decomposed. Notably more surface oxidation than above intervals. White crystalline ppt. at several points.
26		
27	26.3 - 28.1	Dark yellowish orange (10 YR 5/4) to brownish gray (5 YR 4/1) wet and dry. Meta-sandstone material, med.-grained, disaggregated. Moderate oxidation coatings.
28	28.1 - 29.0	Absent interval, hole refusal at 28.1
29		
30	29.0 - 33.7	Begin BH-3 Ext.2. Cont. with 26.3 - 28.1 interval.
31		
32		
33		

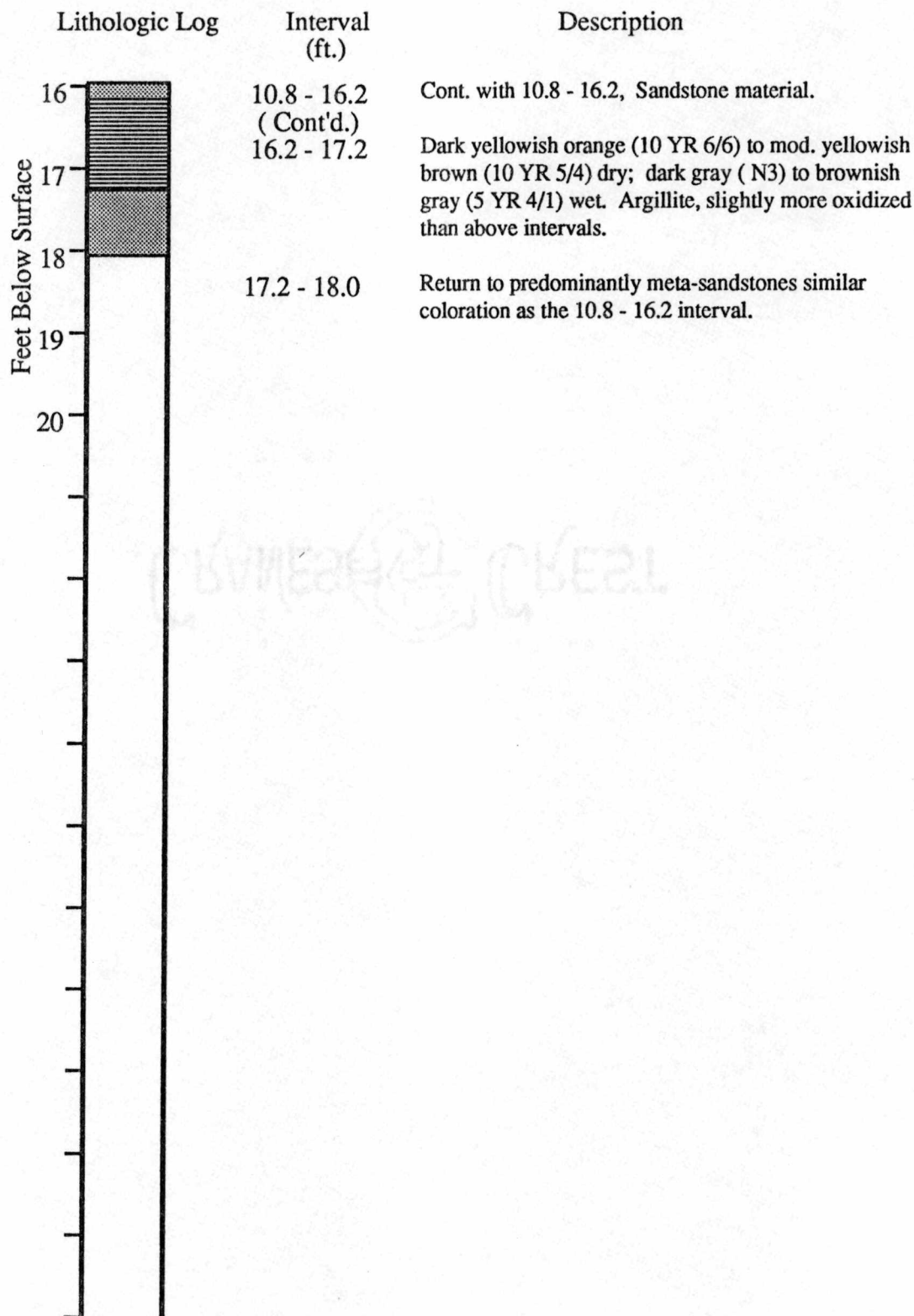
BH-3, BH-3 Ext.1 and BH-3 Ext.2 Auger Boring Log (Continued)



BH-4 Auger Boring Log

Lithologic Log	Interval (ft.)	Description
0	0.0 - 0.2	Limestone aggregate.
0.2	0.2 - 1.1	Moderate brown (5 YR 3/4) dry; grayish brown (5 YR 3/4) wet. Sandy to silty loam topsoil.
1	1.1 - 1.3	Limestone aggregate.
2		
3	1.3 - 4.2	Topsoil interval cont.
4		
4.2	4.2 - 4.4	Limestone aggregate.
5		
6	4.4 - 7.2	Topsoil cont., alkaline zone (HCL reaction) at 6.0.
7		
8	7.2 - 10.3	Moderate brown (5 YR 3/4) dry to grayish brown (5 YR 3/2) wet. Sulfidic meta-sandstones. Med. - grained, spotty oxidation along surfaces, highly weathered, friable in places. Alkaline zones at 8.0 and 10.0
9		
10	10.3 - 10.8	Med. gray (N5) dry to brownish gray (5 YR 4/1) wet. Argillite materials with abundant fresh sulfides.
11		
12	10.8 - 16.2	Return to material characteristics the same as 7.2 - 10.3. Alkaline zones at 12.0 and 14.0. Material is disaggregated with only spotty oxidation.
13		
14		
15		
16		

BH-4 Auger Boring Log (Continued)



VITA

William Kevin Jago was born in Oak Ridge, Tennessee on March 21, 1963. He graduated from Oak Ridge Senior High School in June, 1981. In September 1981 he entered Tennessee Technological University and received his Bachelor of Science in Geology from this institution in December 1985. In September 1986 he entered the University of Tennessee, Knoxville and began study toward a Master of Science degree with a major in Geology. He received this degree in May 1989.

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