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Adsorption isotherm experiments using varying amounts of different apatites and a 10:1 water to soil ratio were used in combination with a thermodynamic model to determine the amount of apatite necessary to treat a given soil. These experiments suggested that soils may be remediated by extrapolating from the isotherm experiments, which equates to 10-50 kg of apatite per treated ton of soil, or less than 1 % by weight. By comparison, grouting techniques can require as much as 30% to 50% by weight, depending upon the porosity of the soil.

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MILESTONE FOUR REPORT: APRIL 1995

APATITE MINERAL FORMULATIONS AND EMPLACEMENT OPTIONS

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EXECUTIVE SUMMARY

The objective of this project is to demonstrate that the incorporation of reactive phosphate materials into contaminated soils stabilizes lead and other heavy metals, preventing leaching into the groundwater. Phosphatic solids, solutions, and slurries react with lead and other heavy metals in contaminated soils and groundwater and cause the precipitation of metal-substituted apatite minerals. Heavy metals sequestered in apatites have great durability and leach resistance that significantly exceeds other chemically stabilized waste forms because the apatite mineral structure is very stable over a wide range of environmental conditions for geologically-long time periods. The results of this project and of previous work by the authors demonstrate that stabilization of contaminated soils and groundwater by apatite has the potential to be an extremely successful and widely applicable remediation strategy for heavy metals and radionuclides.

In the Milestone One Report, we reported the characteristics of various lead-contaminated soils, phosphate-containing materials, and groundwaters to be used in this project, including samples from Keesler Air Force Base, the demonstration site originally intended for this technology, and the Bunker Hill Mining District of Idaho. Lead concentrations in the Keesler samples were found to be relatively low, with soil levels at roughly 100 mg kg^{-1} (ppm) and groundwater in the μg kg^{-1} (ppb) range. Bunker Hill mine tailings and soils contain 1000-4000 mg kg^{-1} (ppm) lead. These soils were selected for subsequent project work.

The Milestone Two Report established the baseline leaching rates of metals from untreated Bunker Hill soils and included some studies of Keesler AFB soils. Without the addition of phosphate, metal concentrations in the leachates from the Bunker Hill soils were in the mg kg^{-1} (ppm) range, well in excess of EPA standards.

The Milestone Three Report showed that in flow-through experiments, the addition of small amounts of a North Carolina apatite to soils reduces the leachate concentrations of lead and other heavy metals to less than 1 μg kg^{-1} (ppb), the detection limit of our analytical tools. Leaching of lead was reduced by three orders of magnitude or more, resulting in leachate samples well below the EPA drinking water standard for lead. Similar results were obtained for cadmium and zinc.

Adsorption isotherm experiments using varying amounts of different apatites and a 10:1 water to soil ratio were used in combination with a thermodynamic model to determine the amount of apatite necessary to treat a given soil. These experiments suggested that soils may be remediated by extrapolating from the isotherm experiments, which equates to 10-50 kg of apatite per treated ton of soil, or less than 1% by weight. By comparison, grouting techniques can require as much as 30% to

50% by weight, depending upon the porosity of the soil.

Some specific highlights of the project to date are:

- All of the concentrations of lead, cadmium, and zinc in the leachate effluents of the flow-through experiments of apatite-treated Bunker Hill soils are below USEPA regulatory limits and most of them are below the detection limits of ICP/MS.
- The change of residence time has no effect on the leaching behaviors of the metals after apatite treatment.
- Using the MINTEQ-A2 geochemical model, thermodynamic predictions for the formations of pyromorphytes (lead apatites) and Hopeite ($Zn_3(PO_4)_2\ 4H_2O$) at less than 1% addition of apatite confirm the molar ratio calculation scenario of $Pb:PO_4$ for pyromorphytes and also confirm the precipitation of Pb and Zn at less than 1% apatite in the adsorption isotherms.
- The kinetics of formation for lead, zinc, and cadmium phosphate complexes are 24 hours or less.

This milestone report evaluates various apatite formulations that could be used in the field for treating contaminated soils. As part of the project, we have tested chemically synthesized and biogenic apatite, mined apatite from deposits in Florida and North Carolina, and the effect of grinding the apatite from a coarse sand consistency to a fine powder. We have treated soils in the laboratory simply by adding dry apatite material to them; however, field emplacement may require the use of solutions or slurries. This report discusses the physical properties of apatite that are relevant to emplacement, including data on the flow characteristics of apatite slurries. Several candidate emplacement strategies, their applicability, and their advantages and disadvantages are also discussed. Finally, treatment costs are estimated for various emplacement scenarios.

1.0 INTRODUCTION

The objective of this project is to develop and demonstrate that phosphatic granules, solutions, and slurries will react with lead and other heavy metals in contaminated soils, causing the precipitation of metal-substituted apatite minerals. Metals sequestered in apatites have great durability and leach resistance that significantly exceeds other chemically stabilized waste forms. Metal-apatite mineral structures are highly insoluble, stable over a wide range of environmental conditions for geologically-long time periods. This is applied research that will lead to advanced technology development that can be implemented to remediate metal and radiologically contaminated soils and groundwater at DoD sites. Potential demonstration sites include Keesler Air Force Base (AFB), Vandenburg AFB, and Kahoolawe Naval Base as well as DOE sites and industrial sites where metal contamination of soils and groundwater is a pervasive problem.

Over 300 apatite (calcium phosphate) minerals exist, incorporating elements from the entire periodic table to replace calcium, phosphate, or hydroxide in the fundamental apatite crystal structure. For instance, the major inorganic constituent of teeth and bones is hydroxyapatite, $Ca_5(PO_4)_3OH$. Fluoridation of drinking water causes fluoride substitution into the hydroxyapatite, producing a less soluble mineral and thereby preventing tooth decay.

Using apatite minerals as a remediation strategy puts to use long recognized geochemical principles. Apatite minerals form naturally and are stable across a wide range of geologic conditions for hundreds of millions of years (Nriagu, 1974; Wright 1990). Wright et al. (1987) investigated the trace element composition of apatite in fossil teeth and bones and in sedimentary phosphorite deposits through geologic time. They found that apatite deposited in seawater adsorbs metals and radionuclides from the seawater to millions of times the ambient concentration. The metals were locked into the apatite structure for up to a billion years with no subsequent desorption, leaching, or exchange, even in the face of subsequent diagenetic changes in the porewater chemistry, pH, or temperatures up to 1000° C.

Apatites are therefore natural concentrators of heavy metals and radionuclides. Apatite deposits in Florida, for example, are known to have accumulated large amounts of uranium, resulting in elevated levels of radon in some homes in that area. These deposits have even been considered as a commercial source of uranium (Eisenbud, 1987). A younger apatite deposit in the U.S. is located in North Carolina, which is mined primarily for fertilizer. Young deposits have had less exposure to metals in the environment and are therefore more reactive because they are more highly carbonated.

Introduction of apatite into a soil that contains mobile metal and other inorganic contaminants provides reactants and nucleating sites, where the metal-enriched apatites precipitate as very insoluble minerals. In this way, water passing through the unsaturated zone or through the water table is purified when it passes by the apatite, which acts like a chemical filter.

The leachability of metals sequestered in apatite is insensitive to pH changes over the range of 2 to 12, and the bioavailability of ingested metals is also limited (Davis et al, 1992; Ruby et al, 1992). The reaction between the apatite and metals is rapid (Ma et al, 1993), and so the treatment is effective immediately, requiring no time for the material to "set up." This project has shown that as little as 1% by weight of apatite could remediate soils.

Addition of apatite would not preclude treatment of other contaminants (volatile organic compounds, etc.). For applications in which both chemical stabilization and physical solidification are desired (in landfills, for example), investigations are underway to combine phosphate and grout or to develop a grout of phosphatic composition for improved stabilization performance.

1.1 MILESTONE ONE

The Milestone One goal was to establish the chemical and mineralogical contents of soils, waters, and phosphatic materials that would subsequently be used in leaching-retardation and sorption-desorption studies from contaminated sites. Chemical analyses of the cationic and anionic compositions and soil and metal mineral speciation were performed on contaminated soils from the following sites: 1) Keesler AFB, Mississippi, a tetraethyl lead (TEL) sludge pit; 2) Keesler AFB, a lead and zinc contaminated landfill; 3) three composite soils with varying levels of metal contamination from the Bunker Hill mining area, Idaho; and 4) two Montana soils with varying levels of metal contamination that serve as National Institute of Standards and Technology (NIST) chemical standards. Chemical analyses were also made on water downgradient from the TEL sludge pit at Keesler AFB. Chemical and mineralogical analyses of several types of phosphatic materials including synthetic hydroxyapatite, natural carbonate fluorapatite from phosphorites, fish and shark teeth, and fish cannery wastes were also performed. The data from the chemical and mineralogical speciation studies were used in the geochemical code MINTEQ to determine the stability relationships of soil minerals under varying conditions.

Lead concentrations in the Keesler AFB samples were found to be relatively low, much lower than expected, with soil levels at roughly 100 mg kg^{-1} (parts per million=ppm) and groundwater in the μg kg^{-1} (parts per billion=ppb) range. These low water concentrations already challenge the detection limits of available analytical methods, Ion Chromatography (IC) for anions and Inductively Coupled Plasma Mass

Spectrometry (ICP/MS) for cations. We anticipate that incorporation of the apatite materials would reduce those concentrations several orders of magnitude, which we would not be able to quantify using the Keesler materials. Therefore, to be able to demonstrate the effectiveness of the remediation technique, we chose to continue our studies using the Bunker Hill mine tailings and soils, which contain 1000-4000 mg kg^{-1} (ppm) of lead.

1.2 MILESTONE TWO

Milestone Two established the baseline contaminant leaching rates from untreated Bunker Hill soils so that comparisons could be made to apatite-treated soils in the Milestone Three Report. Two types of laboratory experiments were performed. In the desorption studies, water was added to small soil samples in centrifuge tubes. The water to soil ratio of 10:1 was selected according to established testing protocols and was useful for studying the basic thermodynamics of the soil system. The concentration of contaminants in solution was monitored over time for up to 336 hours. In the flow-through tests, samples were packed into soil columns or in the Unsaturated Flow Apparatus (the UFA), a new instrument for rapid characterization of unsaturated soils. Water was introduced at the top of the sample, and leachates were collected as a function of the number of pore volumes of solution added.

The results reported for Milestone Two showed that the soil column/UFA leachates from the Bunker Hill soils were in the hundreds of mg kg^{-1} (ppm) range, well in excess of the drinking water standard for lead of 15 $\mu g\ kg^{-1}$ (ppb).

1.3 MILESTONE THREE

The Milestone Three Report established that treatment with apatite reduces leaching of metals from soils. Adsorption isotherm tests and flow-through tests were performed, with small amounts of various apatites added. The results of the adsorption isotherm tests, coupled with modelling by MINTEQ, suggest that these contaminated soils can be remediated by adding as little as 1-5 wt. % apatite. Leachate concentrations for most metals from the flow-through tests were consistently below detection limits of 1 $\mu g\ kg^{-1}$ (ppb). In particular, these experiments demonstrated that apatite can reduce lead leaching by a factor of one thousand, bringing waters that have percolated through soils with 0.4% lead by weight down to below the drinking water standard. Zinc and cadmium, two other hazardous pollutants, are also effectively treated.

1.4 MILESTONE FOUR

This report focuses on apatite formulations that could be used for soil remediation and potential emplacement strategies. Over the course of the project, we have tested mined, chemically synthesized, and several types of biogenic apatite and the effect of grinding the apatite from a coarse sand consistency to a fine powder. In the laboratory, we have incorporated apatite into the treated samples simply by adding dry material to them; however, field emplacement may require the use of solutions or slurries. This report discusses the physical properties of apatite that are relevant to emplacement, including data on the flow characteristics of apatite slurries. Several candidate emplacement strategies are explained, including injection, auguring, horizontal drilling, and excavation and backfilling. Apatite may be placed directly into a contaminated region or downgradient from it, forming a permeable, reactive barrier. The applicability of these various emplacement options and their advantages and disadvantages are discussed. Moreover, the cost of treatment with apatite will vary depending on the emplacement method required. We have included rough estimates of treatment costs in section 5.4, below.

The methodologies used for each type of analytical and experimental procedure and the results of each group of analyses are detailed in the following sections of the report. Information from the Milestone One Report pertaining to the Bunker Hill or Keesler soils is referenced in the text and included in the Appendix. Much of the text of the Milestone Three Report has been included as sections 2.0 (the adsorption tests) and 3.0 (the flow-through tests) for completeness. The conclusions of these tests are summarized in section 4.0. The new material on formulations and emplacement can be found in section 5.0.

2.0 ADSORPTION ISOTHERMS: NORTH CAROLINA APATITE INDUCED PRECIPITATION OF Pb, Zn, Mn AND Cd DESORBED FROM THE BUNKER HILL 4000 SOIL

Adsorption is most often described in terms of isotherms which show the relationship between the bulk activity, or effective concentration in solution, of the species being adsorbed and the actual amount adsorbed at a constant temperature. When plotted, the shape and mathematical expression of the isotherm provide a great deal of information concerning the chemistry and sorption mechanisms within the system.

Although current research demonstrates the successful precipitation of soluble heavy metals when hydroxyapatites are added to a contaminated medium (Misra and Bowen, 1981; Ma, et al. 1993; Xu and Schwartz, 1994), very little attention has been paid to the precise calculation of hydroxyapatite needed to affect precipitation or complexation of metals from contaminated mediums. In this report, the amounts of hydroxyapatite (as North Carolina apatite) calculated to precipitate soluble metals relative to the molar ratios of the precipitated metal-PO_4 complexes will be illustrated as sharp deviations from linearity of the adsorption isotherms, as predicted by MINTEQ-A2, a thermodynamic speciation model. The amounts of apatite required for precipitating the metals in solution can then be extrapolated and scaled for field remediation.

2.1 PRECIPITATION OF SOLUBLE METALS BASED ON MOLAR RATIOS OF METAL-PO_4 COMPOUNDS

The Bunker Hill 4000 soil (BH 4000), so named because of its 4000 ppm lead concentration, was used to demonstrate the precipitation and metal-PO_4 stabilization potential of the North Carolina apatite (NC apatite). A two-week desorption experiment on the BH 4000 resulted in soluble Pb, Zn, Cd and Mn concentrations presented in graphic and tabular format in Figure 1 and Table 1 and described in greater detail in the Milestone II report.

Of particular interest is the type and amount of metals leaching from the BH 4000 soil as a function of time. Particular metals of interest are those that are regulated by federal agencies relative to health impacts. Metals that are regulated in groundwater and drinking water by the United States Environmental Protection Agency (USEPA) have been correlated to the ICP/MS metal analysis data. Those contaminants that have desorbed from the Bunker Hill 4000 soil that are of USEPA regulatory concern are Pb, Zn, Cd and Mn. These contaminants, which desorb in detectable amounts over the two-week test duration will be the focus of this study.

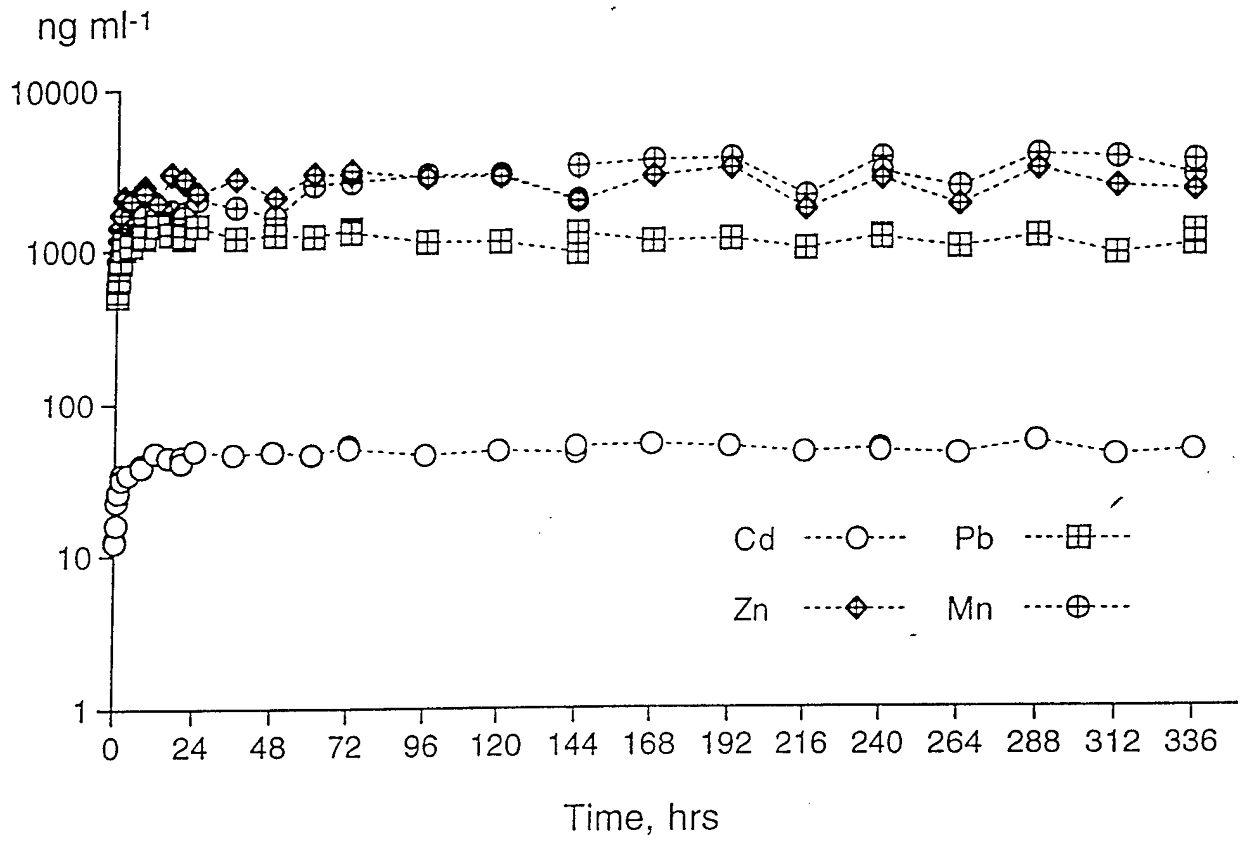


Figure 1. Desorption of Pb, Zn, Mn and Cd From the BH4000 Soil During a two Week Period.

Table 1. Percent Metal Desorption in the BH4000 Soil After 24 Hours.

Element	Total amount mg kg^{-1}	Amount Desorbed mg kg^{-1}	% Desorbed
Mn	1031	37.6	3.65
Zn	1087	30.8	2.83
Pb	4170	14.4	0.35
Ba	808	4	0.5
Sr	120	1.96	1.63
Cd	17	0.52	3.06
Al	79,000	3.75	0.0047

Figure 1 graphically represents the desorption of Pb, Zn, Mn and Cd from the BH 4000 soil during a two-week desorption period. Figure 1 illustrates that the maximum amount of metal desorption occurs within the first 24 hours of desorption.

By adding PO_4 to a solution containing one or more metals, one can induce precipitation/formation of minerals containing the PO_4 and the metal(s). By knowing the type and concentration of a particular metal and the mineral it will form when PO_4 is added, the precise amount of PO_4 to be added can be calculated. Using Pb as an example, stoichiometric amounts of PO_4 (from NC apatite), determined from the molar ratios of the precipitated minerals, can be added to induce the precipitation. In the case of Pb, molar ratios from minerals known as pyromorphytes will be used.

Chloropyromorphyte and hydroxypyromorphyte are the two most likely Pb-PO_4 minerals to form under the given conditions. These two minerals exhibit the fastest kinetic rate of formation (Nriagu, 1974). Although the two minerals are different by chemical formula, they both have the same Pb/PO_4 ratios. The following is the calculation for the molar ratio:

Chemical formula for pyromorphytes $Pb_5(PO_4)_3(OH, Cl)$
(Nriagu, 1972,1973)

Pb: 5@ 207.2 g/mol = 1,036. g/mol
PO_4: 3@94.93 g/mol = 284.79 g/mol
Molar ratio of Pb:PO_4 in pyromorphytes = 3.64

The lead leachate concentration of 1400 µg/kg is equivalent to 6.76×10^{-6} mol/L (M).Therefore,

6.76×10^{-6} M lead / 3.64 moles lead per mole phosphate = 1.86×10^{-6} M,

the concentration of PO_4 needed to drop out the lead, or equivalently,

1.86×10^{-6} M x 94.93 g PO_4/mol = 1.78×10^{-4} g L^{-1} = 0.18 µg PO_4 ml^{-1}.

To convert 0.18 µg PO_4 ml^{-1} to the amount of NC apatite added to cause precipitation, we use the fact that 46.84% by weight of the apatite is PO_4 and assume complete dissolution of the NC apatite. Thus, for example, a .01% addition of NC apatite to the 3 g of BH 4000 soil and 30 ml of water used in these experiments will yield:

0.01% NC apatite = 0.0003g NC apatite = 0.00014 g PO_4/30 ml H_2O=3.3 µg ml^{-1} .

From a proportional calculation, to obtain the concentration of 0.18 µg PO_4 ml^{-1} required for the formation of pyromorphytes, only 0.0005% NC apatite must be added.

It is obvious the resulting concentration of only 0.18 µg PO_4 ml^{-1} required for the formation of a pyromorphyte is substantially less than a 1% addition of NC apatite to the 3 g of contaminated BH 4000 soil. It also must be considered that there are many other metals in the BH 4000 supernatant that will complex with PO_4, which will reduce the overall concentration of PO_4 in solution. It is hypothesized that if metal-PO_4 minerals are to form under these conditions, amounts of up to 1% added NC apatite should cause reductions in most or all of the desorbed metal concentrations.

The formation of pyromorphytes calculated from the molar ratios, shown as such by the reduction of desorbed Pb in the adsorption isotherms, is confirmed by the thermodynamic modeling discussed below. Confirmation of the pyromorphyte formation by this experimental system suggests that PO_4 from the addition of up to 1% NC apatite will also complex with Zn, Mn, and Cd to form stable minerals.

2.2 NC APATITE ADSORPTION ISOTHERM - 24 HOURS REACTION TIME

Using the molar ratio of the pyromorphyte mineral as a beginning concentration range, an adsorption isotherm was conducted to observe the adsorption characteristics of the NC apatite on the desorbed metals from the BH 4000 soil. The nature of the curve, especially the departure from linearity and/or asymptotic characteristics, will determine the NC apatite concentration that induces precipitation of the desorbed metals.

2.2.1 EXPERIMENTAL

Adsorption isotherm tests (Beckwith, 1964), using the NC apatite, were performed on the Bunker Hill 4000 soil. For a 24-hour NC apatite adsorption study, 3 grams of the BH 4000, ground to pass through a 170 mesh screen and weighed to three decimal places, were combined with 1%, 5%, 10% and 20% NC apatite. Thirty ml of deionized water were added to the mixture in 40 ml polycarbonate centrifuge tubes . The polycarbonate tubes containing the 3 grams of BH 4000 soil, incremental percentages of NC apatite and 30 ml of deionized water were shaken continuously for 24 hours. At the end of 24 hours, the samples were taken from the shaker and centrifuged. The supernatant was filtered at 0.2µ, then analyzed for pH, metals, and anions as described in the elemental analysis section of this report. The data for this analysis is presented in Table 2.

Table 2. Metal Analysis for the 24 Hour NC Apatite Adsorption Isotherm for the BH4000 Soil (ng/ml).

% NC Apatite	Pb	Sr	Ba	Al	Fe	Cd	Zn	Mn
0	1600	179	486	68	38	53.6	2760	1740
1	154	157	152	124	41	8.98	536	875
5	220	303	151	304	185	4.3	165	598
10	86	435	130	123	1	2.1	86.1	490
20	23.3	674	137	25	1	1.7	10	359

2.2.2 RESULTS

A number of metals desorbed from the BH 2000 soil, as described in the Milestone 2 report. For brevity, this report will focus on the precipitation of metals that desorbed above their regulatory limits, namely Pb, Zn, Mn, and Cd. Their desorption curves are shown in Figure 1.

2.2.2.1 Pb PRECIPITATION

Figure 2 represents the reduction of desorbed Pb with the addition of 1%, 5%, 10% and 20% NC apatite. At 0% NC apatite, the desorbed amount of Pb in the

24 hour period (control sample) is 1600 ng ml^{-1}. The greatest reduction in Pb occurs with 1% addition of NC apatite, which is a 90% reduction of the desorbed Pb to 154 ng ml^{-1}.Increasing the NC apatite concentration to 5, 10 and 20% show no significant decrease in the desorbed Pb. Therefore, the precipitation of Pb by the addition of NC apatite occurs at 1% or less.

2.2.2.2 Zn PRECIPITATION

Figure 3 represents the reduction of desorbed Zn with the addition of 1%, 5%, 10% and 20% NC apatite. At 0% NC apatite, the desorbed amount of Zn in the 24-hour period (control sample) is 2760 ng ml^{-1}. The greatest reduction in Zn occurs with 1% addition of NC apatite, which is an 81% reduction of the desorbed Zn to 536 ng ml^{-1}. Increasing the NC apatite concentration to 5% decreases the desorbed Zn amount by 13%. Additions of 10 and 20% show no significant decrease in the desorbed Zn. Therefore, the major % of precipitation of Zn by the addition of NC apatite occurs at 1% or less.

2.2.2.3 Mn PRECIPITATION

Figure 4 represents the reduction of desorbed Mn with the addition of 1%, 5%, 10% and 20% NC apatite. At 0% NC apatite, the desorbed amount of Mn in the 24-hour period (control sample) is 1740 ng ml^{-1}. The greatest reduction in Mn occurs with 1% addition of NC apatite, although not as great a reduction as Pb and Zn. The reduction at 1% addition of NC apatite is 50%, with a Mn concentration of 536 ng ml^{-1}. Increasing the NC apatite concentration to 5% decreases the desorbed Mn amount by 16%. Additions of 10 and 20% reduce the desorbed Mn by 6% and 8%, respectively. Therefore, the precipitation of Mn by the addition of NC apatite appears to be greatest at 1% addition of NC apatite, with slight decreases with each incremental addition of the NC apatite.

2.2.2.4 Cd PRECIPITATION

Figure 5 represents the reduction of desorbed Cd with the addition of 1%, 5%, 10% and 20% NC apatite. At 0% NC apatite, the desorbed amount of Cd in the 24 hour period (control sample) is 54 ng ml^{-1}. The greatest reduction in Cd occurs with 1% addition of NC apatite, which is an 83% reduction of the desorbed Cd to 9 ng ml^{-1}. Increasing the NC apatite concentration to 5% decreases the desorbed Cd amount by 8.7%. Additions of 10 and 20% show no significant decrease in the desorbed Cd. Therefore, the major % of precipitation of Cd by the addition of NC apatite occurs at 1% or less.

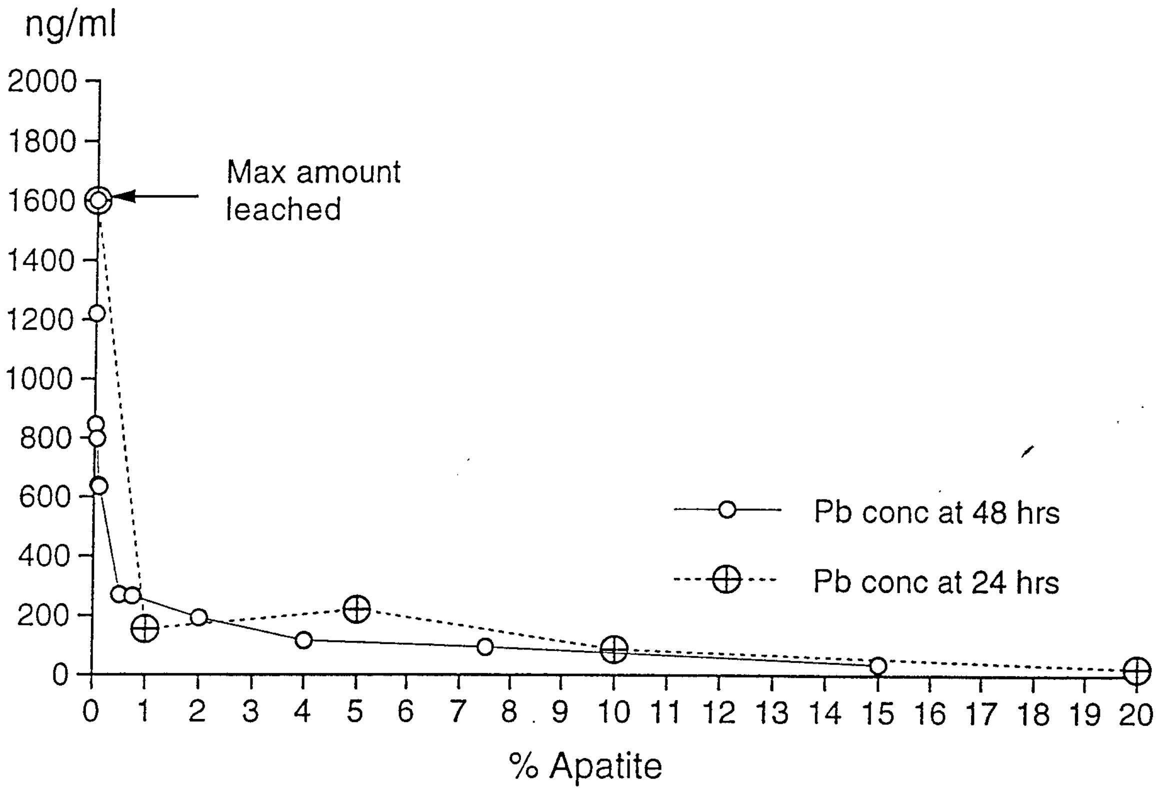


Figure 2. The Reduction of Desorbed Pb by NC Apatite Depicted by 24 and 48 Hour Adsorption Isotherms.

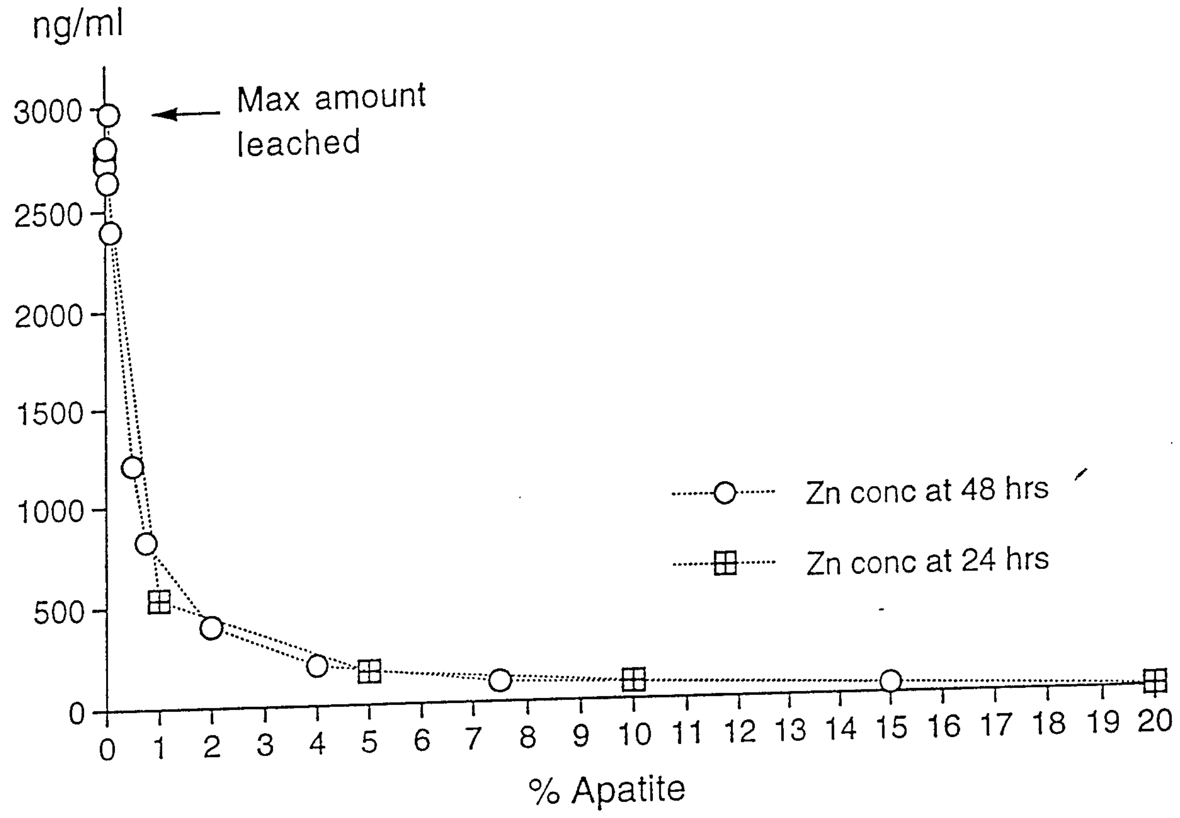


Figure 3. The Reduction of Desorbed Zn by NC Apatite Depicted by 24 and 48 Hour Adsorption Isotherms.

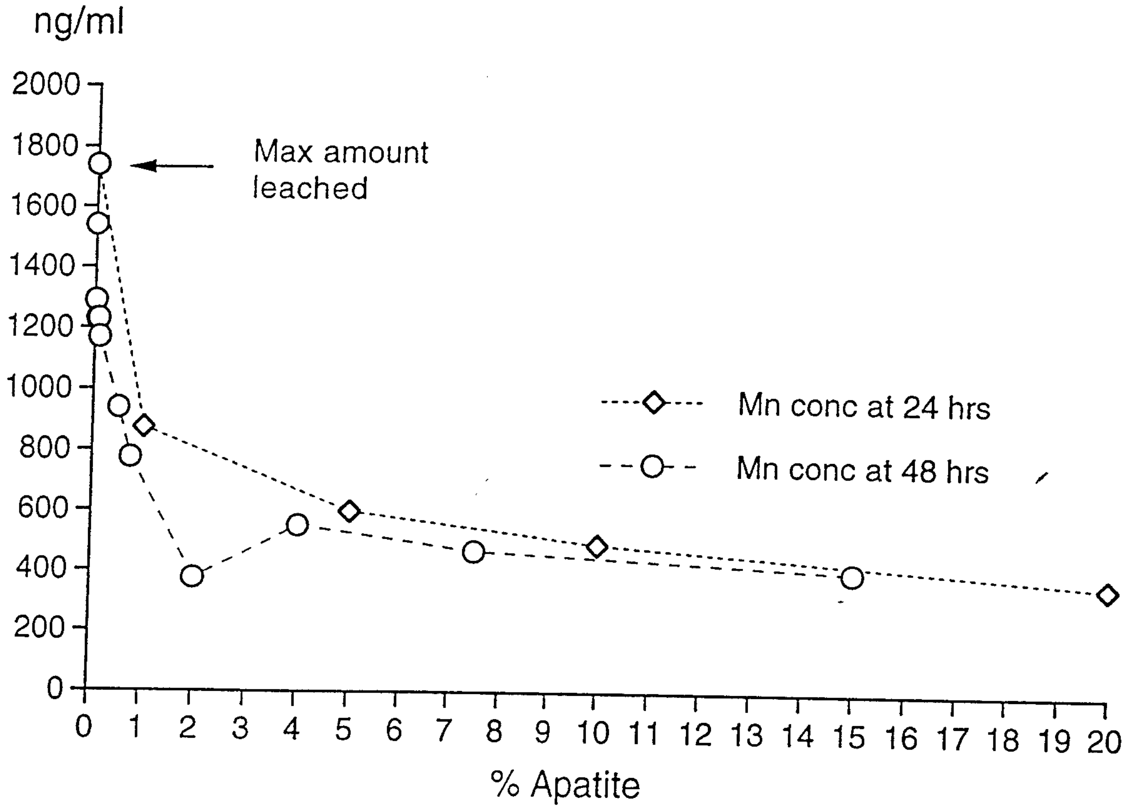


Figure 4. The Reduction of Desorbed Mn by NC Apatite Depicted by 24 and 48 hour Adsorption Isotherms.

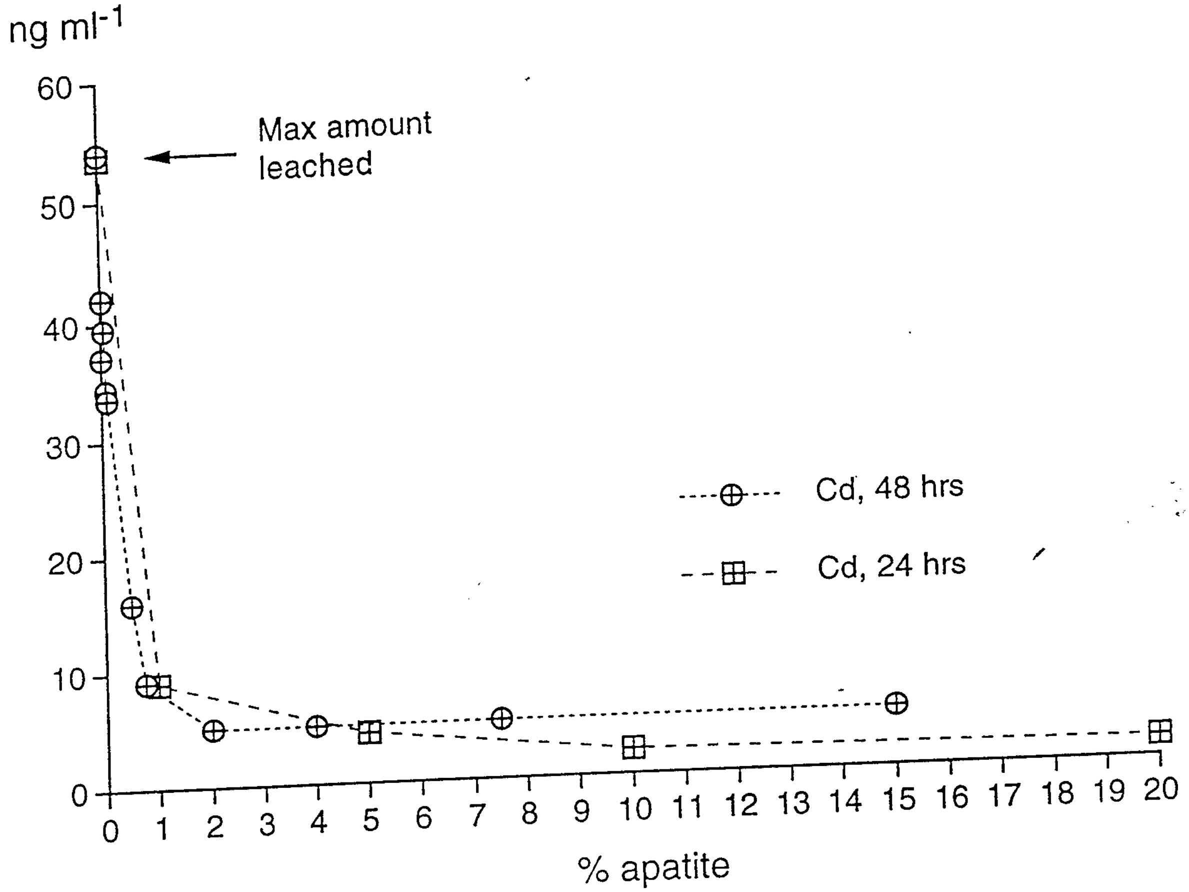


Figure 5. The Reduction of Desorbed Cd by NC Apatite Depicted by 24 and 48 hour Adsorption Isotherms.

2.3 NC APATITE ADSORPTION ISOTHERM - 48 HOURS REACTION TIME

To examine the effect of increasing the contact time between the desorbed metals and the NC apatite, a 48-hour adsorption isotherm was executed. The difference between the 48-hour and 24-hour adsorption isotherms is the amount of NC apatite added during each run.

2.3.1 EXPERIMENTAL

The same NC apatite adsorption isotherm tests were performed on the Bunker Hill 4000 soil as with the 24-hour isotherm tests. Three grams of the BH 4000, ground to pass through a 170 mesh screen and weighed to three decimal places, were combined with the percentages of NC apatite listed in Table 3. Thirty ml of deionized water were added to the mixtures in 40 ml polycarbonate centrifuge tubes. The polycarbonate tubes containing the 3.000 grams of BH 4000 soil, incremental percentages of NC apatite and 30 ml of DI H_2O were shaken continuously for 48 hours. At the end of 48 hours, the samples were taken from the shaker and centrifuged. The supernatant was filtered at 0.2μ, then analyzed for pH, metals, and anions as described in the elemental analysis section of this report. The data for this analysis is presented in Table 4.

2.3.2 RESULTS

2.3.2.1 Pb PRECIPITATION

Figure 2 represents the reduction of desorbed Pb with the addition of 0.005% through 15% NC apatite, with the precise increments listed in Table 2. At 0% NC apatite, the desorbed amount of Pb in the 48-hour period (control sample) is 1600 ng ml^{-1}. As with the 24-hour isotherm, the greatest reduction in Pb occurs at less than 1% addition of NC apatite, which is an 83% reduction of the desorbed Pb to 266 ng ml^{-1}. Increasing the NC apatite concentrations shows no significant decrease in the desorbed Pb. All additions less than 1% reduce the amount of desorbed Pb. The .005% addition of NC apatite reduces the desorbed Pb by 24%, corroborating the molar ratio amount of NC apatite needed to form a pyromorphyte. As also shown by the 24-hour adsorption isotherm, the major % of precipitation of Pb by the addition of NC apatite occurs at 1% or less.

Table 3. Percentages of NC Apatite Added to the BH4000 Soil for 48 Hour Adsorption Isotherm.

0
0.005
0.02
0.08
0.1
0.5
0.75
2
4
7.5
15

Table 4. Metal Analysis for the 48 Hour NC Apatite Adsorption Isotherm for the BH4000 Soil.

% NC apatite	pH	Zn	Pb	Ba	Cd	Mn	Al
15	7.5	44.2	36.5	159	5	402	23
7.5	7	100	92.9	163	5	467	88
4	6.5	201	115	148	5	551	112
2	6.4	401	192	146	5	376	216
0.75	5.1	824	266	154	9.1	776	253
0.5	6.3	1210	270	171	15.9	939	110
0.1	6.3	2400	635	204	33.6	1170	92.3
0.08	6.2	2970	641	345	34.4	1230	66.7
0.05	5.9	2640	798	346	39.5	1230	50.7
0.02	4.95	2805	846	370	42	1290	57
0.005	6.8	2720	1220	304	37.1	1540	55
0	5.5	2760	1600	486	54	1740	68

2.3.2.2 Zn PRECIPITATION

Figure 3 represents the reduction of desorbed Zn with the addition of 0.005% through 15% NC apatite, with the precise increments listed in Table 2. At 0% NC apatite, the desorbed amount of Zn in the 48-hour period (control sample) is 2760 ng ml^{-1}. As with the 24-hour isotherm, the greatest reduction in Zn occurs at less than 1% addition of NC apatite, which is a 70% reduction of the desorbed Zn to 824 ng ml^{-1}. As shown from the adsorption isotherm, increasing the NC apatite concentrations almost parallels the 24-hour adsorption isotherm, strongly suggesting that increasing the contact time to 48 hours does not increase precipitation. As also shown by the 24-hour adsorption isotherm, the major % of precipitation of Zn by the addition of NC apatite occurs at 1% or less.

2.3.2.3 Mn PRECIPITATION

Figure 4 represents the reduction of desorbed Mn with the addition of 0.005% through 15% NC apatite, with the precise increments listed in Table 2. At 0% NC apatite, the desorbed amount of Mn in the 48-hour period (control sample) is 1740 ng ml^{-1}. As with the 24-hour isotherm, the greatest reduction in Mn occurs at less than 1% addition of NC apatite, which is a 55% reduction of the desorbed Mn to 776 ng ml^{-1}. As in the 24-hour isotherm, the addition of NC apatite is not as great a reduction as Pb and Zn. Increasing the NC apatite concentration decreases the desorbed Mn amount more than in the 24-hour isotherm The precipitation of Mn by the addition of NC apatite appears to be greatest at less than 1% addition of NC apatite, with a further 12% decrease at 2% added apatite.

2.3.2.4 Cd PRECIPITATION

Figure 5 represents the reduction of desorbed Cd with the addition of 0.005% through 15% NC apatite, with the precise increments listed in Table 2. At 0% NC apatite, the desorbed amount of Cd in the 48-hour period (control sample) is 54 ng ml^{-1}. As with the 24-hour isotherm, the greatest reduction in Cd occurs at less than 1% addition of NC apatite, which is an 83% reduction of the desorbed Cd to 9.1 ng ml^{-1}. Increasing the NC apatite concentration to 2% decreases the desorbed Cd amount by 7.6%. Increasing the concentration of apatite past 2% does not reduce the concentration of desorbed Cd. As shown from the adsorption isotherm, the 48-hour isotherm parallels the 24-hour adsorption isotherm, strongly suggesting that increasing the contact time to 48 hours does not increase precipitation. It is suggested that the greatest precipitation of Cd by the addition of NC apatite occurs at 1% or less.

2.3.3 PRECIPITATION OF DESORBED METALS AS DEPICTED IN THE 24- AND 48-HOUR ADSORPTION ISOTHERMS

It can be seen from both the 24- and 48-hour NC apatite adsorption isotherms that very little NC apatite is required to reduce the desorbed concentrations of Pb, Zn, Mn and Cd from the BH 4000 soil to within or below regulatory limits. In all cases, the greatest reduction in the desorbed metals occurs at 1% or less added apatite. In all cases the % NC apatite increments less than 1% indicate strong and dramatic reductions of Pb, Zn, Mn and Cd, verifying that NC apatite is causing reduction of the desorbed metals at less than 1%.

Increasing the adsorption isotherm time to 48 hours does not increase the overall effectiveness of NC apatite, except for a slight decrease in the Mn 48-hour adsorption isotherm. Because the increase in contact time to 48 hours does not increase the precipitation for Pb, Zn, and Cd from the 24-hour experiment, it is suggested that the adsorption or formation kinetics of the apatite-metal system for these metals is less than 24 hours. This corroborates the work of other researchers in metal-PO_4 complexation (Ma, et al,1993, Ruby, et al, 1994, Xu and Schwartz, 1994).

2.4 VERIFICATION OF PRECIPITATED METALS USING MINTEQ-A2

In order to gain knowledge about the nature of metal-phosphate complexation and to determine how much PO_4 is needed to complex the desorbed metals of the BH 4000 soil, MINTEQ-A2, a geochemical thermodynamic speciation computer program, was used.

The natural soil system has both a solid phase and a solution phase. When chemical equilibrium is assumed to exist between the soil solution and the associated solid phases of the soil, one can elicit important information about solid phase formations by using thermodynamic calculations performed in geochemical thermodynamic speciation programs. Specifically, this computer program is used to examine the precipitation of selected metals, i.e., Pb, Zn, Mn, and Cd, induced by the application of a specific phosphate compound.

Saturation indices for the BH 4000 soil determined from MINTEQ-A2 indicate whether Pb, Zn, Mn, and Cd-phosphate minerals may be present. The saturation index is defined as

Ion Activity Product/Solubility Product

and is a thermodynamic indication of mineral dissolution or formation. Values < 0 indicate that the mineral is undersaturated with respect t the equilibrium concentration and should not precipitate, while values > 0 indicate saturation with respect to the equilibrium concentration, indicating that precipitation is likely to occur. The higher the number, the greater the probability of precipitation.

2.4.1 EXPERIMENTAL

Input data for the execution of the computer program was acquired from a complete metal and ligand analysis of saturation extracts (Page, et. al, 1982). The computer program used was MacMINTEQ-A2, acquired from Geochem Software, 1994. Metal concentrations on the extract were obtained by ICP analysis and anions by IC analysis (PNL-AL0-211.2 Rev. 0, and PNL-ALO-212 Rev. 1).

2.4.2 RESULTS

A great utility of the MINTEQ-A2 program is the versatility in configuring "what if" scenarios, based on thermodynamic principles. Data produced from the analysis of the BH 4000 saturation extract was input to the program. Included in the data input was the analysis of the metal and ligand concentration, pH, electrical conductivity, redox conditions and carbonate content. The input data exhibited a charge balance difference of 11%, which is within acceptable limits for program operation (Geochem Software, 1994).

The initial input data for the operation of MINTEQ-A2, derived from the analysis of the saturation extract, is presented in Table 5. The "what if" scenario to be analyzed using MINTEQ-A2, from a thermodynamic standpoint, is the effect of increasing amounts of NC apatite added to the BH 4000 soil. By varying the amount of NC apatite PO_4 on the solute composition, solubility products are calculated for possible precipitation reactions of PO_4 with those metals present in the analyzed saturation extract. Each incremental amount of PO_4 added requires a separate execution of the MINTEQ-A2 program. With each program run, the output lists the possible combinations of metal-PO_4 solid phases. The saturation index, described above, is listed in the output for each of the target metal-PO_4 minerals. As a result, each incremental amount of PO_4 added as NC apatite alters the solute composition favorably or unfavorably with respect to the formation of solid phases. The incremental amounts of PO_4 added as NC apatite and the resulting calculated saturation indexes are listed in Table 6.

Figure 6 shows the graphic representation of saturation indexes of Pb-PO_4 minerals relative to increasing amounts of PO_4 from NC apatite, and Figure 7 shows the graphic representation of saturation indexes of Zn, Mn, and Cd phosphate minerals relative to increasing amounts of PO_4 from NC apatite.

Table 5. Metal and Ligand Analysis of the BH 4000 Soil Saturation Extract.

Metal analysis, ng/ml

Na	Mg	Al	K	Ca	Mn	Fe	Ni	Cu	Zn	Sr	Cd	Ba	Pb
14,350	9530	79	19550	95250	6760	197	26	48	8390	556	162	302	581

Anion analysis, µg/ml

F	Cl	NO2	NO3	SO4	PO4
2.49	35.9	0.8	0.3	271	0

pH = 5.6

Electrical conductivity = .984 dS/M

CO3-2 = 3 µg/ml

Table 6. Saturation indexes relative to NC apatite concentrations for the formations of Pb, Cd, Zn and Mn-phosphate minerals.

% NC Apatite	PO_4, mg L^{-1}	Sat. Index $Pb(PO_4)_2$	Sat. Index $PbHPO_4$	Sat. Index $PbAl_3(PO_4)_2(OH)_5H_2O$
0	0	-6.206	-4.076	-10.505
0.02	9.4	1.74	-0.102	-2.559
0.05	23.5	4.065	0.661	1.762
0.07	32.9	4.727	0.893	2.925
0.1	47	5.754	1.209	4.953
0.5	235	7.154	1.91	6.349
1	470	7.759	2.213	6.949

% NC Apatite	PO_4, mg L^{-1}	Sat. Index $Pb_5(PO_4)_3Cl$	Sat. Index $Pb_5(PO_4)_3OH$	Sat. Index $Mn\ HPO_4$
0	0	2.347	-10.646	-0.807
0.02	9.4	14.267	1.273	3.166
0.05	23.5	17.751	5.158	3.933
0.07	32.9	18.744	6.251	4.166
0.1	47	20.283	7.989	4.487
0.5	235	22.382	10.089	5.189
1	470	23.288	10.994	5.492

% NC Apatite	PO_4, mg L^{-1}	Sat. Index $Zn_3(PO_4)\ 4H_2O$	Sat. Index $Cd_3(PO_4)_2$	Sat. Index $Mn_3(PO_4)_2$
0	0	-13.359	-18.771	-21.574
0.02	9.4	-5.412	-10.825	-13.628
0.05	23.5	-3.079	-8.492	-11.294
0.07	32.9	-2.413	-7.825	-10.627
0.1	47	-1.372	-6.784	-9.585
0.5	235	0.03	-5.382	-8.183
1	470	0.636	-4.776	-7.576

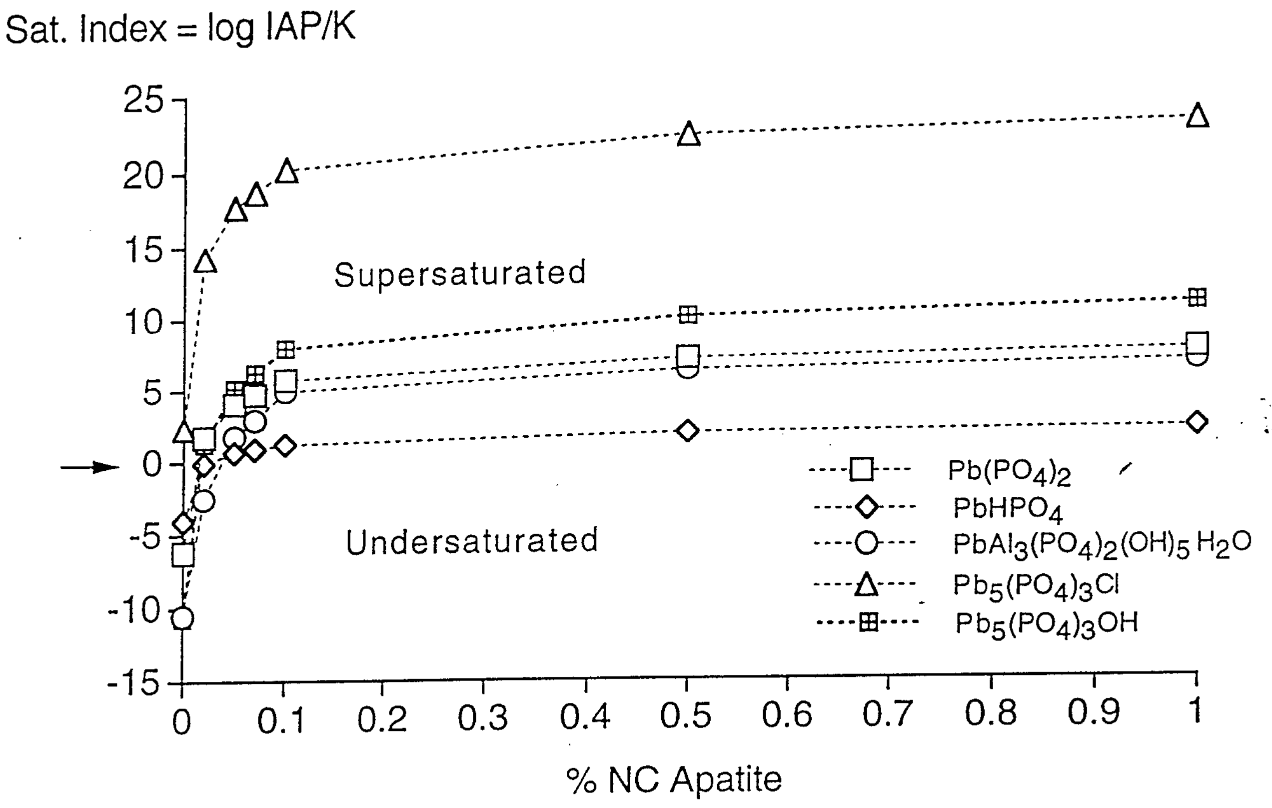


Figure 6. Saturation Indexes Relative to Increasing Amounts of NC Apatite for the Formation of Pb-Phosphate Minerals.

2.4.2.1 Pb-PHOSPHATE PREDICTIONS

The Pb-PO_4 minerals depicted in Figure 6 are all common minerals known to form under the given conditions. The chloro- and hydroxypyromorphytes, with the chemical formula $Pb_5(PO_4)_3(OH, Cl)$, are indicated as having the most positive saturation indexes, and are therefore most likely to form. This is substantiated by X-ray diffraction results on the Bunker Hill soils after treatment with apatite and by other researchers (Nriagu, 1974, Ma, et al, 1993, Ruby et al, 1994). Plumbogummite ($PbAl_3(PO_4)_2(OH)_5\ H_2O$) is also indicated as a possible precipitated mineral, as are two unnamed complexes, $Pb(PO_4)$ and $PbHPO_4$. For all of the Pb-PO_4 minerals presented in the MINTEQ-A2 output, the thermodynamic predictions occur at less than 0.1% addition of NC apatite. This thermodynamic prediction agrees with the previously calculated NC apatite amount from the Pb/PO_4 molar ratios of pyromorphytes and the adsorption isotherm data presented in Figure 2.

2.4.2.2 Mn-PHOSPHATE PREDICTIONS

Figure 7 shows the graphic representation of saturation indexes of Zn, Mn, and Cd phosphate minerals relative to increasing amounts of PO_4 from NC apatite. Rhodochrosite ($MnHPO_4$) shows the highest degree of supersaturation. Based on the solubility reported for $MnHPO_4$, this mineral is very stable in soils. The $MnHPO_4$ mineral is more stable than strengite ($FePO_4\ 2H_2O$), an important competing phase, at most pH and redox conditions of soils (Lindsay, 1979). The saturation index for strengite at .02% NC apatite is 2.910 and 3.166 for Rhodochrosite. The higher saturation index indicates a more likely formation for $MnHPO_4$ and suggests that the prediction is credible. As depicted in Figure 7, supersaturation with respect to $MnHPO_4$ formation exists at concentrations of less than 0.1% NC apatite. This thermodynamic prediction agrees with the NC apatite amounts shown to reduce desorbed Mn concentration in the adsorption isotherm data presented in Figure 4.

2.4.2.3 Zn-PHOSPHATE PREDICTIONS

The mineral hopeite ($Zn_3(PO_4)_2\ 4H_2O$) is reported to have a very low solubility, with a Log K° of -35.3 (Nriagu, 1973). This would indicate extreme stability in the soil environment. As can be noted from the thermodynamic prediction of MINTEQ-A2, the incremental additions of NC apatite raise the saturation index to 0 at 0.5% NC apatite. This condition is favorable for the formation of ($Zn_3(PO_4)_2\ 4H_2O$) but not as positive as Mn or Pb, discussed above. However, the adsorption isotherm presented in Figure 3 shows a drastic reduction of Zn at less than 1% addition of NC apatite, which would indicate a highly supersaturated condition with respect to the formation of $(Zn_3(PO_4)_2$

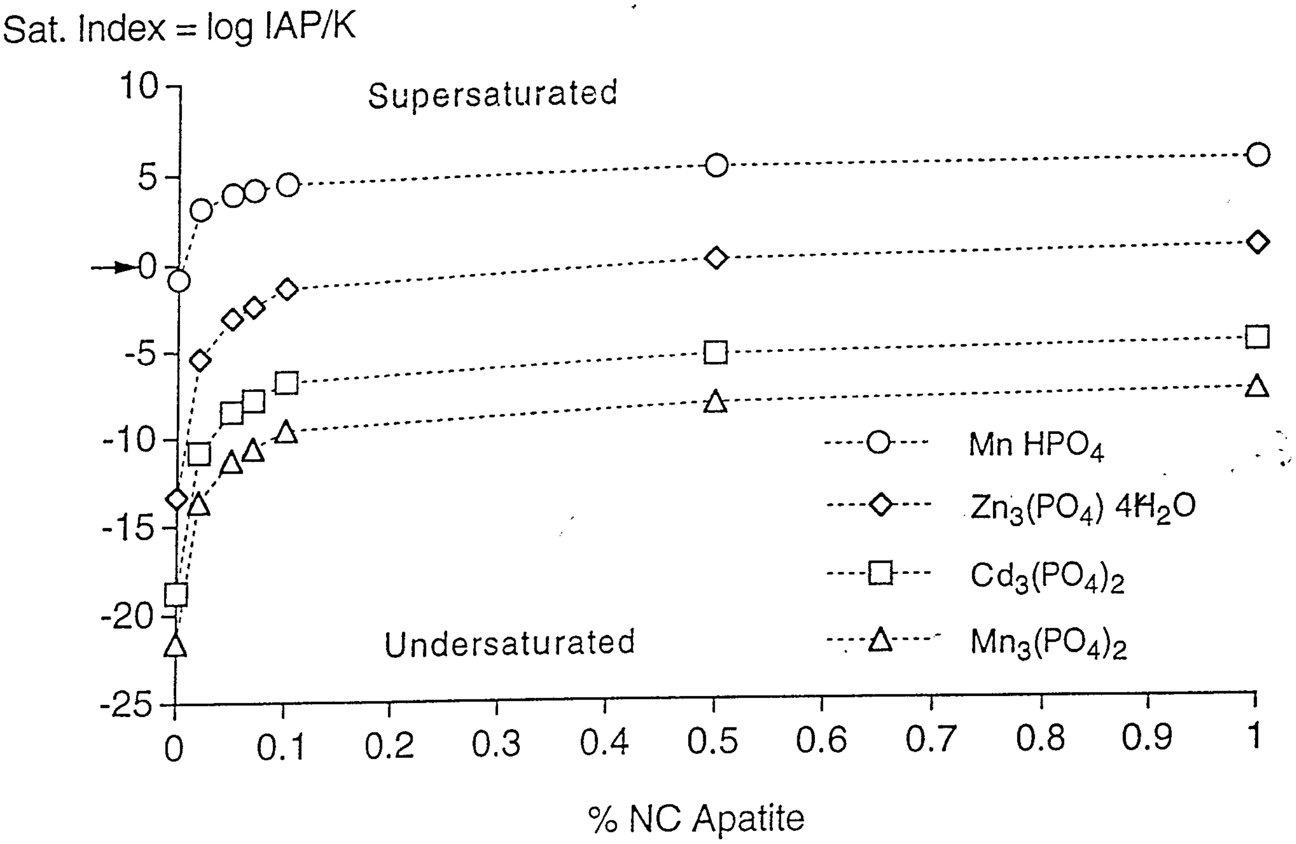


Figure 7. Saturation Indexes Relative to Increasing Amounts of NC Apatite for the Formation of Mn, Zn and Cd-Phosphate Minerals.

$4H_2O$). This discrepancy is best explained by the different solubilities for this mineral presented in the literature by various researchers. The values range from Log K° of -35.3 (Nriagu, 1973) to Log K° of 3.80 (Lindsay, 1979)

Observing the upward trend toward supersaturation at less than 0.1% NC apatite, the thermodynamic prediction partially agrees with the NC apatite amounts shown to reduce desorbed Zn concentration in the adsorption isotherm data presented in Figure 3.

2.4.2.4 Cd-PHOSPHATE PREDICTIONS

As indicated in Figure 7, the formation $Cd_3(PO_4)_2$ is not predicted to occur. The saturation indexes at all increments of less than 1% NC apatite are less than 0, indicating undersaturation with respect to the mineral. This is in contradiction to the adsorption isotherm presented in Figure 5. which depicts an 83% reduction of desorbed Cd at less than 1% addition of NC apatite. As with Zn, this discrepancy is best explained by the different solubilities for $Cd_3(PO_4)_2$ presented in the literature by various researchers. The values range from Log K° of -32.61 (NBS) to Log K° of 1.0 (Lindsay, 1979).

3.0 UNSATURATED FLOW-THROUGH STUDIES IN TREATMENT OF CONTAMINATED SOILS USING APATITE MINERALS

3.1 MATERIALS

The metal-contaminated soils used in this study are composite soils (BH2000 and BH4000) from the Bunker Hill Mining District, Idaho and were obtained from the University of Idaho. A natural apatite from North Carolina was used as a remedial additive to the contaminated soils. The apatites used were either un-ground (as-mined) or ground and sieved through a 170-mesh standard testing sieve (90 μm opening). A synthetic Hanford vadose zone water and deionized water were used in the flow-through experiments.

3.2 SOIL COLUMN AND UFA METHODOLOGY

Flow-through studies of untreated and apatite-treated contaminated soils were performed to replicate actual field conditions that batch studies cannot reproduce, e.g., natural flow rates, low water:soil ratios, channelized flow paths, etc. Two flow methods were used: traditional soil columns and the UFA method. Traditional soil columns consist of a column of soil having solution dripping into the top at a fixed rate and effluent collected as it exits the bottom of the sample. Because the fluid driving force is only the unit gravitational acceleration, which is a very small whole body force, the degree of saturation in the sample is high, nearly saturated, for most soils if the experiment is to take less than a year. To achieve the low water contents that exist in most vadose zones, the flow rates would have to be so low that the experiment would take an unreasonable amount of time. The UFA method is used for unsaturated flow or flow in relatively impermeability materials. The UFA method is based upon open-flow centrifugation and achieves hydraulic steady-state in a matter of hours in most geologic materials even at very low water contents and permeabilities down to 10^{-10} cm/s (Wright et al., 1994). There are specific advantages to using a centripetal acceleration as a fluid driving force. It is a whole-body force similar to gravity, and so acts simultaneously over the entire system and independently of other driving forces, e.g., gravity or matric suction. The use of steady-state centrifugation to measure steady-state hydraulic conductivities has only recently been demonstrated (Nimmo et al., 1987; Conca and Wright, 1992). The UFA consists of an ultracentrifuge with a constant, ultralow flow-rate pump which provides any fluid to the sample surface through a rotating seal assembly and microdispersal system. Accelerations up to 20,000 g are attainable at temperatures from -20° to 150°C and flow rates as low as 0.001 ml/hr. The effluent is collected in a transparent, volumetrically-calibrated container at the bottom of the sample assembly which can be observed during centrifugation using a strobe light.

3.3 EXPERIMENTAL PROCEDURE

3.3.1 LEACHING OF UNTREATED CONTAMINATED SOILS

Two 3-cm diameter, 5-cm long core sample holders were each packed with 40 g of dry Bunker Hill 2000 soils. One of these two samples was for the UFA run, the other for the traditional soil column experiment. To reduce the possibility of preferential flow and fingering the samples were pre-wetted: 5 ml and 8 ml of synthetic vadose water were added to the UFA and column samples, respectively. Then, the column sample was placed on a sample rack with a pumping rate of 1 ml per hour, and the UFA sample was set up at 400 rpm and 1 ml per hour. Leachates were observed after variable amounts of water flow into the samples (5 ml for the UFA sample and 8 ml for the column). About four pore volumes of leachates were collected for each sample during the 47 hours of the experiment After the first 3 effluents were collected for each sample, the experiment was stopped and the samples were placed upright for 2 days in order to detect the effect of residence time on the leaching behavior. One half of each leachate was filtered through a 0.2 micron disposable filter, and the other half was analyzed unfiltered. Finally, selected filtered samples and unfiltered portions of the samples were analyzed by ICP/MS. The results from these leaching studies will be used as baselines for the flow-through studies of apatite treatment as described below.

3.3.2 APATITE TREATMENT

The contaminated Bunker Hill soils were treated with North Carolina natural apatite in two different ways, either as a layer at the bottom of a UFA sample holder to reproduce the effect of field-emplaced permeable reactive barrier or mixed into the soils as an additive to reflect auguring or soil mixing as a field emplacement technology (Figure 8).

In the experiment of using an apatite layer at the bottom of a sample holder, 20 grams each of un-ground North Carolina (NC) natural apatite and Bunker Hill 2000 soil were packed into a UFA sample holder. To reduce the possibility of preferential flow and fingering, the sample was pre-wetted with 5 ml of synthetic vadose zone water. Then, the sample was run at 400 rpm and 1 ml per hour in a UFA. Leachate was observed after an additional 2 ml of water entered the sample. In total, about 7.5 pore volumes of leachate were collected from the sample during the 47 hours of the experiment. After the first three effluents were collected for each sample, the experiment was stopped and the samples were placed upright for two days in order to detect the effect of residence time on the metal leaching behavior after apatite treatment. One half of each leachate was filtered through a 0.2 micron disposable filter, and other half was analyzed unfiltered. Finally, selected filtered samples and unfiltered portions of the samples were analyzed by ICP/MS.

The Bunker Hill contaminated soils were also treated by mixing with ground and unground NC apatites. The unground apatite was mixed with Bunker Hill 2000 soil in the ratio of 10% apatite and 90% soil by weight, while the ground apatite was blended with Bunker Hill 4000 soil in the ratio of 1% apatite and 99% soil. Before each of the mixtures of soils and apatites were packed into UFA sample holder, a thin layer (~ 0.5 cm thick) of clean soil (McGee Ranch soil), which was also mixed with a corresponding amount of apatite, was packed into the bottom of the sample holder to serve as the lower contaminant boundary. All of the soil and apatite mixtures were packed pre-wetted into sample holders in a solid:water ratio of 5.5:1, in order to reduce the possibility of preferential flow and fingering. In the test of Bunker Hill 2000 soil mixed with unground apatite (10% by weight), two identical UFA samples were prepared, which were run with deionized water and with synthetic vadose zone water, respectively. The weights of the samples before and after running on a UFA at 1000 rpm and 0.6 ml per hour did not change much, indicating that the steady-state volumetric water content in the UFA run was approximately 30% and was reached

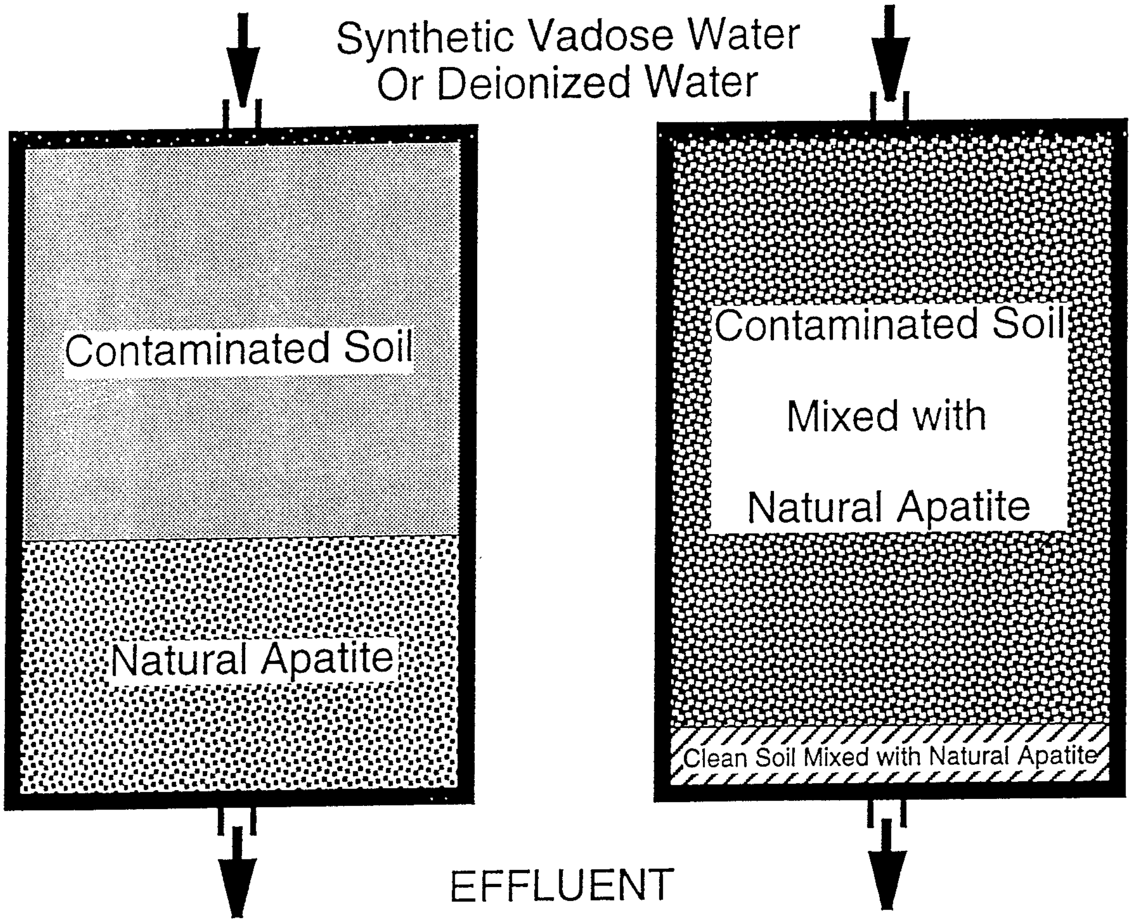


Figure 8. Apatite Treatment Experimental Designs for UFA Runs.

almost immediately. Leachates were collected every 24 hours in volumes equal to one effective pore volume. In total, thirty-two pore volumes were collected for the Bunker Hill 2000 soil with 10% un-ground apatite run with synthetic vadose water, eighteen for the Bunker Hill 2000 soil with 10% un-ground apatite run with deionized water, and fifty for the Bunker Hill 4000 soil with 1% ground apatite run with synthetic vadose water. Selected leachates were analyzed by ICP/MS and ion chromatography.

3.4 LEACHATE ANALYSIS

The leachate samples were analyzed for metal and anion concentrations on a VG PlasmaQuad II+ ICP/MS and an ion chromatograph. Two consecutive analytical runs were acquired for each sample. Results were then calculated using vendor-supplied software.

3.5 RESULTS

3.5.1 LEACHING OF UNTREATED CONTAMINATED SOILS

The elemental concentrations of the leachates from the UFA and column flow-through experiments are shown in Table 7 and Figures 9 and 10. In the UFA run, Pb concentrations constantly decrease from 586 $\mu g\ kg^{-1}$ in the first effluent of leachate to 296 $\mu g\ kg^{-1}$ in the fifth effluent, Zn from 17300 to 5400 $\mu g\ kg^{-1}$, and Cd from 256 to 49.5 $\mu g\ kg^{-1}$. In the soil column experiment, Pb concentrations range from 376 $\mu g\ kg^{-1}$ in the first leachate to 184 $\mu g\ kg^{-1}$ in the fifth leachate, Zn from 10700 to 3890 $\mu g\ kg^{-1}$, and Cd from 152 to 20.9 $\mu g\ kg^{-1}$. These suggest that the concentrations of the metals under progressive leaching decrease by several orders of magnitude. The metal leaching behaviors in the UFA and soil column runs are similar. The difference was observed in their response to the change in residence time. The fourth effluent of the leachates collected from the soil column after letting the sample sit for two days had higher Pb (but not Cd and Zn) concentrations than those of the third effluent, an effect not observed in the UFA run (Figures 9 and 10). However, the concentrations of Cd (but not Pb and Zn) in the fifth effluent of UFA run are slightly higher than those of the fourth effluent, which is different from the soil column data and may result from the variable response to the two-day sitting of the samples. Thus, it seems: 1) residence time has a significant effect on metal leaching, i.e., longer residence times may increase metal mobility; 2) UFA and soil column runs may respond to residence time differently, i.e., soil column run reacts faster than UFA runs; and 3) different metals may have variable responses to residence time even in the same run.

Table 7. Elemental Concentrations of untreated Bunker Hill Soil Leachates From UFA and Soil Column Experiments.

	Sample Type	Leaching Method	Filtered Leachate	Mg mg/L	Si mg/L	K mg/L	Ca mg/L	Mn mg/L	Zn mg/L	Al µg/L	Fe µg/L
1	BH2000	UFA-1	No	49.7	24.4	39.4	310	14	17.3	157	<100
2	BH2000	UFA-2	Yes	23.9	20.1	31.3	168	9.42	10.9	132	<100
3	BH2000	UFA-2	No	23.2	19.2	27.8	161	8.82	10.6	95.1	<100
4	BH2000	UFA-3	Yes	13.5	17.1	23.2	98.1	6.51	5.82	85.7	<100
5	BH2000	UFA-3	No	12.4	16.9	24.6	99.9	8.27	8.46	60.5	<100
6	BH2000	UFA-4	No	9.49	14.7	21	74	6.2	5.97	46.1	<100
7	BH2000	UFA-5	No	11.9	18.7	25.4	91.4	6.08	5.4	37	<100
8	BH2000	Column-1	Yes	31.1	19.7	32.4	198	9.36	10.7	156	<100
9	BH2000	Column-1	No	37.2	22.2	35.7	238	11.3	13.4	109	<100
10	BH2000	Column-2	Yes	19	18.1	26.6	128	8.25	8.56	102	<100
11	BH2000	Column-2	No	21.2	18.5	28	137	8.48	7.99	75.6	<100
12	BH2000	Column-3	Yes	11.9	14.8	23.3	94	7.08	6.48	82.2	<100
13	BH2000	Column-3	No	11.8	16	22.3	89.8	6.68	6.11	94.8	<100
14	BH2000	Column-4	No	13	19.4	22.4	81.4	7.89	5.34	737	800±100
15	BH2000	Column-5	No	11.3	16±2	20.1	75.2	16.3	3.89	255	490±50

	Sample Type	Leaching Method	Filtered Leachate	Ni µg/L	Cu µg/L	As µg/L	Sr µg/L	Cd µg/L	Ba µg/L	Hg µg/L	Pb µg/L
1	BH2000	UFA-1	No	51.577	42.36	<5	1080	255.5	274.73006	<5	586
2	BH2000	UFA-2	Yes	31.149	27±4	<5	675.08	125.7	165.82143	<5	449
3	BH2000	UFA-2	No	28.541	24±3	<5	640.49	121	156.32192	<5	442
4	BH2000	UFA-3	Yes	18.156	22.96	<5	418.25	59.31	131.48754	<5	353
5	BH2000	UFA-3	No	17.342	15.78	<5	430.06	72.19	146.56854	<5	339
6	BH2000	UFA-4	No	14±2	15.08	<5	331.76	43.37	129.84484	<5	327
7	BH2000	UFA-5	No	18±5	26±5	<5	429.26	49.52	155.91141	<5	296
8	BH2000	Column-1	Yes	73.614	34.45	<5	790.55	151.9	199.3599	<5	364
9	BH2000	Column-1	No	102.34	42±5	<5	885.47	175.2	219.40941	<5	376
10	BH2000	Column-2	Yes	28.656	23.12	<5	536.8	90.3	135.18587	<5	349
11	BH2000	Column-2	No	34±4	25±5	<5	581.52	98.04	143.40855	<5	367
12	BH2000	Column-3	Yes	22.206	15±2	<5	413.5	59.64	125.15782	<5	258
13	BH2000	Column-3	No	18.947	10.66	<5	392.73	53.97	116.19437	<5	264
14	BH2000	Column-4	No	30.163	19±4	<5	348.59	37.36	141.45405	<5	353
15	BH2000	Column-5	No	20.682	11.6	<5	364.7	20.94	125.46775	<5	184

Note --- Cs, La, Ce, Pr, Nd, Eu, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th, and U were all detected at < 5 ppb.

Table 8. Soil Column and UFA Leaching Results for Pb, Zn, and Cd in Bunker Hill 2000 Soil.

Soil Column

Effluent Number	Filtered Leachate	Leachate Volume (ml)	Cumulative Pore Vol.	Zn (mg/kg) wt.%	Cd (mg/kg) wt.%	Pb (mg/kg) wt.%
1	Yes	6	1.75	0.0014	0.1519	0.0027
1	No	6	1.75	0.0017	0.1752	0.0028
2	Yes	6	2.50	0.0011	0.0903	0.0026
2	No	6	2.50	0.0010	0.0980	0.0028
3	Yes	5	3.13	0.0007	0.0497	0.0016
3	No	5	3.13	0.0007	0.0450	0.0017
4	No	6	3.50	0.0007	0.0374	0.0026
5	No	7	3.94	0.0006	0.0244	0.0016
Total		47	3.94	0.0078	0.6720	0.0184
ppm Concentration in Soil >>>>>>				1171	15	2000

UFA

Effluent Number	Filtered Leachate	Leachate Volume (ml)	Cumulative Pore Vol.	Zn (mg/kg) wt.%	Cd (mg/kg) wt.%	Pb (mg/kg) wt.%
1	No	6	1.50	0.0022	0.2555	0.0044
2	Yes	6	2.50	0.0014	0.1257	0.0034
2	No	6	2.50	0.0014	0.1210	0.0033
3	Yes	5	3.33	0.0006	0.0494	0.0022
3	No	5	3.33	0.0009	0.0602	0.0021
4	No	6	3.83	0.0008	0.0434	0.0025
5	No	7	4.42	0.0008	0.0578	0.0026
Total		41	4.42	0.0081	0.7129	0.0204
ppm Concentration in Soil >>>>>>				1171	15	2000

Table 8 shows the leaching behaviors of Cd, Pb, and Zn in the UFA and soil column experiments. After approximately four pore volumes of synthetic vadose water had flowed through the samples, less than 1 percent of each metal in the soil was leached out from the UFA and soil columns. This indicates that water leachable metals account for only a small amount of the total metals bound to the Bunker Hill samples. This is similar to other leaching studies on various metal-contaminated soils (e.g. Silviera and Sommers, 1977; Förstner and Kersten, 1988; Howard and Sova, 1993). In addition, the mobilities of the metals shown in Table 8 are in the order: Cd > Pb > Zn.

The above concentrations of metals in the leachates are from tens to tens of thousands of $\mu g\ kg^{-1}$(ppb) and establish the general ranges of metal concentrations in leachates to be expected during subsequent leaching tests. These are the concentrations that must be addressed by the apatite treatments.

3.5.2 APATITE TREATMENT

The elemental and anion concentrations of selected leachates from the UFA flow-through experiments are shown in Tables 9 and 10. The concentrations of selected metals (Pb, Cd, and Zn) are plotted along with untreated soil leachate metal concentrations, demonstrating the efficacy of the North Carolina apatite in the remediation of metal-contaminated soils (Figures 11 to 14). With the treatment by apatite either as a layer at the bottom of a UFA sample holder (Figure 11) or as a mixing additive (10% by weight) to the contaminated soils (Figures 12 and 13), the metal concentrations of the leachates are substantially decreased, most of them below ICP/MS detection limits. Even with only 1% ground apatite mixed with BH4000, the leachates have Pb, Cd, and Zn concentrations below ICP/MS detection limits (Figure 14). The use of synthetic vadose zone water or deionized water on the UFA runs does not show a major effect on the leaching behavior of apatite-treated soils (Figures 12 and 13). Although longer residence times increase metal mobility and different metals have variable responses to residence time in the leaching experiments of the untreated soils (Figures 9 and 10), the leaching behavior of the metals are not affected by the change of residence time after apatite treatment (Figure 11 to 14).

Table 9. Elemental Concentrations of Bunker Hill Soil Leachates From UFA Experiments After Apatite Treatment (Part 1).

Sample Type	Apatite (wt%)	Ground Apatite	Apatite Treatment	Water Used	Pore Volumes	Filtered Leachate	Mg (25) ng/ml	Al (27) ng/ml	Si (29) ng/ml	K (39) ng/ml	Ca (44) ng/ml	Mn (55) ng/ml
BH2		No	Layer	SVW	2.57	Yes	29200	33.9	14100	24300	174000	1720
BH2		No	Layer	SVW	2.57	No	27300	25.1	14600	24900	173000	1610
BH2		No	Layer	SVW	4.29	No	24300	27.5	12500	21400	138000	739
BH2		No	Layer	SVW	5.71	Yes	18000±2000	<5	9500±1200	16400	117000	420
BH2		No	Layer	SVW	5.71	No	22200	<5	12000	20600	138000	465
BH2		No	Layer	SVW	6.57	No	24000±3000	25.0	12000	21100	148000	416
BH2		No	Layer	SVW	7.43	No	36600	<5	8160	19500	215000	198
BH2	10	No	Mixed	DI	1	No	54100	73.3	25300	18500	295000	610
BH2	10	No	Mixed	DI	2	No	39000	21±5	20200	17800	232000	1410
BH2	10	No	Mixed	DI	3	No	28500	13±4	20100	17400	188000	1730
BH2	10	No	Mixed	DI	10	No	8310	15.1	12600	9890	96200	2330
BH2	10	No	Mixed	DI	18	No	4970	44±10	10900	6800	67400	2310
BH2	10	No	Mixed	SVW	1	No	58600	31±4	25800	18100	306000	123
BH2	10	No	Mixed	SVW	2	No	43500	19±3	21600	19200	247000	1420
BH2	10	No	Mixed	SVW	3	No	31800	15.2	20100	18900	182000	941
BH2	10	No	Mixed	SVW	10	No	9510	65±27	12200	11400	100000	2390
BH2	10	No	Mixed	SVW	20	No	6260	11±3	11000	8360	76700	2840
BH2	10	No	Mixed	SVW	30	No	5180	<5	13800	8270	70300	5420
BH2	10	No	Mixed	SVW	40	No	4740	<5	12700	6410	60300	5610
BH4	1	Yes	Mixed	SVW	1	No	42700	17±2	25700	15900	245000	17.3
BH4	1	Yes	Mixed	SVW	2	No	31000	18±5	20400	13600	195000	342
BH4	1	Yes	Mixed	SVW	3	No	22700	24±15	23900	16900	185000	969
BH4	1	Yes	Mixed	SVW	10	No	8740	<5	18800	12600	108000	4650
BH4	1	Yes	Mixed	SVW	20	No	4080	<5	13300	7320	72700	5510

Note: DI = Deionized water; SVW = Synthetic vadose water.

Table 9. Elemental Concentrations of Bunker Hill Soil Leachates From UFA Experiments After Apatite Treatment (Part 2).

Sample Type	Apatite (wt%)	Ground Apatite	Apatite Treatment	Water Used	Pore Volumes	Filtered Leachate	Fe (56) ng/ml	Ni (60) ng/ml	Cu (65) ng/ml	Zn (68) ng/ml	As (75) ng/ml
BH2		No	Layer	SVW	2.57	Yes	<100	31.0	8.6±3.2	198	<5
BH2		No	Layer	SVW	2.57	No	<100	34±6	7.1±2.8	200±30	<5
BH2		No	Layer	SVW	4.29	No	<100	31.1	<5	74.7	<5
BH2		No	Layer	SVW	5.71	Yes	<100	21.6	<5	22.2	<5
BH2		No	Layer	SVW	5.71	No	<100	29.2	<5	20±10	<5
BH2		No	Layer	SVW	6.57	No	<100	42.6	<5	51.4	<5
BH2		No	Layer	SVW	7.43	No	<100	60±7	<5	19±3	<5
BH2	10	No	Mixed	DI	1	No	(<50)	20±4	79.4	<1	54±6
BH2	10	No	Mixed	DI	2	No	(<50)	12±2	33.7	<1	21.8
BH2	10	No	Mixed	DI	3	No	(<50)	11.0	11.2	<1	17.1
BH2	10	No	Mixed	DI	10	No	(82±20)	10.6	7.5±2.0	<1	30.2
BH2	10	No	Mixed	DI	18	No	(682)	3.1±0.5	6.87	<1	42.0
BH2	10	No	Mixed	SVW	1	No	(<50)	14.2	62.6	<1	43.1
BH2	10	No	Mixed	SVW	2	No	(<50)	8.8±1.1	32.4	<1	29.3
BH2	10	No	Mixed	SVW	3	No	(<50)	10.3	25.7	<1	24±3
BH2	10	No	Mixed	SVW	10	No	(<50)	10.3	8.52	<1	36.3
BH2	10	No	Mixed	SVW	20	No	(641)	5.73	6.5±3.2	<1	46.5
BH2	10	No	Mixed	SVW	30	No	1850	7.26	<5	<5	44.0
BH2	10	No	Mixed	SVW	40	No	1670	<5	<5	<5	37.1
BH4	1	Yes	Mixed	SVW	1	No	(<50)	11.4	45.0	<1	57.2
BH4	1	Yes	Mixed	SVW	2	No	(<50)	6.8±2.2	21±7	<1	37.0
BH4	1	Yes	Mixed	SVW	3	No	<100	9.31	9.05	<5	24±6
BH4	1	Yes	Mixed	SVW	10	No	<100	8.35	<5	<5	15.1
BH4	1	Yes	Mixed	SVW	20	No	543	<5	10.5	<5	27.7

Note: DI = Deionized water; SVW = Synthetic vadose water.

Table 9. Elemental Concentrations of Bunker Hill Soil Leachates From UFA Experiments After Apatite Treatment (Part 3).

Sample Type	Apatite (wt%)	Ground Apatite	Apatite Treatment	Water Used	Pore Volumes	Filtered Leachate	Sr (88) ng/ml	Cd (114) ng/ml	Ba (138) ng/ml	Hg (200) ng/ml	Pb (208) ng/ml
BH2		No	Layer	SVW	2.57	Yes	1710	<5	10.3	<5	1.7±1.5
BH2		No	Layer	SVW	2.57	No	1600	<5	9.59	6.26	<1
BH2		No	Layer	SVW	4.29	No	1510	<5	<5	<5	<1
BH2		No	Layer	SVW	5.71	Yes	1340	<5	<5	<5	<1
BH2		No	Layer	SVW	5.71	No	1560	<5	<5	<5	<1
BH2		No	Layer	SVW	6.57	No	1670	<5	<5	<5	<1
BH2		No	Layer	SVW	7.43	No	2570	<5	<5	<5	<1
BH2	10	No	Mixed	DI	1	No	1700	<5	795	<5	<1
BH2	10	No	Mixed	DI	2	No	1310	<5	695	<5	<1
BH2	10	No	Mixed	DI	3	No	979	<5	541	5.5±1.4	<1
BH2	10	No	Mixed	DI	10	No	501	<5	247	<5	<1
BH2	10	No	Mixed	DI	18	No	371	<5	148	<5	<1
BH2	10	No	Mixed	SVW	1	No	1670	<5	867	<5	<1
BH2	10	No	Mixed	SVW	2	No	1350	<5	706	<5	<1
BH2	10	No	Mixed	SVW	3	No	1110	<5	501	<5	<1
BH2	10	No	Mixed	SVW	10	No	594	<5	274	<5	<1
BH2	10	No	Mixed	SVW	20	No	449	<5	173	<5	<1
BH2	10	No	Mixed	SVW	30	No	432	<5	133	<5	<5
BH2	10	No	Mixed	SVW	40	No	388	<5	110	<5	<5
BH4	1	Yes	Mixed	SVW	1	No	1120	<5	575	<5	<1
BH4	1	Yes	Mixed	SVW	2	No	1020	<5	563	<5	<1
BH4	1	Yes	Mixed	SVW	3	No	979	<5	560	<5	<5
BH4	1	Yes	Mixed	SVW	10	No	520	<5	352	<5	<5
BH4	1	Yes	Mixed	SVW	20	No	376	<5	222	<5	<5

Note: DI = Deionized water; SVW = Synthetic vadose water.

Table 10. Anion Concentrations of Bunker Hill Soil Leachates From UFA Experiments After Apatite Treatment.

Sample	Apatite	Ground	Apatite	Water	Pore	pH	Phosphate	Fluoride	Chloride	Nitrite	Nitrate	Sulfate
Type	(wt%)	Apatite	Treatment	Used	Volumes		µg/ml	µg/ml	µg/ml	µg/ml	µg/ml	µg/ml
BH2	10	No	Mixed in	DI	1	NA	0.19	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	DI	2	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	DI	3	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	DI	6	8.0	<0.10	0.90	1.90	<0.90	1.62	133.00
BH2	10	No	Mixed in	DI	10	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	DI	16	4.2	<0.10	0.75	2.02	<0.90	1.55	22.20
BH2	10	No	Mixed in	SVW	1	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	SVW	2	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	SVW	6	8.1	<0.10	1.04	21.50	<0.90	1.66	175.00
BH2	10	No	Mixed in	SVW	10	NA	<0.10	NA	NA	NA	NA	NA
BH2	10	No	Mixed in	SVW	16	8.4	<0.10	0.96	22.00	<0.90	1.60	56.90
BH2	10	No	Mixed in	SVW	20	NA	<0.10	NA	NA	NA	NA	NA
BH4	1	Yes	Mixed in	SVW	1	NA	0.22	NA	NA	NA	NA	NA
BH4	1	Yes	Mixed in	SVW	2	NA	0.13	NA	NA	NA	NA	NA

Note: DI = Deionized water; SVW = Synthetic vadose water; NA = Not analyzed.

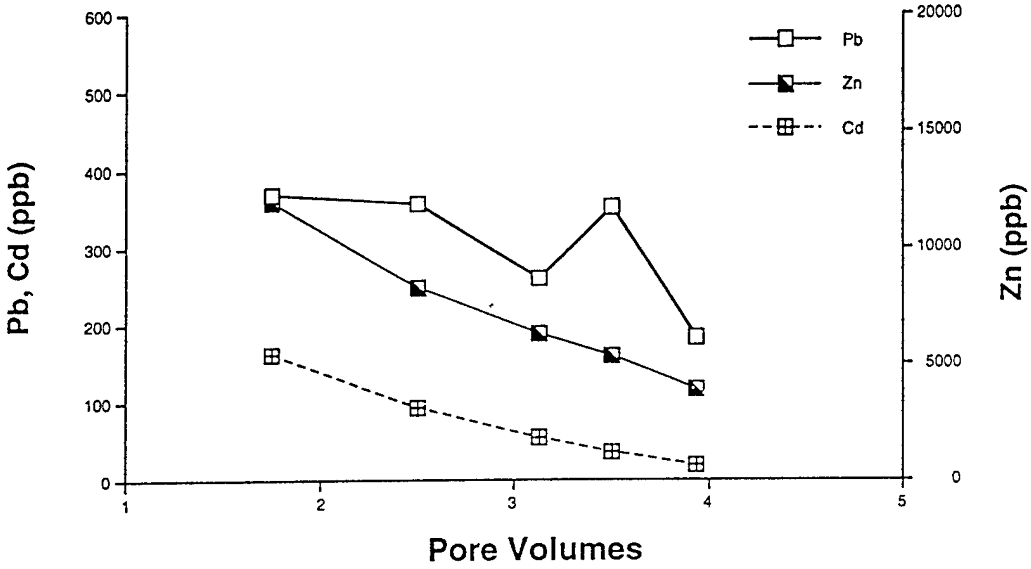


Figure 9. Concentrations of Metals in Effluents From the Soil Column Gravity Drain Experiment on Untreated BH2000 Soil.

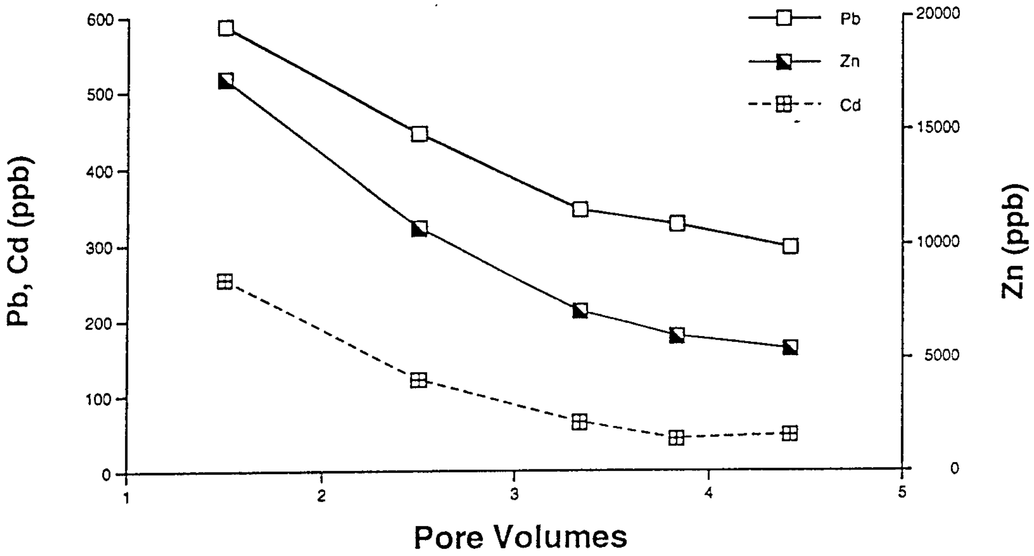


Figure 10. Concentrations of Metals in Effluents From UFA Flow Through Experiments on Untreated BH2000 Soil.

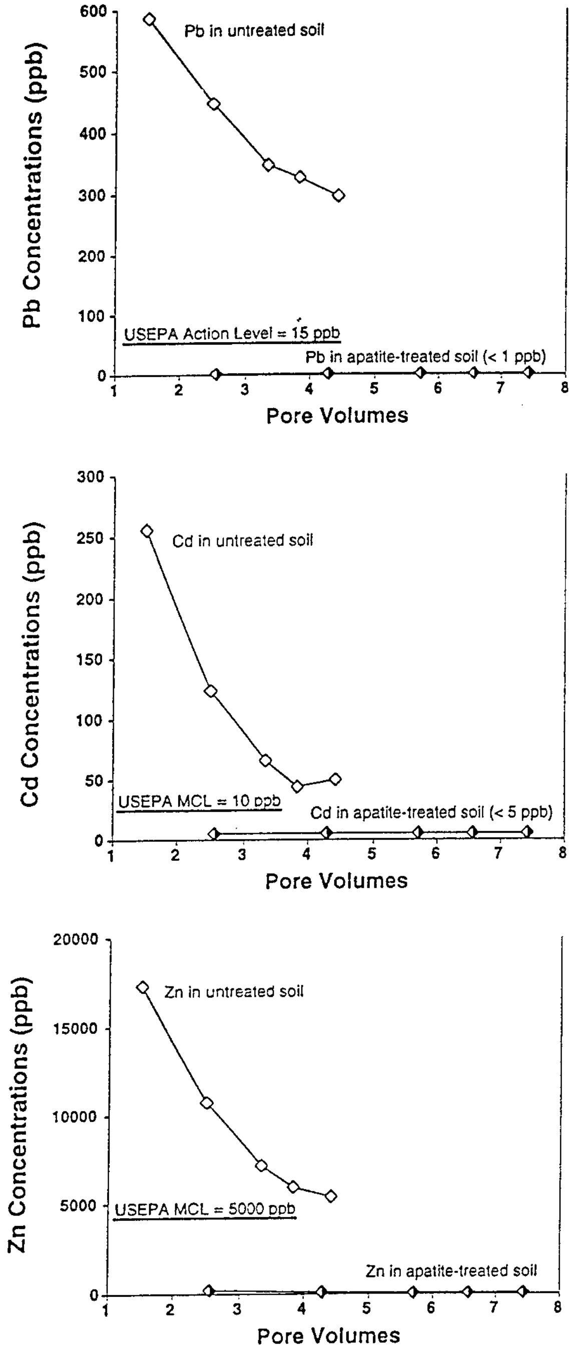


Figure 11. UFA Desorption/Sorption run on BH2000 Soil With a Layer of Un-Ground NC Apatite at the Bottom of the Sample Holder using Synthetic Vadose Zone Water, Recharge = 2 x 10^{-7}cm/s.

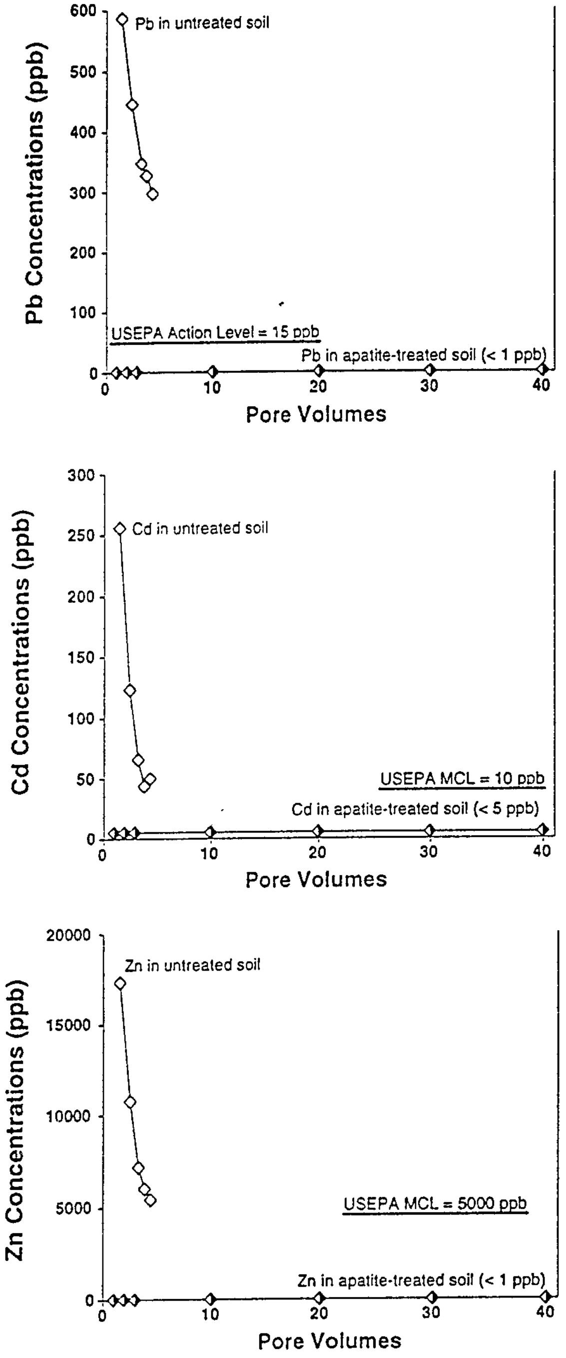


Figure 12. UFA Desorption/Sorption run on BH2000 Soil Mixed With 10% Un-Ground NC Apatite using Synthetic Vadose Zone Water, Recharge = 2 x 10^{-7}cm/s.

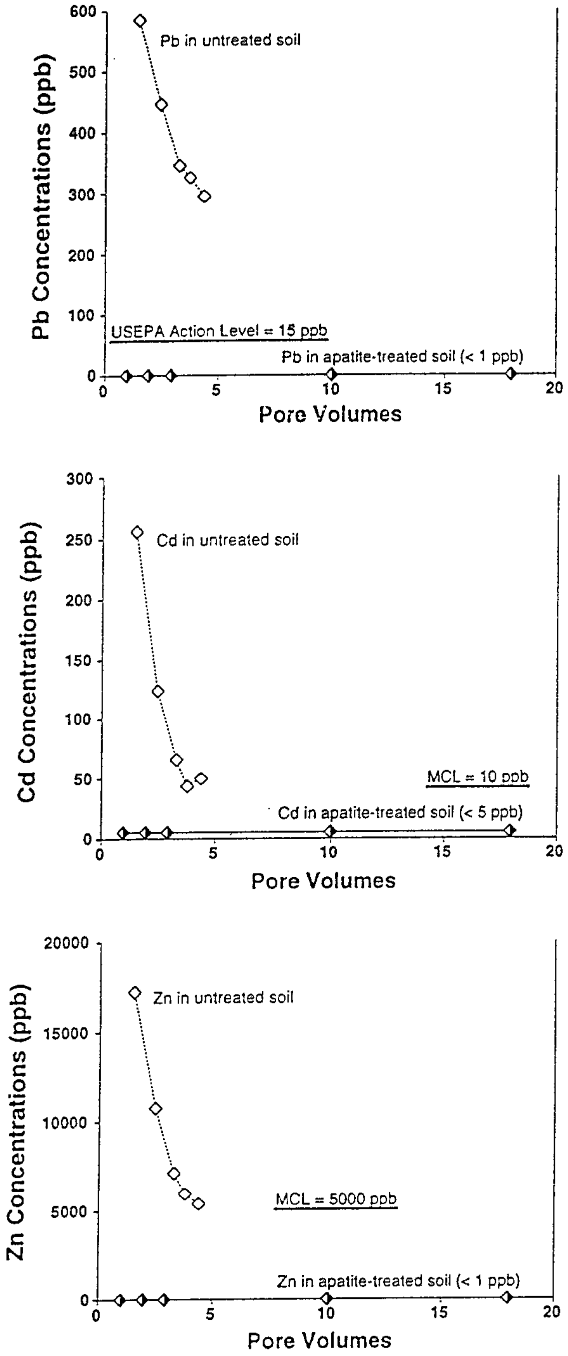


Figure 13. UFA Desorption/Sorption run on BH2000 Soil Mixed With 10% Un-Ground NC Apatite using Deionized Water, Recharge = 2 x 10^{-7}cm/s.

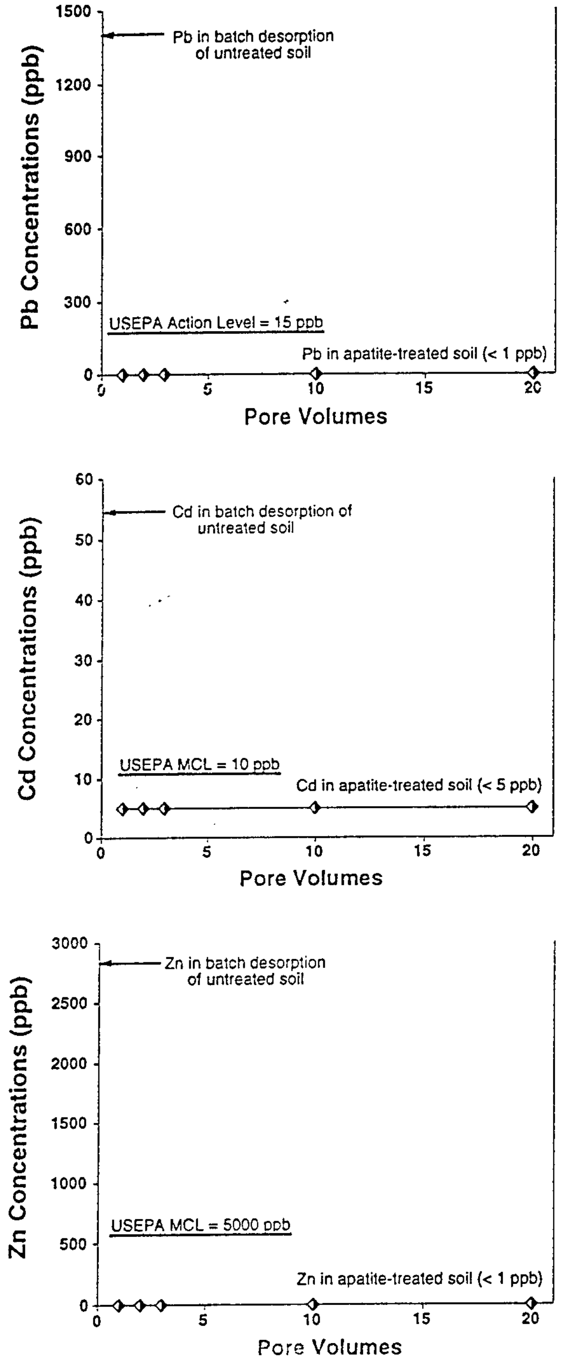


Figure 14. UFA Desorption/Sorption run on BH4000 Soil Mixed With 1% Ground NC Apatite using Synthetic Vadose Zone Water, Recharge = 2×10^{-7}cm/s.

4.0 CONCLUSIONS

In summary, the results of the batch and flow-through experiments of both untreated and apatite-treated contaminated soils result in the following conclusions.

- The concentrations of Zn, Pb, and Cd in the leachate effluents of the UFA and soil column flow through experiments for the untreated Bunker Hill contaminated soils differ by several orders of magnitude, varying from tens to tens of thousands of μg/kg (ppb).
- The metal leaching behaviors in the UFA and soil column runs for the untreated soils are similar. A difference was observed in their response to the change of residence time. Soil column runs react faster than UFA runs, and different metals may behave differently within each of the flow through experiments.
- Longer residence times increase metal mobility in the untreated soils.
- Water leachable metals account for only a small amount of the total metals in the untreated soils. The mobility of the primary metals of concern are in this order: Cd > Pb > Zn.
- All of the concentrations of Pb, Cd, and Zn in the leachate effluents of the UFA flow-through experiments of apatite-treated Bunker Hill soils are below USEPA regulatory limits and most of them are below the detection limits of ICP/MS.
- The change of residence time has no apparent effect on the leaching behaviors of the metals after apatite treatment.
- During the 24-hour adsorption isotherm, the greatest reduction of desorbed Pb, Zn, Mn, and Cd by the addition of NC apatite is at 1% or less.
- During the 48-hour adsorption isotherm, the greatest reduction of desorbed Pb, Zn, Mn and Cd by the addition of NC apatite is at 1% or less and is actually depicted by the NC apatite concentrations of .005, .002, and .08%.
- The greatest reduction of desorbed Pb at less than 1% added NC apatite confirms the molar ratio calculation scenario of $Pb:PO_4$ for pyromorphytes.
- The kinetics of formation for Pb, Zn, and Cd phosphate complexes are 24 hours or less.
- Thermodynamic predictions for the formations of pyromorphytes at less than 1% addition of NC apatite confirm the molar ratio calculation scenario of $Pb:PO_4$ for

pyromorphytes and also confirm the precipitation of Pb at less than 1% NC apatite in the adsorption isotherms.

- Thermodynamic predictions for the formation of rhodochrosite ($MnHPO_4$) at less than 1% addition of NC apatite confirm the precipitation of Mn at less than 1% NC apatite in the 24- and 48-hour adsorption isotherms.
- Thermodynamic predictions for the formation of Hopeite ($Zn_3(PO_4)_2\ 4H_2O$) at less than 1% addition of NC apatite confirm the precipitation of Zn at less than 1% NC apatite in the 24- and 48-hour adsorption isotherms.
- The thermodynamic prediction for the formation of $Cd_3(PO_4)_2$ is not substantiated by MINTEQ-A2. However, the adsorption isotherm shows an 83% reduction of desorbed Cd at less than 1% addition of NC apatite.

5.0 APATITE FORMULATIONS AND EMPLACEMENT STRATEGIES

The results of the experiments described above establish that apatite can be an effective chemical stabilization agent for lead, cadmium, manganese, and zinc. The purpose of this section is to discuss potential apatite formulations, both chemical and physical, that could be used for remediating contaminated soils or other solids. The chemical properties of apatite vary depending on its source. It may be chemically synthesized, biogenic, or mined, and the particular source of the mined deposit or biogenic material will affect its chemical constituents and its reactivity. Grinding the material has also been seen to improve its reactivity, perhaps by creating a larger and "fresher" surface for reaction with ions in solution. Several types of apatite have been tested as part of this project, and the results are presented in section 5.1 below.

In addition to the chemical makeup, the physical formulation of the apatite can be varied. In our experiments to date, apatite material was simply added as a granulated solid to the samples being treated. However, we recognize that remediation of soils or other solids in the field may require delivery of the apatite into the ground in the form of a slurry or solution. Section 5.2 discusses several potential emplacement strategies, technical issues associated with those strategies, characteristics of sites for which those strategies are appropriate, and their relative advantages and disadvantages. An emplacement contractor will require certain data on the physical properties of the apatite in order to ensure that the equipment can deliver it. Section 5.3 provides such data, including measurements of the flow properties of apatite slurries as a function of solids content and particle size. Finally, costs of apatite treatment per unit of treated soil are estimated in section 5.4.

5.1 CHEMICAL FORMULATION

Apatite is available commercially from a variety of sources, each having slightly different chemical compositions. These materials vary in their effectiveness in immobilizing metals depending on their carbonate and trace metal concentrations. Carbonate substitution into apatite increases the solubility of its the phosphate (Chien and Hammond,1978), which can then react with metal contaminants. However, trace metal impurities reduce phosphorus solubility and hence effectiveness.

We compared the effectiveness of four different apatites using batch adsorption tests of the type described above in section 3. The four apatites tested were:

- A synthetic hydroxyapatite (HAP), tribasic calcium phosphate, from Aldrich Chemical Company. This material is a reagent grade, laboratory precipitated powder with few impurities. Its chemical composition is given in Table 11.

Table 11. Reported Analysis for Reagent Grade Synthetic Apatite.

CALCIUM PHOSPHATE TRIBASIC **CERTIFIED**
Precipitated powder

Hydroxylapatite
Approx. $Ca_{10}(OH)_2(PO_4)_5$

Product Specifications
Actual Lot Analysis is reported on label.

Insolube in dilute HCl	≤0.010%
Dibasic or Free CaO	To pass test
Chloride	≤0.010%
Sulfate	≤0.02%
Ammonia	≤0.02%
Arsenic	≤1ppm
Barium	≤0.01%
Heavy Metals (as Pb)	≤0.002%
Iron	≤0.005%
Magnesium	≤0.20%
Soluble Salts	≤1.5%

- SRM 120b Florida phosphate rock, a naturally occuring apatite mineral mined in Florida. This material serves as a NIST chemical standard, for which it has been ground into a fine powder and is well mixed to provide homogeneous aliquots. The composition of Florida apatite is given in Table 12.

- North Carolina apatite, an unprocessed (not acidified or ground), natural ore commercially available from Texasgulf, Inc, for use as a fertilizer. Its composition is given in Table 13.

- A biogenic apatite from fish cannery wastes. This material is primarily fish bones, cleaned and dried to remove most of the organic material and ground to pass a 170-mesh (0.090 mm) sieve. Such wastes are a potential low-cost source of apatite, but they also contain organics, the effect of which have not been investigated, although they appear to have little influence on the stabilization of metals.

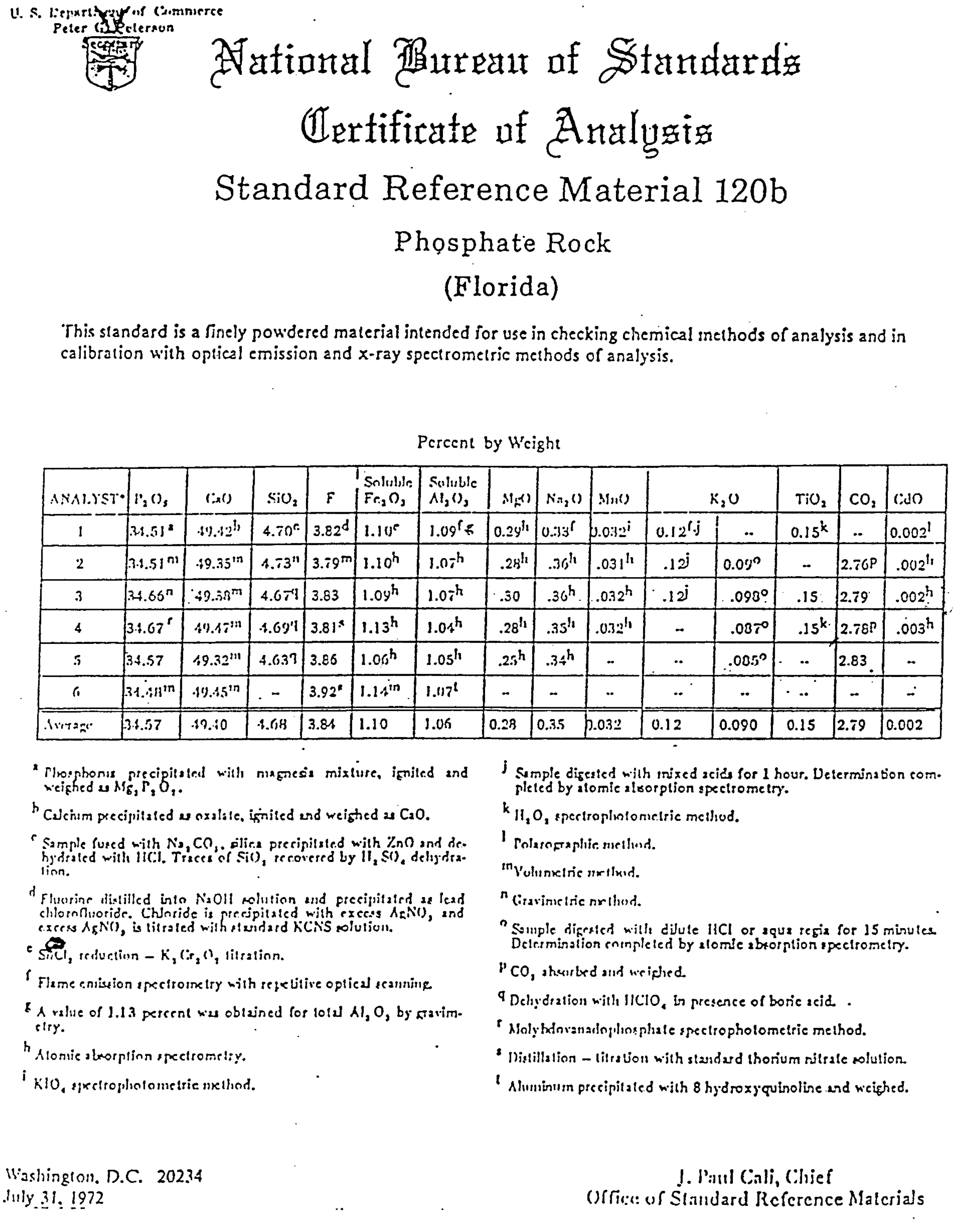
Both the Florida and North Carolina apatites are carbonate fluorapatites from naturally occurring marine deposits. Therefore, they contain some impurities that will affect the amount of phosphate available for dissolution.

As received from the supplier, the North Carolina apatite is a fairly coarse material, with more than 50% retained on a 65-mesh (0.210 mm) screen. The other apatite samples are fine powders, which have larger specific surface areas and can also dissolve quickly. To control for and study the effect of particle size, we also tested a sample of the North Carolina apatite ground to pass a 170-mesh sieve.

In each experiment, three grams of the BH4000 soil was mixed with apatite at apatite-to-soil ratios of 1:100, 1:20, 1:10, and 1:5 by weight. Thirty grams of deionized water were added to the solids in polycarbonate tubes. The tubes containing the slurries were shaken continuously for either 24 or 48 hours. Supernatants were obtained by centrifuging and filtering the samples and were analyzed by ICP-MS.

The results for several metals are shown in Figures 15-18. Similar tests without apatite, described in the Milestone Two Report, established the baseline concentrations of leached metals. These values are included in the figures as the results for 0% apatite. The treated values are reported as 1%, 5%, 10%, and 20% apatite as a fraction of total solids. Figure A shows lead concentration versus per cent apatite addition for the different types of apatite. The cannery material is the most effective at pulling lead out of solution, with 1% apatite sufficient to bring the lead concentration nearly below the ICP-MS detection limit of 1 ng ml^{-1} (ppb). The synthetic, powdered hydroxyapatite is nearly as effective, and the ground NC apatite also performs well. The unground NC apatite and the Florida apatite are less effective.

Table 12. Reported Analysis for Florida Phosphate Rock



U. S. Department of Commerce
Peter G. Peterson
Secretary

National Bureau of Standards
Certificate of Analysis
Standard Reference Material 120b
Phosphate Rock
(Florida)

This standard is a finely powdered material intended for use in checking chemical methods of analysis and in calibration with optical emission and x-ray spectrometric methods of analysis.

Percent by Weight

ANALYST*	P_2O_5	CaO	SiO_2	F	Soluble Fe_2O_3	Soluble Al_2O_3	MgO	Na_2O	MnO	K_2O		TiO_2	CO_2	CdO
1	34.51[a]	49.42[b]	4.70[c]	3.82[d]	1.10[e]	1.09[f,g]	0.29[h]	0.33[f]	0.032[i]	0.12[f,j]	--	0.15[k]	--	0.002[l]
2	34.51[m]	49.35[m]	4.73[n]	3.79[m]	1.10[h]	1.07[h]	.28[h]	.36[h]	.031[h]	.12[j]	0.09[o]	--	2.76[p]	.002[h]
3	34.66[n]	49.38[m]	4.67[q]	3.83	1.09[h]	1.07[h]	.30	.36[h]	.032[h]	.12[j]	.098[o]	.15	2.79	.002[h]
4	34.67[r]	49.47[m]	4.69[q]	3.81[s]	1.13[h]	1.04[h]	.28[h]	.35[h]	.032[h]	--	.087[o]	.15[k]	2.78[p]	.003[h]
5	34.57	49.32[m]	4.63[q]	3.86	1.06[h]	1.05[h]	.25[h]	.34[h]	--	--	.085[o]	--	2.83	--
6	34.48[m]	49.45[m]	--	3.92[s]	1.14[m]	1.07[t]	--	--	--	--	--	--	--	--
Average	34.57	49.40	4.68	3.84	1.10	1.06	0.28	0.35	0.032	0.12	0.090	0.15	2.79	0.002

[a] Phosphorus precipitated with magnesia mixture, ignited and weighed as $Mg_2P_2O_7$.

[b] Calcium precipitated as oxalate, ignited and weighed as CaO.

[c] Sample fused with Na_2CO_3, silica precipitated with ZnO and dehydrated with HCl. Traces of SiO_2 recovered by H_2SO_4 dehydration.

[d] Fluorine distilled into NaOH solution and precipitated as lead chlorofluoride. Chloride is precipitated with excess $AgNO_3$ and excess $AgNO_3$ is titrated with standard KCNS solution.

[e] $SnCl_2$ reduction – $K_2Cr_2O_7$ titration.

[f] Flame emission spectrometry with repetitive optical scanning.

[g] A value of 1.13 percent was obtained for total Al_2O_3 by gravimetry.

[h] Atomic absorption spectrometry.

[i] KIO_4 spectrophotometric method.

[j] Sample digested with mixed acids for 1 hour. Determination completed by atomic absorption spectrometry.

[k] H_2O_2 spectrophotometric method.

[l] Polarographic method.

[m] Volumetric method.

[n] Gravimetric method.

[o] Sample digested with dilute HCl or aqua regia for 15 minutes. Determination completed by atomic absorption spectrometry.

[p] CO_2 absorbed and weighed.

[q] Dehydration with $HClO_4$ in presence of boric acid.

[r] Molybdovanadophosphate spectrophotometric method.

[s] Distillation – titration with standard thorium nitrate solution.

[t] Aluminum precipitated with 8 hydroxyquinoline and weighed.

Washington, D.C. 20234
July 31, 1972

J. Paul Cali, Chief
Office of Standard Reference Materials

Table 13. Reported Analysis for North Carolina Natural Phosphate

Texasgulf

North Carolina Natural Phosphate (NCNP)

30% P_2O_5 - For Use As A Fertilizer In Acid Soil

NCNP is a natural source of Phosphorus and Calcium derived from marine sediments. NCNP has not been subjected to acidulation or grinding.

Typical Analysis - (dry basis)

Component	Typical Percent
Total Phosphorus, as P	13.2
Total Phosphorus, as P_2O_5	30.3
Calcium, as CaO	48.8
Magnesium, as MgO	0.6
Total Sulphur, as S	1.3
Total Carbon, as C	3.1
Zinc, as Zn	313 ppm
Boron, as B	95 ppm
Molybdenum, as Mo	45 ppm
Copper, as Cu	13 ppm

Soluble Phosphorus	% of total P
–in Water	0
–in Neutral Ammonium Citrate	13
–in 2% Citric Acid	37
–in 2% Formic Acid	72
–in HNO_3/HCl	100

Physical Characteristics

Screen Analysis (Tyler)	Sieve Opening	%
Passing 14 mesh	1.190 mm	100
Passing 35 mesh	0.420 mm	97
Passing 65 mesh	0.210 mm	49
Passing 100 mesh	0.149 mm	19
Passing 200 mesh	0.074 mm	1
Surface Area (B.E.T.)	22 m^2/mg	

Bulk Density	
Loose	1.44 g/cm^3 (90 lbs/ft^3)
Tamped	1.60 g/cm^3 (100 lbs/ft^3)

Color	Brownish Black

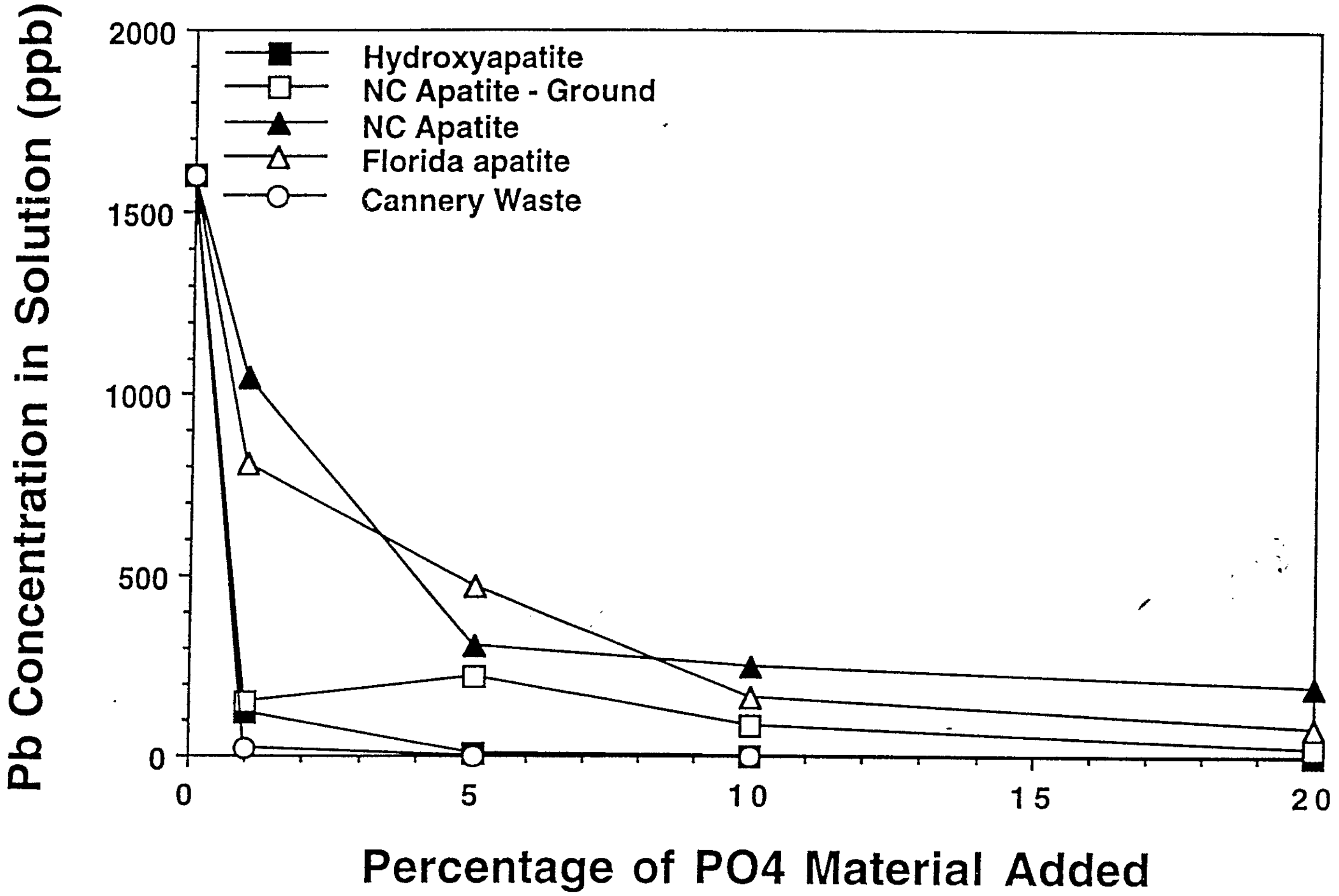


Figure 15. Lead Desorption/Sorption Results From Batch Tests Using Bunker Hill 4000 Soil and Deionized Water in a Water:Soil Ratio of 10:1. Lead Concentrations are Plotted as a Function of Phosphate Material Added as a Weight Percent of Total Sample.

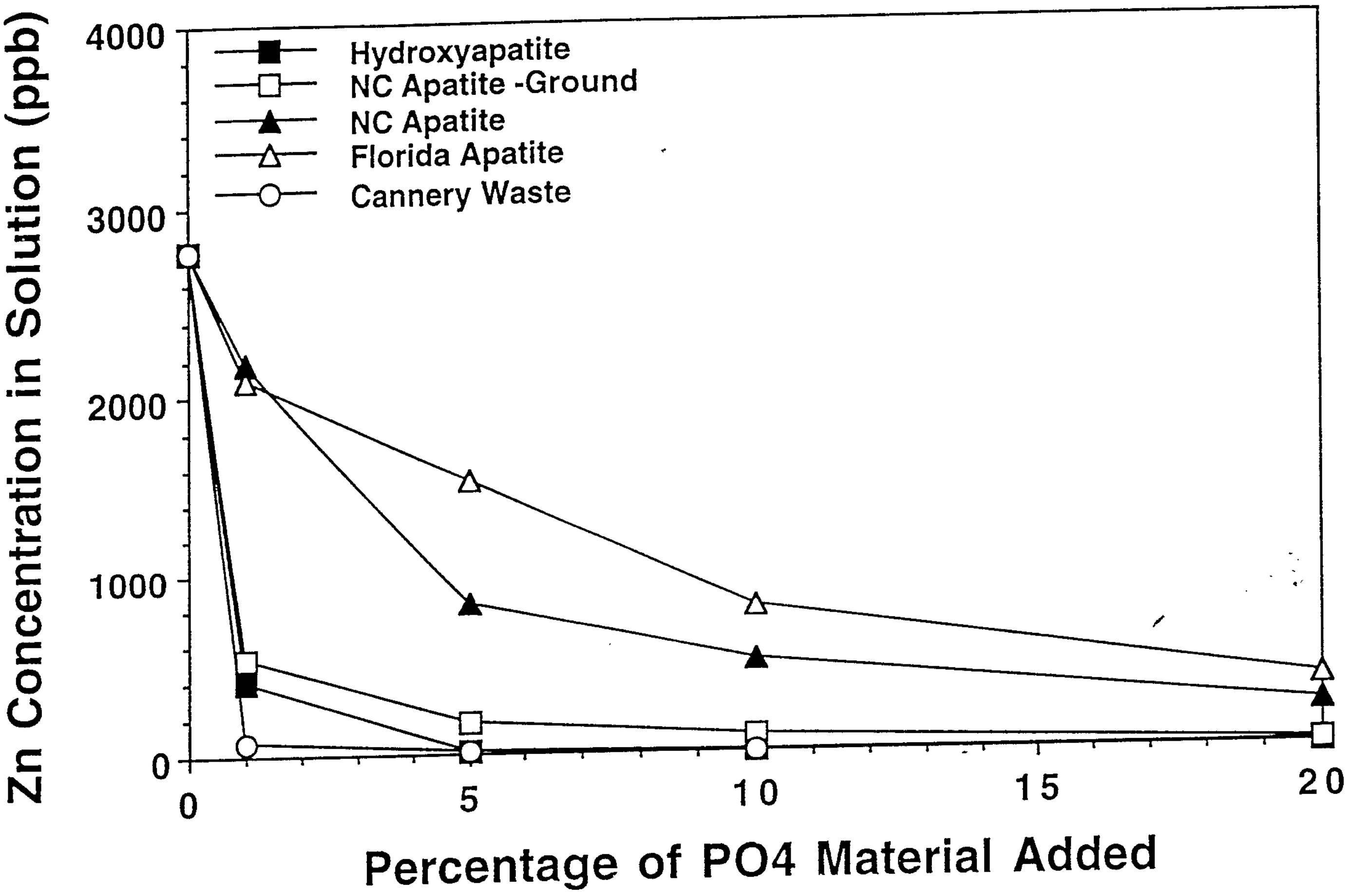


Figure 16. Zinc Desorption/Sorption Results From Batch Tests Using Bunker Hill 4000 Soil and Deionized Water in a Water:Soil Ratio of 10:1. Zinc Concentrations are Plotted as a Function of Phosphate Material Added as a Weight Percent of Total Sample.

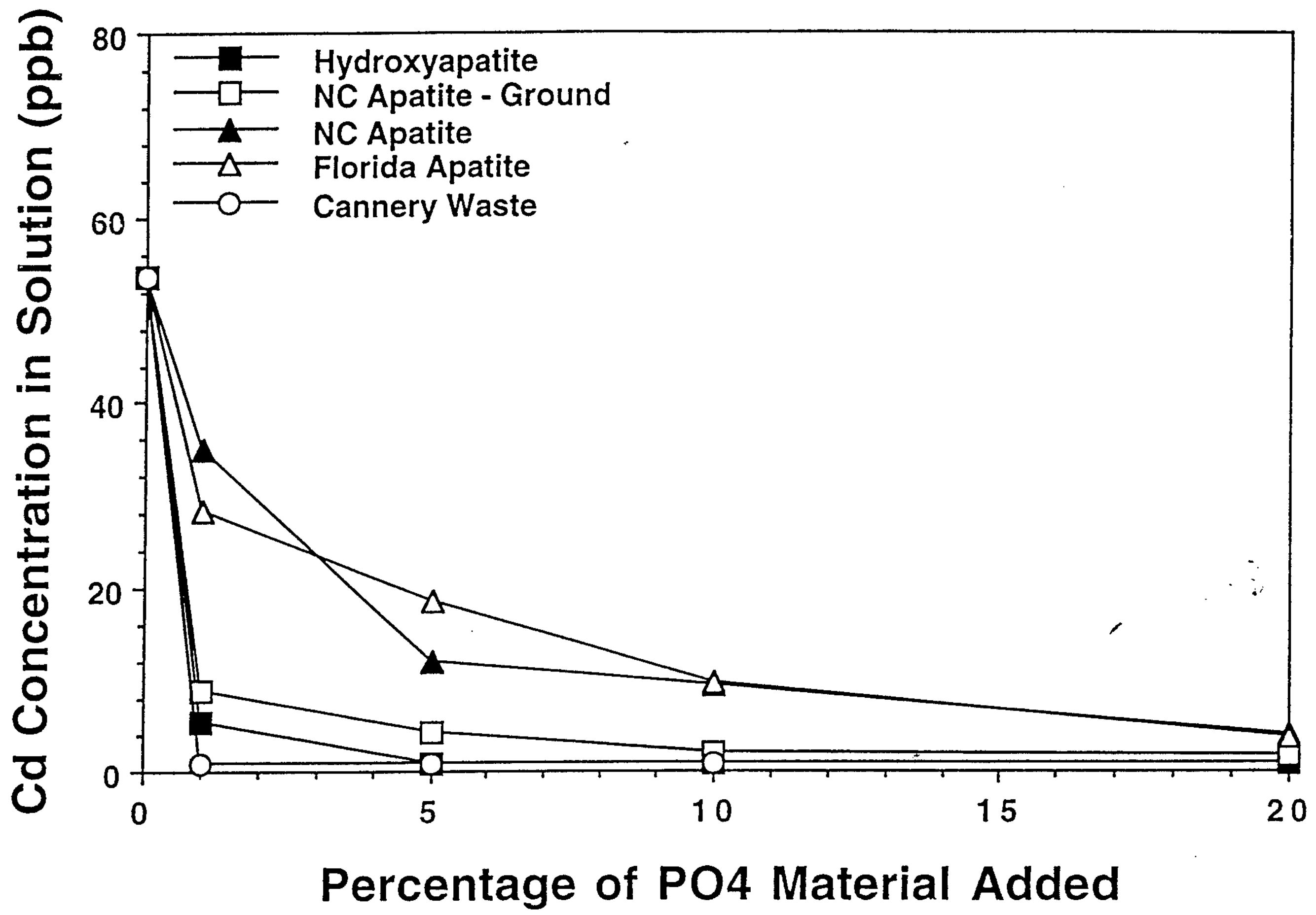


Figure 17. Cadmium Desorption/Sorption Results From Batch Tests Using Bunker Hill 4000 Soil and Deionized Water in a Water:Soil Ratio of 10:1. Cadmium Concentrations are Plotted as a Function of Phosphate Material Added as a Weight Percent of Total Sample.

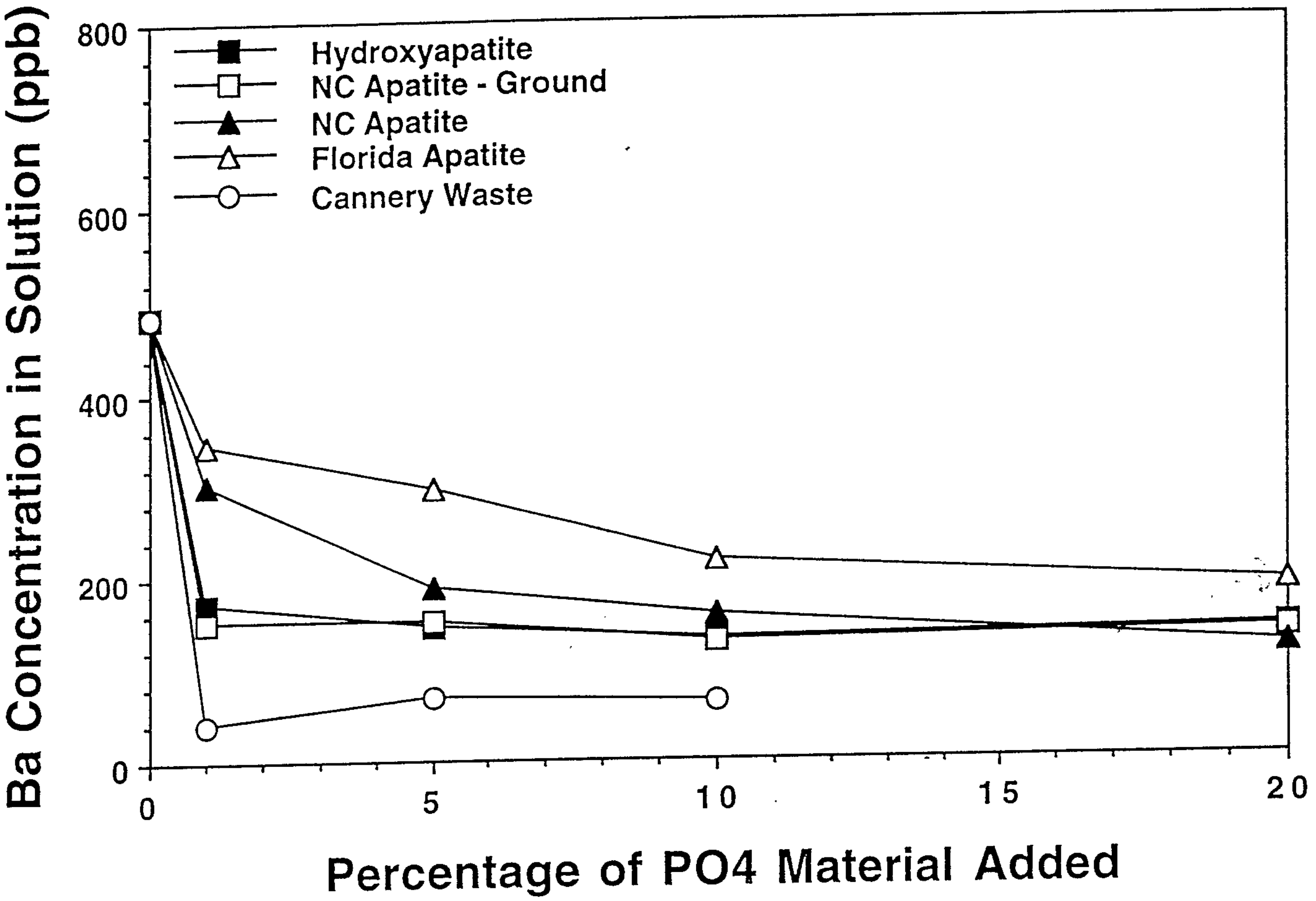


Figure 18. Barium Desorption/Sorption Results From Batch Tests Using Bunker Hill 4000 Soil and Deionized Water in a Water:Soil Ratio of 10:1. Barium Concentrations are Plotted as a Function of Phosphate Material Added as a Weight Percent of Total Sample.

(Note that the flow-through tests discussed in section 4 showed that even the unground NC apatite would bring lead leachate concentrations below detection limits under more soil-like conditions.) The results for ground and unground NC apatite show that particle size does affect the amount of lead immobilized.

Figure 16 shows results for zinc. Again, even though the Florida apatite was finely-ground, it is not as effective as even the unground NC apatite. The cannery material, the ground NC apatite, and the synthetic HAP have the best performance. Less than 5% of the biogenic apatite or the HAP drops the zinc concentration below the detection limit of 1 ng ml^{-1}, while small amounts of zinc remain in solution for the other materials. Figure 17 shows results for cadmium, with similar results. The detection limit for cadmium is 5 ng ml^{-1}. Finally, the results for barium in solution are shown in Figure 18. In this case, biogenic apatite is able to reduce the leachate concentration by a factor of ten or so, but none of the five materials tested can bring the level below a threshold of about 50 ng ml^{-1}.

In all of these results, the cannery material (ground fish bones and teeth) is the most effective at reducing dissolved metal concentrations. When available locally, cannery wastes may be an inexpensive raw material for soil remediation. If, however, processing is required to clean and grind the material before it can be used, its cost effectiveness may decline. Its properties may also vary from source to source. The highly pure, high-surface area synthetic material is also very effective. Synthetic hydroxyapatite has not been exposed to metals and other ions in a natural environment, which tends to reduce apatite's reactivity. The Florida deposits, being geologically older than those in North Carolina, produce a less reactive material. Surface area is also clearly a factor, as the ground and unground NC apatite results show. Higher surface areas make dissolution kinetics faster. However, increasing the reaction time from 24 to 48 hours was shown in section 4 to not substantially affect metal immobilization. Grinding the material may simply be exposing more reactive material to the metal-containing solutions. Precipitation onto apatite surfaces may also be effectively "extinguishing" them, preventing further dissolution of phosphate or direct reaction between the solid apatite and dissolved metals.

While synthetic hydroxyapatite is highly effective, it may not be the material of choice for soil remediation due to its higher cost. A kilogram purchased from Aldrich Chemical Company costs $155. Limited quantities (200-1000 kg) at bulk rates are available for about $20/kg from Sigma Chemical. There may be other sources of bulk hydroxyapatite as well at somewhat lower purity. Alternatively, Texasgulf charges only $85/ton for its NC apatite, $185/ton delivered from the East Coast to the West Coast.

5.2 POTENTIAL EMPLACEMENT STRATEGIES AND METHODS

This section discusses several methods that could be used to introduce apatite into a soil for in situ treatment. The treatment strategy can be broken down into two general categories: direct treatment and barrier placement. In many cases, the geotechnical methods for emplacing the apatite can be used for either strategy.

In direct treatment, apatite is delivered into the contaminated soil region. The contaminant and the apatite are therefore mixed and in intimate contact. Heavy metals in solution in the soil pore waters are rapidly immobilized, and metal ions that go into solution at a later time are similarly precipitated in place. Leaching of metals into groundwater from the contaminated region is thereby prevented. Note that apatite acts on leached metals in solution. There is some evidence that if dissolved metals precipitate out of solution as insoluble phosphates and rind, or coat, individual metal-bearing particles, those particles have reduced metal bioavailability (Davis et al, 1992; PTI Environmental Services, 1994). However, apatite treatment cannot convert entire metal-containing solid particles into a harmless form. Neither does it form a solid monolith of physically stabilized material. As such, it is not an appropriate remediation technology for cases such as blowing dust or particulates swept into surface waters.

Apatite can also be emplaced as a permeable, reactive barrier downgradient of a contaminated region. All groundwater seeping through the metal-containing soil would pass through the barrier. The apatite would react with the dissolved metals, stripping them out of solution and purifying the water. In this strategy, apatite acts much like a chemical filter.

The factors that determine which treatment strategy to apply include physical characteristics of the site, cost, client preference, and regulatory issues. Direct treatment is just that -- direct, and simple. One application mixes all of the contaminant with the treatment agent, and the problem is over. However, there are cases in which a barrier approach may be preferable. For very large sites, delivery of apatite into the whole soil volume may be prohibitively expensive. If the contaminants are highly toxic (such as radionuclides), worker exposure and contamination of equipment may be a concern. Drilling, mixing, and excavation operations may be more safely undertaken in relatively clean soil downgradient from the plume. If the metals have economic value, a barrier may be a way to concentrate and recover some of the material. The barrier could be periodically "mined" and replaced with fresh apatite.

Reactive barriers would be somewhat more complicated to engineer than direct treatment. The permeability of the barrier should be greater than or equal to that of the surrounding soil or aquifer, or else contaminated water may go around the barrier instead of through it. The barrier should be reasonably contiguous, with no large gaps. A barrier may need to be placed under a plume as well as to the sides. For both remediation strategies, the apatite particle size cannot be too much smaller than the soil particle size in order to keep the apatite from being washed out. In some cases where groundwater flow rates are very high, a barrier may need to be lined with a geofabric or other material to hold the apatite in place.

5.2.1 INJECTION

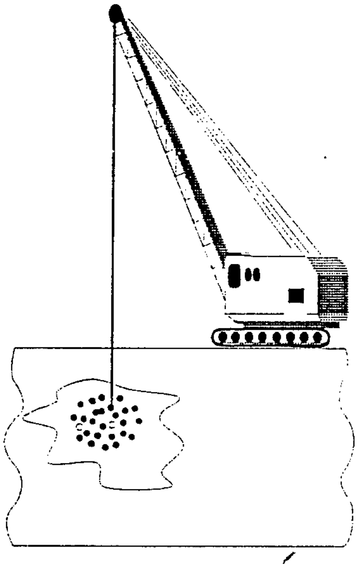


Figure 19. Slurry Injection

Figure 19 illustrates emplacement of apatite by injection. Here we envision injection of a slurry of apatite particles in water rather than a solution. Hydroxyapatite is only sparingly soluble in water: with a pKs of 116.4, its solubility at a pH of 7.15 is 5.73 µmol/liter (Christoffersen and Christoffersen, 1982). Only with the addition of strong acids does the phosphorus dissolve out of the mineral, as shown in Table 13. Very little material could be injected as a solution, and the dissolved apatite would probably be washed out of the soil readily. Slurries can be injected by direct pumping into wells, but frequently the particles are unable to penetrate far due to the filtering action of the soil. The borehole clogs as the sides are coated in particles. Slurry injection therefore has a limited range. However, new techniques have been developed which overcome this problem, such as jet injection. Jet injection uses high pressures to fluidize the soil in the region around the injection nozzle. A two-inch diameter borewell can produce a well-mixed region three to six feet in diameter, depending on the soil type and fluids used (Malone and Lundquist, 1994; Phillips, 1995). Solids can be injected into the fluidized region with air, water, or both. Treatment of a large area is accomplished by injecting in a pattern of overlapping circles. Treatment depths of up to 150 feet are possible, with 90 feet more typical.

We are currently developing a proposal to deliver apatite by jet injection using the Casa Grande system developed by Westinghouse Hanford Company. This demonstration, to be submitted to the Department of Energy, would be for protection against radionuclide migration in soils at the Idaho National Engineering Laboratory.

5.2.2 SOIL MIXING

For very shallow contaminant plumes, apatite can be mixed into the soil by simply spreading it on the surface and using a rotary tiller, as was done in a demonstration at an orchard in Wisconsin involving lead arsenate pesticides (Stanforth and Chaudhuri, 1994). For deeper applications, equipment is available that can mix soil and a treatment agent in place. The arrangement is shown in figure 20. "Shallow" soil mixing uses a twelve-foot diameter auger on a crawler crane to mix material to a depth of ten to twenty feet. The treatment material is introduced coaxially through the drill string. Processing rates of 500-1,000 yd^3/day are typical (Malone and Lundquist, 1994). "Deep" soil mixing is a unique capability of the geotechnical firm GeoCon, Inc. Their deep soil mixing equipment consists of four three-foot diameter augers operated in parallel from a crane. Treatment depths of up to 150 feet are claimed, and processing rates are 150-400 yd^3/day. As part of the EPA SITE program, GeoCon demonstrated deep soil mixing using a proprietary pozzolonic grout material at a PCB-contaminated site in Florida (U.S. EPA, 1989).

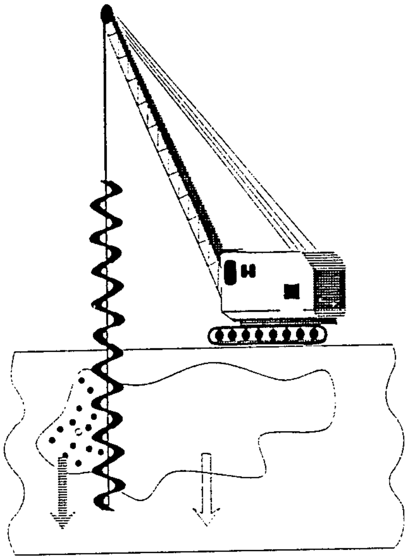


Figure 20. Soil Mixing/Auguring

As with jet injection, large areas can be treated by auguring in a pattern of overlapping circles. We have contacted GeoCon and secured their interest in using deep soil mixing in an apatite demonstration.

Injection and soil mixing can both be used for introducing apatite directly into a contaminated soil region. They can also be used to emplace a downgradient permeable barrier.

5.2.3 EXCAVATION AND BACKFILL

Creation of a barrier by excavation and backfill is shown in Figure 21. A backhoe can dig a fairly shallow trench without the need for sheetpile or other confining walls. A dragline or clamshell crane can dig a deeper trench if confining walls are driven or vibrated into place. Material may also be sluiced out with jets of water. After excavation, the trench is filled with granular material. Apatite could be added as is or mixed with some of the excavated soil.

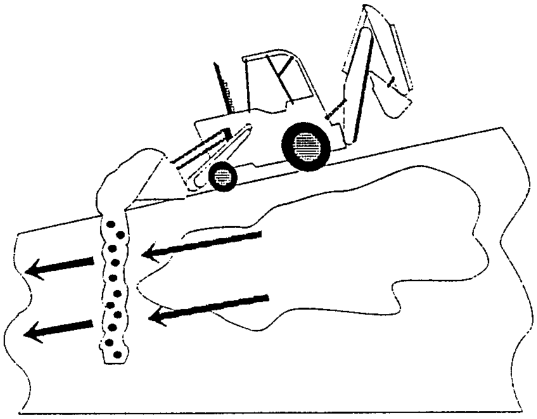


Figure 21. Excavation and Backfill

5.2.4 HORIZONTAL OR OFF-VERTICAL DRILLING

To emplace a barrier underneath a plume, somewhat more innovative (and less mature) methods are necessary. Figure 22 illustrates one approach, horizontal/off-vertical well drilling. Another technology, still in a developmental stage with support from the Department of Energy, is to jet inject horizontally through a rectangular manifold buried beneath the plume. This approach is being investigated for emplacing concrete barriers and slurry walls beneath existing waste tanks, etc. Overlapping "panels", each twelve feet long, 1.5 feet wide, and two feet thick, would be jet grouted beneath a plume.

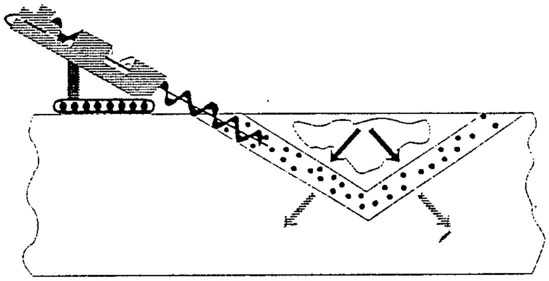


Figure 22. Horizontal Drilling

5.3 PHYSICAL PROPERTIES

Geotechnical contractors will require some information about the physical properties of apatite in order to ensure that it can be handled properly in the field. In discussions with potential emplacement collaborators, particularly the jet injection experts at Westinghouse Hanford Company, several key properties were identified. These include solubility in water, specific gravity, particle size distribution, and slurry viscosity.

5.3.1 SOLUBILITY

As discussed earlier, apatite is only sparingly soluble in natural water. Table 13 shows the percentage of total soluble phosphate from the rock in a media of increasing acidity. (Christoffersen and Christoffersen, 1982) report hydroxyapatite solubility as a function of pH, shown in Table 14.

Table 14. Solubility of Hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, at Various pH Values.

pH	Solubility, µmol/liter
5.03	442.
5.51	146.
6.31	26.9
6.76	11.3
7.15	5.73

5.3.2 SPECIFIC GRAVITY

The material safety data sheet provided by Texasgulf gives the specific gravity of the North Carolina apatite as between 2.9 and 3.1 g/cm^3. Other sources (Weast, 1983) list a range of 3.1 to 3.35 g/cm^3. As a granular solid or powder, a bulk density of 90-100 lbs per cubic foot (1.4-1.6 g/cm^3) is typical.

5.3.3 PARTICLE SIZE DISTRIBUTION

Particle size distribution is determined by processing history. Table 13 gives the screen analysis for the Texasgulf material. As received from the supplier, nearly all of the material is less than 0.5 mm in diameter, and very little is smaller than 0.074 mm. We ground the synthetic hydroxyapatite until it would pass a 170 mesh sieve.

5.3.4 SLURRY VISCOSITY

Several of the emplacement methods deliver the treatment agent in the form of a slurry, i.e. solids suspended in water. In order to ensure that such slurries can be pumped through equipment and to predict what pressures will be required to do so,

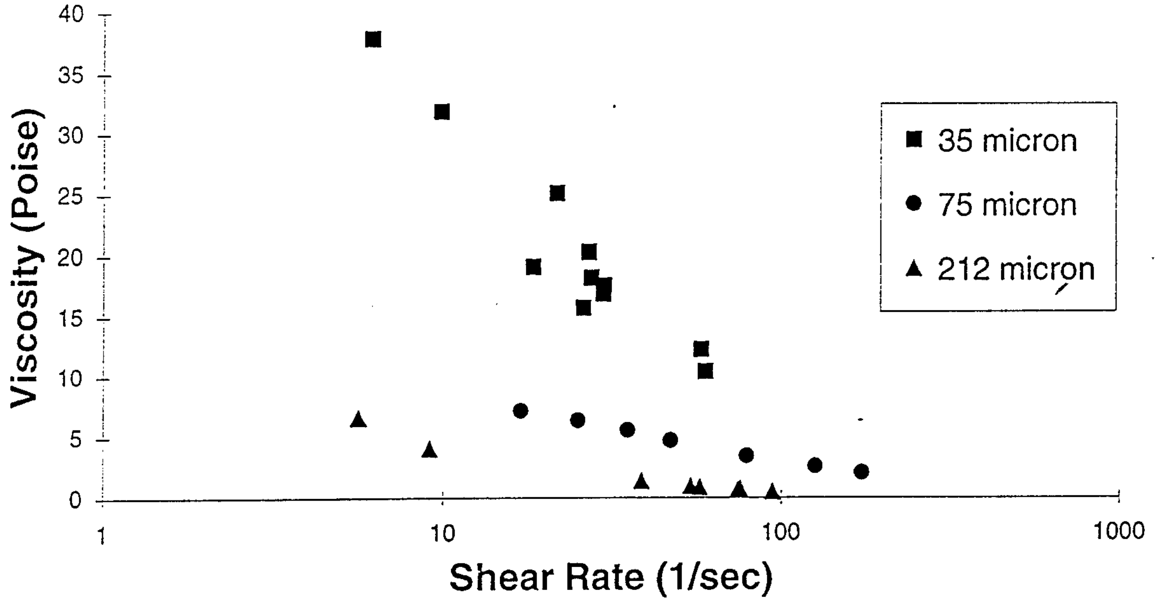


Figure 23. Viscosity as a Function of Shear Rate for Apatite Slurries of Various Particle Sizes.

5.4 TREATMENT COST

The cost of treatment will depend significantly on the emplacement method required and the amount of apatite added. For this kind of work, raw materials (including delivery to the site) and equipment operator expenses dominate the economics (Malone and Lundquist, 1994). One literature citation quotes $12/treated ton of soil for the apatite used in their demonstration (Stanforth and Chowdhury, 1994). For in situ grout treatment, a similar technology, costs run about $50/yd^3 for shallow contaminants and $150/yd^3 for deep ones (Malone and Lundquist, 1994). The deep soil mixing demonstration with grout by IWT and GeoCon (EPA, 1989) quoted a cost of $111/treated ton or $194/treated ton for a one- or four-auger system, respectively.

We expect that treatment with apatite will be less than that for grouting because much less additive is required. For shallow soil mixing or jet injection applications, we would estimate treatment costs at $35-$50/treated ton of soil. Deep soil mixing would probably be substantially more but less than for the grout demonstration. Vertical barriers could be substantially less expensive per treated ton, since a single barrier could filter contaminated waters from a very large area.

6.0 FUTURE WORK

The next milestone report will conclude our bench-scale studies of heavy metal treatment using apatite. It will include results from microscopy studies to demonstrate the creation of new mineral phases from precipitated metal phosphates. We also hope to submit a sample of treated soil for a Toxicity Characteristic Leaching Procedure (TCLP), the standard EPA test for validating stabilization treatment methods.

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APPENDIX

MILESTONE ONE REPORT: JUNE 1994

CHARACTERIZATION OF SOILS, APATITES, AND GROUNDWATER

A.1.0 INTRODUCTION

The objective of this project is to develop and demonstrate that phosphatic solutions and slurries will react with lead, other heavy metals including lanthanides and actinides, in contaminated soils and cause the precipitation of metal-substituted apatite minerals. Metals sequestered in apatites have great durability and leach resistance that significantly exceeds other chemically stabilized waste forms because the apatite mineral structure is very stable over a wide range of environmental conditions for geologically-long time periods. This is applied research that will lead to advanced technology development that can be implemented to remediate tetraethyl lead (TEL) sludge contaminated soils and groundwater at Keesler Air Force Base (AFB) as well as metal and radiologically contaminated soils at other DoD, DOE, or industrial sites where metal contamination of soils and groundwater is a pervasive problem.

Results of Phase One activities are included in this report. In Phase One the goal was to establish the chemical and mineralogical baseline for soils, waters, and phosphatic materials that would subsequently be used in leaching-retardation and sorption-desorption studies from contaminated sites. Chemical analyses of the cationic and anionic compositions and soil and metal mineral speciation were performed on contaminated soils from the following sites: 1) Keesler AFB,Mississippi, a tetraethyl lead (TEL) sludge pit; 2) Keesler AFB, a lead and zinc contaminated landfill; 3) three soils with varying levels of metal contamination from Bunker Hill Mine, Idaho; and 4) two Montana soils with varying levels of metal contamination that serve as National Institute of Standards and Technology (NIST) chemical standards. Chemical analyses were also made on water downgradient from the TEL sludge pit at Keesler AFB. Chemical and mineralogical analyses of several types of phosphatic materials including synthetic hydroxylapatite, natural carbonate fluorapatite from phosphorites, fish and shark teeth and fish cannery wastes are also reported. The data from the chemical and mineralogical speciation studies were used in the geochemical code MINTEQ to determine the stability relationships of soil minerals under varying conditions.

The methodologies used for each type of analytical procedure and the results of each group of analyses are detailed in the following sections of the report.

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A.2.0 METHODOLOGY

A.2.1 ELEMENTAL ANALYSIS

Elemental contents were determined by a series of methods depending on the sample type and particular element of interest. X-ray fluorescence (XRF) analyses on powder mounts following standard PNL procedure PNL-7-40.48 (Rev. 1) were used for total elemental analysis. For separate cation analyses, major and trace metals were determined by Inductively Coupled Argon Emission Spectrometer (ICP) on a Jarrell-Ash Model 975 following standard PNL procedure PNL-ALO-211.2 (Rev. 0). Major anion contents were determined by ion chromatography (IC) on a Dionex Series 4000i following standard PNL procedure PNL-ALO-212.1 (Rev. 1). For both ICP and IC, elements were put into solution using a nitric acid leach. Total and organic carbon contents were determined by Xertex-Dohrmann Model DC-80 Carbon Analyzer, with inorganic carbon content calculated from the difference (PNL-ALO-382.1 (Rev.0)). The analytical errors associated with the various techniques are estimated to be ±10% of the reported values.

Input data for the execution of the computer program was acquired from a complete metal and ligand analysis of saturation extracts (Page, et. al, 1982). The computer program used was MacMINTEQ-A2, acquired from Geochem Software, 1994. Metal concentrations on the extract was accomplished by ICP analysis, and anions by IC analysis (PNL-AL0-211.2 Rev. 0, and PNL-ALO-212 Rev. 1).

A.2.2 MINERALOGY

Mineralogical information was obtained by utilizing X-ray diffraction and electron microprobe techniques. X-ray diffraction (XRD) analyses were employed to characterize the mineralogy of bulk soil samples and were done for clay-sized (smaller than 2 µm), and silt- and sand-sized (larger than 2 µm) fractions. The different grain-sized fractions of each sample were separated by following the procedures proposed by Ingram (1971) and Galehouse (1971). Oriented samples of the smaller than 2 µm fraction were prepared for XRD analysis by pipetting clay suspension into a beaker containing a glass slide. When the beaker was placed in an oven at 40°C, the water evaporated and the clays settled onto the slide. XRD analyses were performed using a Siemen 500 diffractometer operated at 35 kV and 30 mA using CuKa radiation. Data were collected in a step scanning mode using a 0.02° step and a count time of 0.5 seconds per step. The scanning range of 2° angle is from 2° to 34° for oriented clay samples and from 10° to 50° for randomly oriented powders of the coarser than 2 µm fraction of the samples. Each oriented clay sample was made into an air-dried, ethylene glycolated mount, heat treated to 375°C and 550°C, and analyzed (Starkey et al. 1984). The compositions of the larger than 2 µm fractions were estimated by combining XRD data with information gathered through visual inspection using optical microscopy. Semi-quantitative estimations of clay minerals were determined by a method modified from Weir et al. (1975), in which clay mineral XRD intensities (I) are normalized to variations in crystallinity as follows:

$$I_{kaolinite}/2.5 + I_{illite} + I_{smectite} + I_{chlorite}/2.0 = <2\ \mu m \text{ fraction}$$

If any non-clay minerals were detected in the smaller than 2 µm fraction XRD scans, estimates of their relative weight percent were subtracted from the weight percent smaller than 2 µm fraction prior to the clay mineral normalization. The estimated accuracy for these techniques is ±10% to 50% depending on the particular mineral.

For the examination of the Keesler and Bunker Hill samples with electron microprobe, a small portion of each sample was mounted on a piece of conducting double sided tape with an area of about 1 cm^2. The samples were then carbon coated to provide the necessary conducting surface. Preliminary investigation of the samples was done with a Cameca Camebax Microprobe equipped with an energy dispersive spectrometer (EDS) and three wavelength dispersive spectrometers (WDS). The X-ray spectrometers were used to analyze the elements present in the samples, in which the WDS have a better sensitivity for the detection of trace elements, and a better resolution for separation of interfering elements, for example sulfur and lead. The machine was operated at a beam accelerating voltage of 20 kv, and a beam current of 12 nA. To find Pb-bearing particles, a WDS spectrometer was positioned on the Pb peak position with the audio signal turned on. Then, the electron beam in point mode was traversed across the sample until Pb was detected. Generally, the WDS was used to determine the presence of P, S, and Cl, the EDS was used to acquire an EDS spectrum, and Back-scattered electron mode (BSE) was used to examine the morphology of the particles.

A.3.0 RESULTS

This Milestone Report provides characterization data on samples to be utilized in this project. In addition to Kessler AFB samples, a number of mining soils are also included. Due to the relatively low Pb concentrations in the Keesler soils, the highly Pb contaminated mining soils are included in the project to demonstrate the utility of apatite based remediation over a large range of soil Pb contaminations.

A.3.1 PRELIMINARY SOILS DATA

A.3.1.1 ELEMENTAL ANALYSIS

Table A1 contains the data on elemental concentrations for the Keesler AFB samples. Concentrations for cation data are determined by ICP/ES, anion data by IC, and carbon data by carbon analyzer. The three listed samples show a range in Pb concentration from less than 10 to slightly greater than 100 mg kg^{-1}. Table A2 contains elemental data from XRF analysis of three Bunker Hill mining soils (with Pb from 1000 to 4000 mg kg^{-1}) and one Keesler soil (a duplicate from Table A1a). XRF analysis was chosen to characterize the elemental contents in the mining soils because of concerns that acid leaching might not provide total Pb elemental contents due to the variable Pb mineralogy in mining soils. The comparable data for Keesler HA7-8 given in Tables A1a and A2 show this is not a problem for the much lower Pb contents and consistent mineralogy present in the Keesler soils.

Tables A3 and A4 show the elemental contents for NIST standard reference material (SRM) mining soils SRM 2710 and SRM 2711. These samples are included in the project to provide an extremely well characterized set of mining soils with high Pb contents (from 1000 to 5000 mg kg^{-1}). The multiple analytical methods used to obtain this chemical characterization data are given in Table A5. Tables A3, A4, and A5 are taken directly from the NIST Certificate of Analysis for these soils.

A.3.2 MINERALOGY

A.3.2.1 KEESLER SOILS

Tables A6 and A7 contain information on the mineralogy of the Keesler bulk soil samples. Quartz dominates the mineralogical composition of the soils. Very small amounts of rock fragments and clay minerals occur in the samples. In addition, calcite from shell fragments is also present in the sample of HA7-8. The clay minerals present in the Keesler soils are vermiculite, illite, and kaolinite. Minor hematite also occurs.

Figures A1 to A4 show X-ray spectra obtained from 2 Keesler soil samples (HA7-8 and HA7-15). Another 2 Keesler soil samples were also examined with electron microprobe. However, no Pb-bearing particle was detected because of low total Pb concentration in the samples. Most of the particles examined were small, commonly surrounded by other particles. Therefore, it is believed that most of the spectra are probably not only of the Pb-bearing materials, but of the underlying and adjacent materials as well, which is suggested by most of the spectra exhibiting very large Si Kα peaks.

The spectra shown in Figures A1 and A2 were taken from the Keesler sample HA7-8. The spectrum #1 was from an area of Pb detectability of about 10 microns across, occurring on a quartz or feldspar grain, which is very high in Mn. Other metals include Zn, Fe, Ca, and Al. No P or Cl were detected. Note that the background is low in the low energy portion (left side) of the spectrum, and the Pb Mα peak is missing. It is believed that this is because the secondary X-ray was partially blocked by another particle. Pb, Ti, Fe, Ca, and Al are present in the spectrum #2, in which minor S, P, and Cl were detected. In the spectrum #3 and #4, Pb is the only heavy metal occurring. Both P and Cl are present in small amounts in the spectrum #3. The Cl peak position is on the side of the Pb Mα peak, and in EDS is not visible in small amounts. In this case the Cl peak was only detected by WDS. The high lead concentration in the spectrum #4 is also shown in Figure A11A as small bright areas, in which the lead is attached to the surface of a quartz grain that is much larger than the field of view. Minor P and S were detected in the spectrum #4. Heavy metals Pb, Zn, Mn, Fe, and Ti are high in concentration in the spectrum #5. They are associated with high concentration of P. As for the spectrum #5, the spectrum #6 contains major Zn, in addition to Pb. Ti and Fe are also present. Minor P and Cl were detected.

Figures A3 and A4 show the spectra obtained from the Keesler soil HA7-15. Although ICP/MS whole sample analysis was only 166 mg kg^{-1} (ppm) of Pb, several areas of high Pb concentration were found. Only minor Pb was observed in the spectrum #1 and #2, in which the difference is that the spectrum #2 contains significant P in proportion to Pb. High concentration of Pb is shown in the spectrum #3 and #4. There is high Cl in the spectrum #3, which also contains minor Zn, Fe, Cu, and Ti. However, no associated P or Cl occurs in the spectrum #4.

A.3.2.2 BUNKER HILL SOILS

Sulfur was common in the Bunker Hill soils. In the EDS spectrum, the S Kα and Pb Mα peaks overlap, but they are resolved nicely using WDS. Thus the presence or absence of S was determined using WDS.

The spectra obtained from Bunker Hill 1000 are shown in Figures A5 and A6. Pb is associated with Fe, without other heavy metals present. The spectrum #1 was from a 15 micron irregularly shaped particle with a hollow middle. It contains major S, perhaps more than required to form PbS. A small amount of P was also detected. No Cl was observed. However, low S present in the spectrum #2 and #3 as well as several other particles. The spectrum #4 was taken from a 2 micron lenticular grain with no P, S, or Cl, in which Pb is the only major element detected; Al, Si, and Fe were minor compared to Pb in this spectrum.

Figures A7 and A8 shows the spectra of Bunker Hill 2000, in which Pb is always associated with Fe, with minor other heavy metals such as Zn, Mn, and Ti in some grains. In the spectrum #1, major S was present, but sulfur concentrations about half as great were detected in the immediate vicinity without associated Pb. No Cl or P were detected. A 50-60 micron grain of the spectrum #2, mostly Fe, with major S (more than required for PbS), some P, and no Cl, are shown in Figure A11B. The Fe in this grain may be in the form of FeS_x. The spectrum #3 is from a 20 micron area on an alumina silicate, with some P, no S or Cl. The spectrum #4 was obtained from a 15 micron grain, probably PbS.

Figures A9 and A10 contain the spectra of the Bunker Hill 4000 (BH4). Heavy metal association is similar to Bunker Hill 2000. The spectrum #1 is from a 15 micron grain, with very high S, which is more than required for PbS, thus it is suspected FeS_x also present. Pb dominate the spectrum #2, with minor S, Al, Fe, and S. The spectrum #3 is obtained from a 10 micron grain, with S present in about the right proportion for PbS, without P or Cl present. No S, P, or Cl occur in the spectrum #4, which is a 25 micron grain. It is probably PbO_x.

A.3.2.3 NIST STANDARD REFERENCE MATERIAL

Table A8 is a list of the Pb-bearing minerals occurring in the NIST standard reference material (SRM) mining soils SRM2710 and SRM2711. Additional data is being obtained to allow quantification of the data and determination of the relative amounts of the various minerals.

A.3.3 PRELIMINARY APATITE DATA

Tables A9, A10, and A11 contain characterization data on the apatite samples that have been selected for use in the project. The hydroxyapatite (Tribasic Calcium Phosphate, TCP) is a reagent grade laboratory-precipitated powder with few impurities (Table A9). SRM 120b Florida Phosphate Rock is a naturally occurring apatite that serves as a NIST chemical standard (Table A10). It has therefore been ground into a fine powder and well mixed to provide homogeneous sample aliquots. The North Carolina Apatite is an unprocessed (not acidified or ground) natural sample commercially available from Texasgulf Inc. as a fertilizer supplement for soils (Table A11). The Florida and North Carolina apatite samples are both carbonate fluorapatites obtained from naturally occurring marine deposits and therefore contain additional impurities that will affect the amount of phosphate available for dissolution. Table A12 contains ICP/ES data on these three samples along with some biogenic apatites for comparison. The biogenic apatites are included in this study since it is expected that fishery wastes would be readily available as less costly apatite sources, but they also contain many impurities and the amount of available phosphate is correspondingly lower.

A.3.4 PRELIMINARY WATERS DATA

Table A11 contains information on the waters used in this study. Concentrations for cation data are determined by ICP/ES, anion data by IC, and carbon data by carbon analyzer. Data from a laboratory synthetic groundwater to be used in leach studies is shown to be comparable to the naturally occurring groundwater at Keesler AFB. Additional studies will also utilize distilled and nanopure filtered water that is below detection limits for Pb and other heavy metals.

A.3.5 PRELIMINARY MODELING DATA

A.3.5.1 GEOCHEMICAL THERMODYNAMIC SPECIATION

In order to gain knowledge about the nature of lead complexation and to determine how much PO_4 is needed to complex the groundwater available lead in the Keesler soils, a geochemical thermodynamic speciation computer program was implemented.

The natural soil system has a solid phase and a solution phase. When chemical equilibrium is assumed to exist between the soil solution and the associated solid phases of the soil, one can elicit important information about solid phase formations by using thermodynamic calculations performed in geochemical thermodynamic speciation programs. Specifically, this computer program is used to examine the precipitation of a selected metal, i.e., lead, induced by the application of a specific phosphate compound.

Saturation Indices (determined from MINTEQ-A2) for the following Keesler soils exemplify the lead containing minerals that may be present. The saturation index is defined as

Ion Activity Product/Solubility Product

and is a thermodynamic indication of mineral dissolution or formation. Values < 0 indicate that the mineral is undersaturated with respect t the equilibrium concentration, and values > 0 indicate saturation with respect to the equilibrium concentration. The higher the number, the greater the probability of precipitation.

Keesler soil HA 7-8 :

Mineral	Saturation Index
PbCrO4	0.197
Cerrusite	0.537
Hydroxypyromorphite	0.742
$Pb_3(PO_4)_2$	0.982
Hercynite	2.347
Plumbgummite	8.458
Chloropyromorphyte	11.612

Keesler soil HA 7-12:

Mineral	Saturation Index
Plumbgummite	8.458
Chloropyromorphyte	11.612

Keesler soil HA 7-15:

Mineral	Saturation Index
Plumbgummite	5.637

Table A1a. Elemental Contents for Keesler AFB Soil Samples

Sample ID # >>>		Detection	94-04579	94-03086	94-03087
Sample ID >>>>		Limit	HA-7-8	HA-7-12	HA-7-15
Type or Form of Sample >>>>>			dry	dry	dry
Aluminum	Al	0.005	2680	4990	5560
Boron	B	0.02	31.8	99.4	104
Barium	Ba	0.0005	57.9	32	33
Calcium	Ca	0.01	3110	48	252
Cadmium	Cd	0.001	1.8	3.3	1.4
Cobalt	Co	0.001	< 1	4.9	3.3
Chromium	Cr	0.002		16.9	10.6
Copper	Cu	0.0005	31	1.8	4.8
Iron	Fe	0.005	3270	3990	1370
Potassium	K	0.2	< 210	250	170
Lithium	Li	0.003	< 3	2.5	1.9
Magnesium	Mg	0.005	273	239	194
Manganese	Mn	0.0005	463	51	27
Sodium	Na	0.05	55.6	112	112
Nickel	Ni	0.003	< 3	2.8	3.1
Phosphorus	P	0.03	287	34	71
Lead	Pb	0.005	119	3.4	3
Selenium	Se	0.01	< 10	14	31
Silicon	Si	0.01	191	860	700
Tin	Sn	0.015	< 10	26	14
Strontium	Sr	0.0005	9.7	2.4	43
Titanium	Ti	0.001	60.7	1980	1300
Zinc	Zn	0.003	16.4	17	12
Zirconium	Zr	0.001	< 1	5.9	8
Dilution Factor			106	155	100

*note: All amounts are in ppm

Table A1b. Elemental Contents for Keesler AFB soil samples (anions)

Sample ID # >>>		94-04579	94-03086	94-03087
Sample ID >>>>		HA-7-8	HA-7-12	HA-7-15
Sample Form >>>		dry	dry	dry
Flourine	F			
Chlorine	Cl	<4	16.3	43.7
Nitrate	NO3	59	29.3	91.7
Sulfate	SO4	15	204	588
Organic	C	0.49	109	953
Inorganic	C	0.4	21	53
Total	C	0.89	130	1006

Table A2. XRF Data for Bunker Hill (BH) and Keesler AFB Samples

Sample>>>	BH 1000		BH 2000		BH 4000		HA7-8	
		%		%		%		%
	ppm solid	oxide	ppm solid	oxide	ppm solid	oxide	ppm solid	oxide
Na AA	7000	0.94	9900	1.33	10300	1.39	1300	0.18
Mg AA	6634	1.1	6031	1	5307	0.88	603	0.1
Al AA	72600	13.72	70000	13.23	79000	14.93	2360	0.45
Si AA	313000	66.96	296000	63.32	293000	62.68	417000	89.21
Al xrf	76100	14.38	84400	15.95	93200	17.61	2900	0.55
Si xrf	301000	64.39	287000	61.4	304000	65.03	426000	91.13
P xrf	2330	0.53	3020	0.69	2670	0.61	1070	0.25
S xrf	0	0	430	0.11	0	0	300	0.08
Cl xrf	430	0.04	919	0.09	1860	0.19	0	0
K xrf	22900	2.76	23200	2.79	26800	3.23	568	0.07
Ca xrf	4490	0.63	7110	0.99	4930	0.69	6410	0.9
Ti xrf	4340	0.72	4320	0.72	4440	0.74	1011	0.17
V xrf	91	0.01	76	0.01	115	0.02	10	0
Cr xrf	33	0	36	0.01	38	0.01	30	0
Mn xrf	777	0.1	1167	0.15	1031	0.13	66	0.01
Fe xrf	31700	4.53	35900	5.13	38800	5.55	4180	0.6
Ni xrf	22	0	23	0	25	0	6	0
Cu xrf	40	0.01	69	0.01	119	0.01	27	0
Zn xrf	257	0.03	1171	0.15	1087	0.14	186	0.02
Ga xrf	11	0	6	0	0	0	2	0
Se xrf	0	0	0	0	0	0	0	0
Pb xrf	1157	0.13	2000	0.23	4170	0.48	142	0.02
Rb xrf	115	0.01	121	0.02	137	0.02	3	0
Sr xrf	79	0.01	146	0.02	120	0.01	16	0
Y xrf	27	0	32	0	31	0	3	0
Zr xrf	335	0.05	320	0.04	314	0.04	179	0.02
Nb xrf	13	0	14	0	15	0	4	0
Mo xrf	0	0	0	0	2	0	0	0
Ru xrf	0	0	0	0	0	0	0	0
Rh xrf	0	0	0	0	0	0	0	0
Pd xrf	0	0	0	0	0	0	0	0
Ag xrf	0	0	0	0	0	0	0	0
Cd xrf	12	0	0	0	17	0	0	0
Sn xrf	0	0	15	0	0	0	0	0
Sb xrf	27	0	24	0	72	0.01	0	0
Te xrf	0	0	20	0	0	0	0	0
Cs xrf	0	0	0	0	0	0	0	0
Ba xrf	664	0.07	823	0.09	808	0.09	94	0.01
La xrf	89	0.01	70	0.01	66	0.01	0	0
Ce xrf	62	0.01	62	0.01	95	0.01	0	0
LOI Wt %		7.49		7.92		7.25		3.97
Wt.% total		99.9		98.09		99.12		96.05
xrf		97.99		98.89		104.16		98.08

Table A3. Elemental Contents for NIST SRM 2710

Certified Values

Element	wt. %	Element	µg/g
Aluminum	6.44 ± 0.08	Antimony	38.4 ± 3.0
Calcium	1.25 ± 0.03	Arsenic	626 ± 38
Iron	3.38 ± 0.10	Barium	707 ± 51
Magnesium	0.853 ± 0.042	Cadmium	21.8 ± 0.2
Manganese	1.01 ± 0.04	Copper	2950 ± 130
Phosphorus	0.106 ± 0.015	Lead	5532 ± 80
Potassium	2.11 ± 0.11	Mercury	32.6 ± 1.8
Silicon	28.97 ± 0.18	Nickel	14.3 ± 1.0
Sodium	1.14 ± 0.06	Silver	35.3 ± 1.5
Sulfur	0.240 ± 0.006	Vanadium	76.6 ± 2.3
Titanium	0.283 ± 0.010	Zinc	6952 ± 91

Noncertified Values: Noncertified values, shown in parentheses, are provided for information only. An element concentration value may not be certified if a bias is suspected in one or more of the methods used for certification, or if two independent methods are not available. Certified values for some of these elements will eventually be provided in a revised certificate when more data is available.

Noncertified Values

Element	wt.%	Element	µg/g
Carbon	(3)	Bromine	(6)
		Cerium	(57)
		Cesium	(107)
		Chromium	(39)
		Cobalt	(10)
		Dysprosium	(5.4)
		Europium	(1)
		Gallium	(34)
		Gold	(0.6)
		Hafnium	(3.2)
		Holmium	(0.6)
		Indium	(5.1)
		Lanthanum	(34)
		Molybdenum	(19)
		Neodymium	(23)
		Rubidium	(120)
		Samarium	(7.8)
		Scandium	(8.7)
		Strontium	(240)
		Thallium	(1.3)
		Thorium	(13)
		Tungsten	(93)
		Uranium	(25)
		Ytterbium	(1.3)
		Yttrium	(23)

Table A4. Elemental Contents for NIST SRM 2711

Certified Values

Element	wt. %	
Aluminum	6.53	± 0.09
Calcium	2.88	± 0.08
Iron	2.89	± 0.06
Magnesium	1.05	± 0.03
Phosphorus	0.086	± 0.007
Potassium	2.45	± 0.08
Silicon	30.44	± 0.19
Sodium	1.14	± 0.03
Sulfur	0.042	± 0.001
Titanium	0.306	± 0.023

Element	µg/g	
Antimony	19.4	± 1.8
Arsenic	105	± 8
Barium	726	± 38
Cadmium	41.70	± 0.25
Copper	114	± 2
Lead	1162	± 31
Manganese	638	± 28
Mercury	6.25	± 0.19
Nickel	20.6	± 1.1
Selenium	1.52	± 0.14
Silver	4.63	± 0.39
Strontium	245.3	± 0.7
Thallium	2.47	± 0.15
Vanadium	81.6	± 2.9
Zinc	350.4	± 4.8

Noncertified Values: Noncertified values, shown in parentheses, are provided for information only. An element concentration value may not be certified, if a bias is suspected in one or more of the methods used for certification, or if two independent methods are not available. Certified values for some of these elements will eventually be provided in a revised certificate when more data is available.

Noncertified Values

Element	wt. %
Carbon	(2)

Element	µg/g
Bromine	(5)
Cerium	(69)
Cesium	(6.1)
Chromium	(47)
Cobalt	(10)
Dysprosium	(5.6)
Europium	(1.1)
Gallium	(15)
Gold	(.03)
Hafnium	(7.3)
Holmium	(1)
Indium	(1.1)
Iodine	(3)
Lanthanum	(40)
Molybdenum	(1.6)
Neodymium	(31)
Rubidium	(110)
Samarium	(5.9)
Scandium	(9)
Thorium	(14)
Tungsten	(3)
Uranium	(2.6)
Ytterbium	(2.7)
Yttrium	(25)
Zirconium	(230)

Table A5. Analytical Methods for Tables A3 and A4

Element	Certification Methods *
Ag	ID ICPMS; RNAA; INAA
Al	XRF1; XRF2; DCP; ICP
As	RNAA; HYD AAS; ICP; INAA
Au	INAA; FAAS
Ba	XRF2; FAES
Br	INAA
C	COUL
Ca	XRF1; XRF2; DCP
Cd	ID ICPMS; RNAA
Ce	INAA; ICP
Co	INAA; ETAAS; ICP
Cr	INAA; DCP; ICP
Cs	INAA
Cu	RNAA; FAES; ICP
Dy	INAA
Eu	INAA
Fe	XRF1; XRF2; DCP; INAA; ICP
Ga	INAA; ICP
Hf	INAA
Hg	CVAAS
Ho	INAA
In	INAA
K	XRF1; XRF2; FAES; ICP
La	INAA; ICP
Mg	XRF1; ICP
Mn	INAA; DCP; XRF2
Mo	ID ICPMS
Na	INAA; FAES
Nd	ICP
Ni	ID ICPMS; ETAAS; INAA
P	DCP; COLOR; XRF1; XRF2
Pb	ID TIMS; POLAR; ICP
Rb	INAA
S	ID TIMS
Sb	RNAA; ETAAS
Sc	INAA; ICP
Si	XRF1; XRF2; GRAV
Sm	INAA
Sr	ID TIMS; INAA; ICP
Th	ID TIMS; INAA; ICP
Ti	XRF1; XRF2; DCP
Tl	ID TIMS; LEAFS
U	ID TIMS; INAA
V	INAA; ICP
W	INAA
Y	ICP
Yb	INAA
Zn	ID TIMS; ICP; INAA; POLAR

*Methods in bold were used to corroborate certification methods or to provide information values.

COLOR - Colorimetry; lithium metaborate fusion.
COUL - Combustion coulometry.
CVAAS - Cold vapor atomic absorption spectrometry.
DCP - Direct current plasma atomic emission spectrometry; lithium metaborate fusion.
ETAAS - Electrothermal atomic absorption spectrometry; mixed acid digestion.
FAAS - Flame atomic absorption spectrometry; mixed acid digestion except for Au, leached with $HBr-Br_2$.
FAES - Flame atomic emission spectrometry; mixed acid digestion.
GRAV - Gravimetry; sodium carbonate fusion.
HYD AAS - Hydride generation atomic absorption spectrometry.
ICP - Inductively coupled plasma atomic emission spectrometry; mixed acid digestion.
ID ICPMS - Isotope dilution inductively coupled plasma mass spectrometry; mixed acid digestion.
ID TIMS - Isotope dilution thermal ionization mass spectrometry; mixed acid digestion.
INAA - Instrumental neutron activation analysis.
LEAFS - Laser enhanced atomic fluorescence spectrometry; mixed acid digestion.
POLAR - Polarography.
RNAA - Radiochemical neutron activation analysis; mixed acid digestion.
XRF1 - Wavelength dispersive x-ray fluorescence on fused borate discs.
XRF2 - Wavelength dispersive x-ray fluorescence spectrometry on pressed powder.

Table A6. Mineralogical Composition of Keesler bulk soil samples

Sample ID >>>>	HA7-8	HA7-11	HA7-12	HA7-13	HA7-14	HA7-15
Quartz	96.57	98.6	99	97.7	97.38	97.18
Rock fragments	0.38	0.57	0.22	0.7	1.9	0.68
Calcite	1.81	0	0	0	0	0
Clay	1.01	0.97	0.72	1.96	1.46	2.29
Total	99.77	100.14	99.94	100.36	100.74	100.15

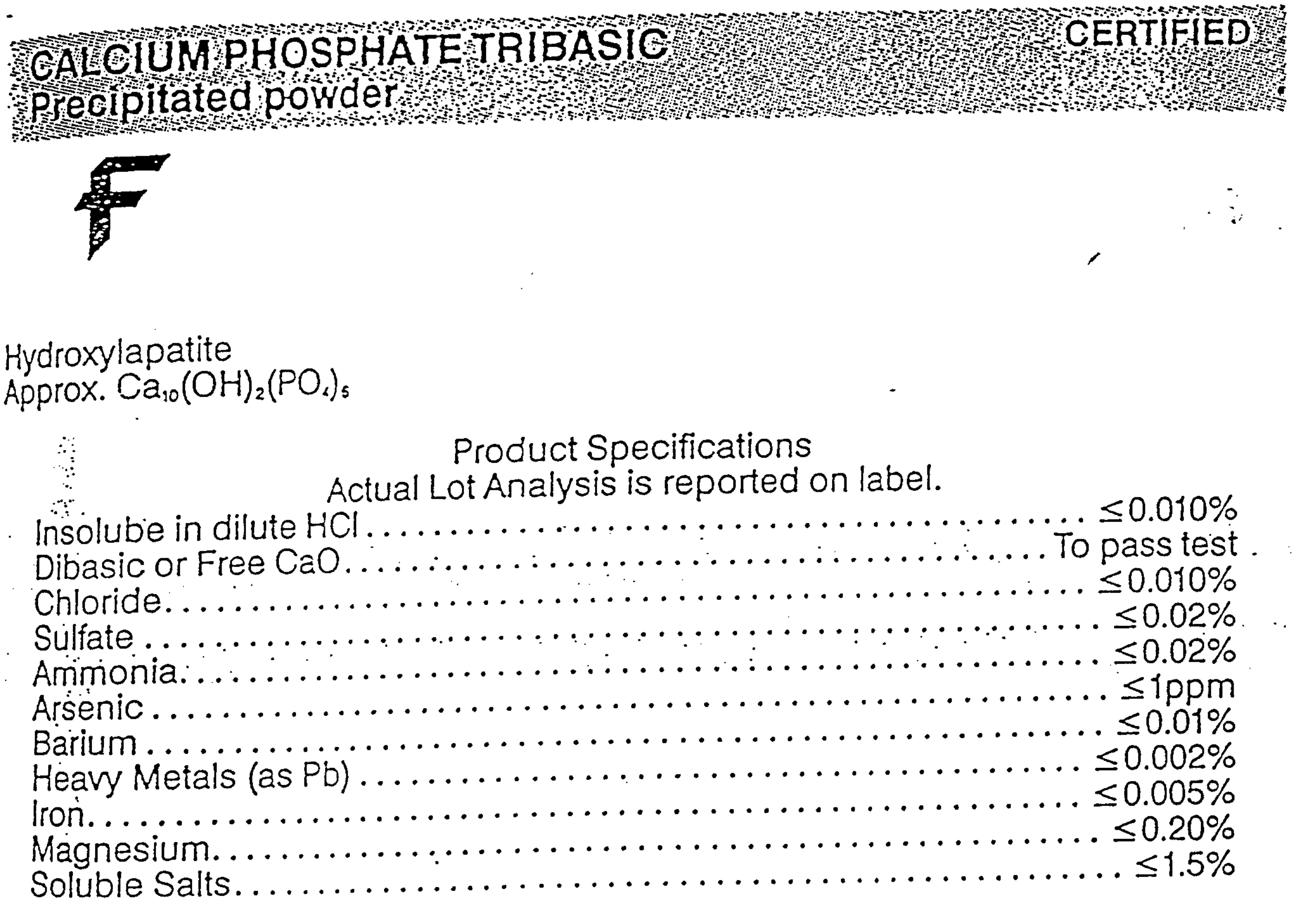
Table A7. Clay-size minerals occurring in Keesler soil samples.

Mineral >>>>>>	Vermiculite	Illite	Kaolinite	Quartz	Hematite
HA7-8 Percentage in < 2 um fraction	13	9	6	65	7
percentage in whole sample	0.14	0.09	0.06	0.65	0.07
HA7-11 percentage in < 2 um fraction	69	1	6	23	0.5
percentage in whole sample	0.67	0.01	0.06	0.23	0.01
HA7-12 percentage in < 2 um fraction	71	2	7	21	NA
percentage in whole sample	0.51	0.01	0.05	0.15	NA
HA7-13 percentage in < 2 um fraction	3	8	3	82	5
percentage in whole sample	0.06	0.15	0.05	1.6	0.09
HA7-14 percentage in < 2 um fraction	14	8	7	65	7
percentage in whole sample	0.2	0.11	0.1	0.95	0.1
HA7-15 percentage in < 2 um fraction	21	4	3	69	3
percentage in whole sample	0.48	0.09	0.07	1.57	0.07

Table A8. **List of the lead-bearing minerals occurring in the samples of NIST standard reference material (SRM) mining soil SRM2710 and SRM2711.**

Anglesite
Mn-Pb oxide
$PbSiO_4$
Fe-Pb oxide
Fe-Pb sulfate
Pb phosphate
Pb organic material
Galena

Table A9. **Reported Analysis for Reagent Grade Synthetic Apatite**



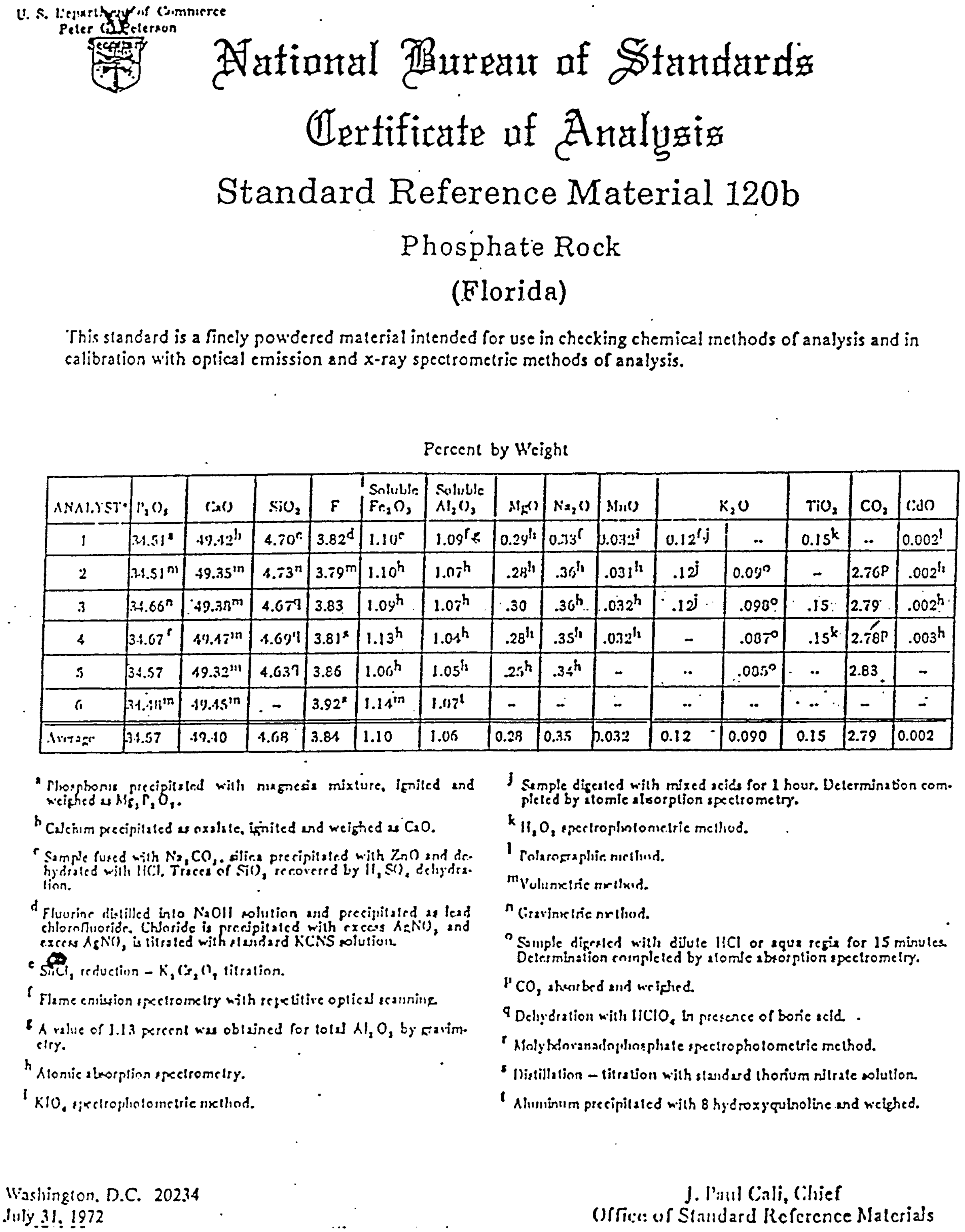
CALCIUM PHOSPHATE TRIBASIC CERTIFIED
Precipitated powder

Hydroxylapatite
Approx. $Ca_{10}(OH)_2(PO_4)_6$

Product Specifications
Actual Lot Analysis is reported on label.

Insolube in dilute HCl	≤0.010%
Dibasic or Free CaO	To pass test
Chloride	≤0.010%
Sulfate	≤0.02%
Ammonia	≤0.02%
Arsenic	≤1ppm
Barium	≤0.01%
Heavy Metals (as Pb)	≤0.002%
Iron	≤0.005%
Magnesium	≤0.20%
Soluble Salts	≤1.5%

Table A10. Reported Analysis for Florida Phosphate Rock



U. S. Department of Commerce
Peter G. Peterson
Secretary

National Bureau of Standards
Certificate of Analysis
Standard Reference Material 120b
Phosphate Rock
(Florida)

This standard is a finely powdered material intended for use in checking chemical methods of analysis and in calibration with optical emission and x-ray spectrometric methods of analysis.

Percent by Weight

ANALYST*	P_2O_5	CaO	SiO_2	F	Soluble Fe_2O_3	Soluble Al_2O_3	MgO	Na_2O	MnO	K_2O		TiO_2	CO_2	CdO
1	34.51[a]	49.42[b]	4.70[c]	3.82[d]	1.10[e]	1.09[f,g]	0.29[h]	0.33[f]	0.032[i]	0.12[f,j]	--	0.15[k]	--	0.002[l]
2	34.51[m]	49.35[m]	4.73[n]	3.79[m]	1.10[h]	1.07[h]	.28[h]	.36[h]	.031[h]	.12[j]	0.09[o]	--	2.76[p]	.002[h]
3	34.66[n]	49.38[m]	4.67[q]	3.83	1.09[h]	1.07[h]	.30	.36[h]	.032[h]	.12[j]	.098[o]	.15	2.79	.002[h]
4	34.67[r]	49.47[m]	4.69[q]	3.81[s]	1.13[h]	1.04[h]	.28[h]	.35[h]	.032[h]	--	.087[o]	.15[k]	2.78[p]	.003[h]
5	34.57	49.32[m]	4.63[q]	3.86	1.06[h]	1.05[h]	.25[h]	.34[h]	--	--	.085[o]	--	2.83	--
6	34.48[m]	49.45[m]	--	3.92[s]	1.14[m]	1.07[t]	--	--	--	--	--	--	--	--
Average	34.57	49.40	4.68	3.84	1.10	1.06	0.28	0.35	0.032	0.12	0.090	0.15	2.79	0.002

[a] Phosphorus precipitated with magnesia mixture, ignited and weighed as $Mg_2P_2O_7$.

[b] Calcium precipitated as oxalate, ignited and weighed as CaO.

[c] Sample fused with Na_2CO_3, silica precipitated with ZnO and dehydrated with HCl. Traces of SiO_2 recovered by H_2SO_4 dehydration.

[d] Fluorine distilled into NaOH solution and precipitated as lead chlorofluoride. Chloride is precipitated with excess $AgNO_3$ and excess $AgNO_3$ is titrated with standard KCNS solution.

[e] $SnCl_2$ reduction – $K_2Cr_2O_7$ titration.

[f] Flame emission spectrometry with repetitive optical scanning.

[g] A value of 1.13 percent was obtained for total Al_2O_3 by gravimetry.

[h] Atomic absorption spectrometry.

[i] KIO_4 spectrophotometric method.

[j] Sample digested with mixed acids for 1 hour. Determination completed by atomic absorption spectrometry.

[k] H_2O_2 spectrophotometric method.

[l] Polarographic method.

[m] Volumetric method.

[n] Gravimetric method.

[o] Sample digested with dilute HCl or aqua regia for 15 minutes. Determination completed by atomic absorption spectrometry.

[p] CO_2 absorbed and weighed.

[q] Dehydration with $HClO_4$ in presence of boric acid.

[r] Molybdovanadophosphate spectrophotometric method.

[s] Distillation – titration with standard thorium nitrate solution.

[t] Aluminum precipitated with 8 hydroxyquinoline and weighed.

Washington, D.C. 20234
July 31, 1972

J. Paul Cali, Chief
Office of Standard Reference Materials

Table A11. Reported Analysis for North Carolina Natural Phosphate

Texasgulf

North Carolina Natural Phosphate (NCNP)

30% P_2O_5 - For Use As A Fertilizer In Acid Soil

NCNP is a natural source of Phosphorus and Calcium derived from marine sediments. NCNP has not been subjected to acidulation or grinding.

Typical Analysis - (dry basis)

Component	Typical Percent
Total Phosphorus, as P	13.2
Total Phosphorus, as P_2O_5	30.3
Calcium, as CaO	48.8
Magnesium, as MgO	0.6
Total Sulphur, as S	1.3
Total Carbon, as C	3.1
Zinc, as Zn	313 ppm
Boron, as B	95 ppm
Molybdenum, as Mo	45 ppm
Copper, as Cu	13 ppm

Soluble Phosphorus	% of total P
–in Water	0
–in Neutral Ammonium Citrate	13
–in 2% Citric Acid	37
–in 2% Formic Acid	72
–in HNO_3/HCl	100

Physical Characteristics

Screen Analysis (Tyler)	Sieve Opening	%
Passing 14 mesh	1.190 mm	100
Passing 35 mesh	0.420 mm	97
Passing 65 mesh	0.210 mm	49
Passing 100 mesh	0.149 mm	19
Passing 200 mesh	0.074 mm	1
Surface Area (B.E.T.)	22 m^2/mg	

Bulk Density	
Loose	1.44 g/cm^3 (90 lbs/ft^3)
Tamped	1.60 g/cm^3 (100 lbs/ft^3)

Color	Brownish Black

Table A13a. ICP Data for Synthetic and Keesler Groundwaters

Sample ID # >>>		Detection	94-03084	94-03085
Sample ID >>>>		Limit	HVS Water	Keesler H2O
Type or Form of Sample >>>>>			aqueous	aqueous
Aluminum	Al	0.005	< 0.09	0.02
Boron	B	0.02	< 0.3	
Barium	Ba	0.0005		0.01
Calcium	Ca	0.01	16	16.2
Cadmium	Cd	0.001		
Cobalt	Co	0.001		
Chromium	Cr	0.002		
Copper	Cu	0.0005		
Iron	Fe	0.005		
Potassium	K	0.2	12	1.5
Lithium	Li	0.003		
Magnesium	Mg	0.005	6.75	1.3
Manganese	Mn	0.0005		
Sodium	Na	0.05	20.6	11.1
Nickel	Ni	0.003		
Phosphorus	P	0.03	4.2	
Lead	Pb	0.005	< 0.08	< 0.007
Selenium	Se	0.01		
Silicon	Si	0.01	0.99	3.2
Tin	Sn	0.015		
Strontium	Sr	0.0005	0.086	0.057
Titanium	Ti	0.001		
Zinc	Zn	0.003		0.008
Zirconium	Zr	0.001		
Dilution Factor			1.7	1.02x

*note: All amounts are in ppm

Table A13b. ICP Data for Synthetic and Keesler Groundwaters (Anions)

Sample ID # >>>		94-03084	94-03085
Sample ID >>>>		HVS Water	Keesler H2O
pH		7.73	8.22
Flourine	F		
Chlorine	Cl	22	13
Nitrate	NO3	10.7	<0.1
Sulfate	SO4	38	11.2
Organic	C	0.67	4.65
Inorganic	C	7.09	17.5
Total	C	7.76	22.2

Table A12. ICP Data for Apatite Samples

Sample ID # >>>		Detection	94-4580	94-4581	94-4582	94-3090	94-3088	94-3089
Sample ID >>>>		Limit	Florida	N. Carolina	Tribasic	Fish	Shark	Fish
Type or Form of Sample >>>>>			apatite	apatite	CaHPO4	Bits (misc.)	Teeth Sheath	Bone
Aluminum	Al	0.005	7980	2480	35.5	62	268	
Boron	B	0.02	5820	1880		20	727	46
Barium	Ba	0.0005	63.9	42.8	< 3		4	
Calcium	Ca	0.01	364000	359000	392000	168000	313000	205000
Cadmium	Cd	0.001	26.4	50.8	< 6			
Cobalt	Co	0.001				23		
Chromium	Cr	0.002	71	135	20			
Copper	Cu	0.0005						
Iron	Fe	0.005	7600	4420	331	20	40	
Potassium	K	0.2				2000		
Lithium	Li	0.003						
Magnesium	Mg	0.005	1770	2950	2560	2420	2400	3400
Manganese	Mn	0.0005	257	62	15	7	6	8
Sodium	Na	0.05	6770	832	140	2930	10100	3080
Nickel	Ni	0.003						
Phosphorus	P	0.03	160000	140000	177000	85400	160000	105000
Lead	Pb	0.005	< 80	47	< 60		< 28	
Selenium	Se	0.01						
Silicon	Si	0.01	7630	8390	1520	170	6400	250
Tin	Sn	0.015						
Strontium	Sr	0.0005	7390	2430	145	452	1640	530
Titanium	Ti	0.001	418	360	< 6			
Zinc	Zn	0.003	121	362	< 2	76	462	105
Zirconium	Zr	0.001	100	34	< 6	-		
Dilution Factor			803	638	596	246	393	433

*note: All amounts are in ppm

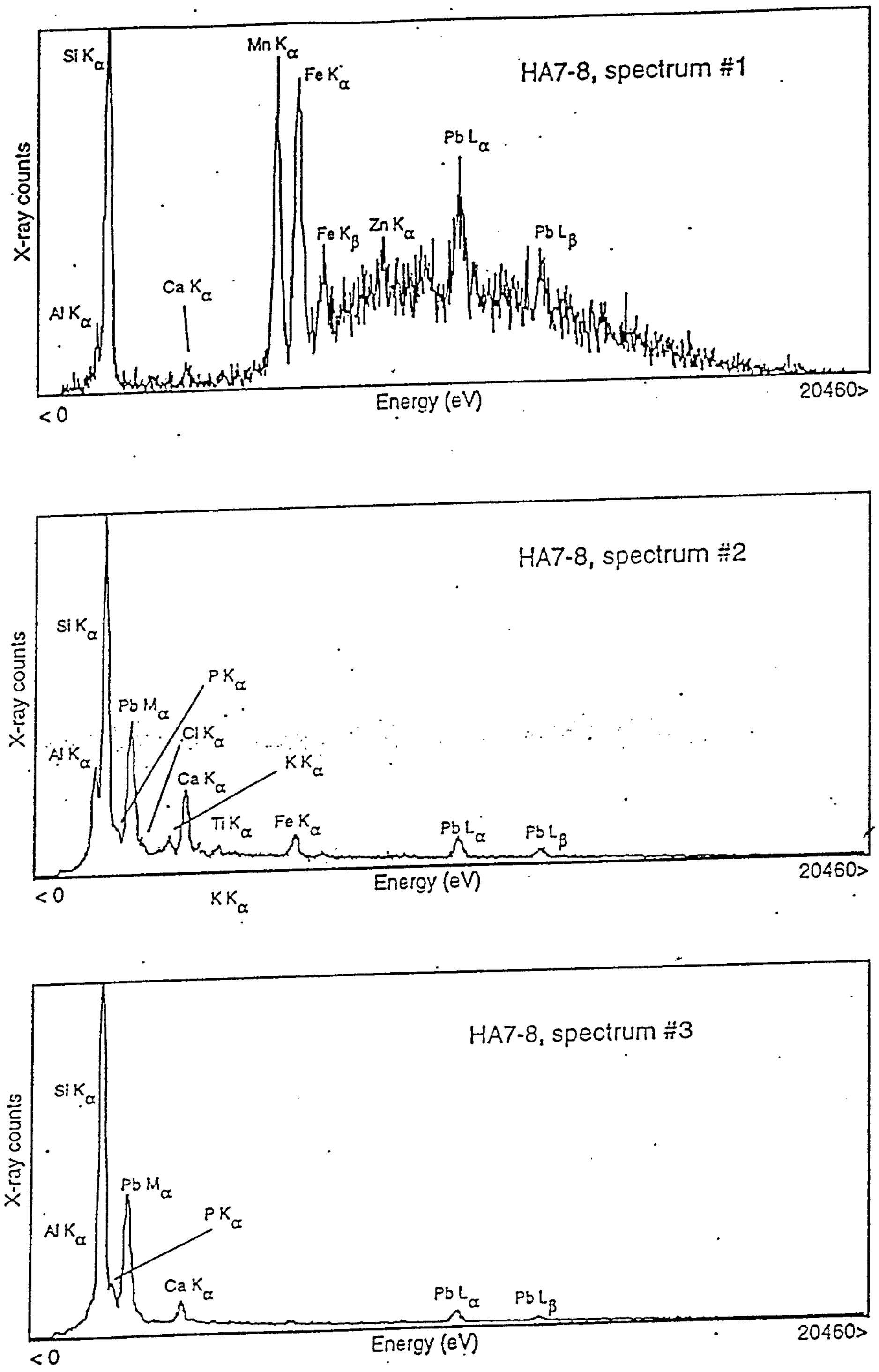


Figure A1. X-ray Energy Dispersive Spectra for Keesler AFB Soil Sample HA7-8.

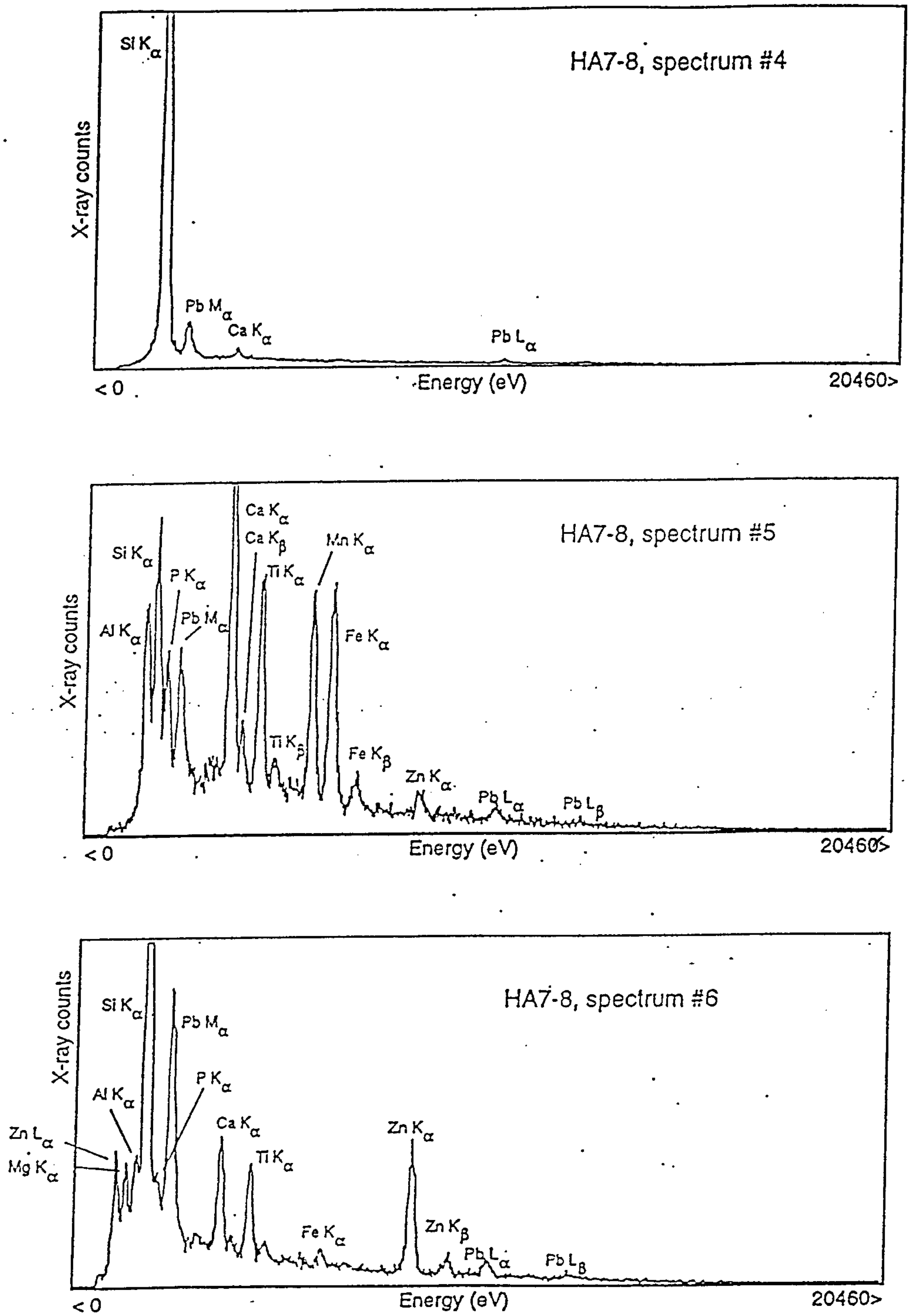
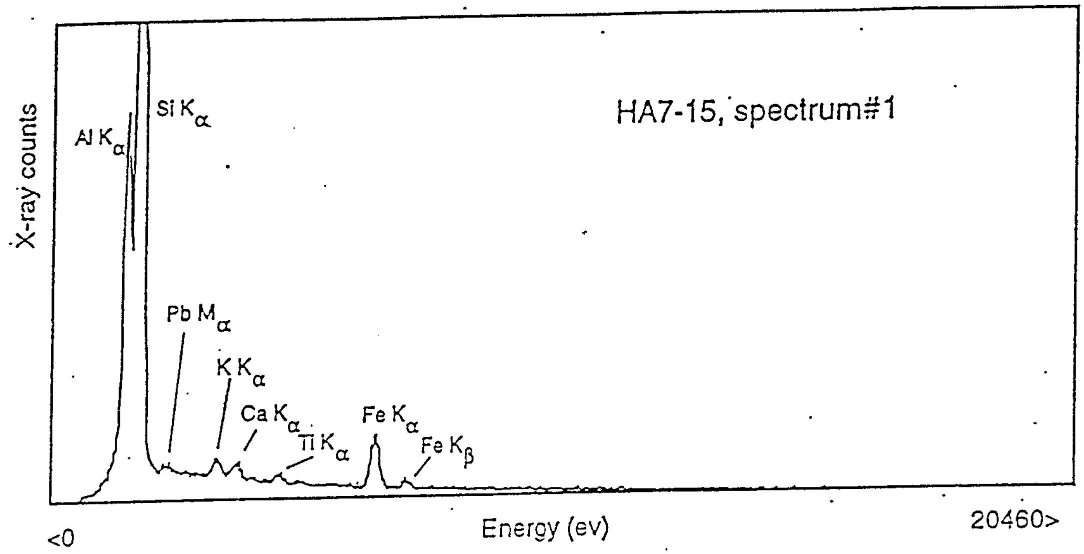


Figure A2. X-ray Energy Dispersive Spectra for Keesler AFB Soil Sample HA7-8.



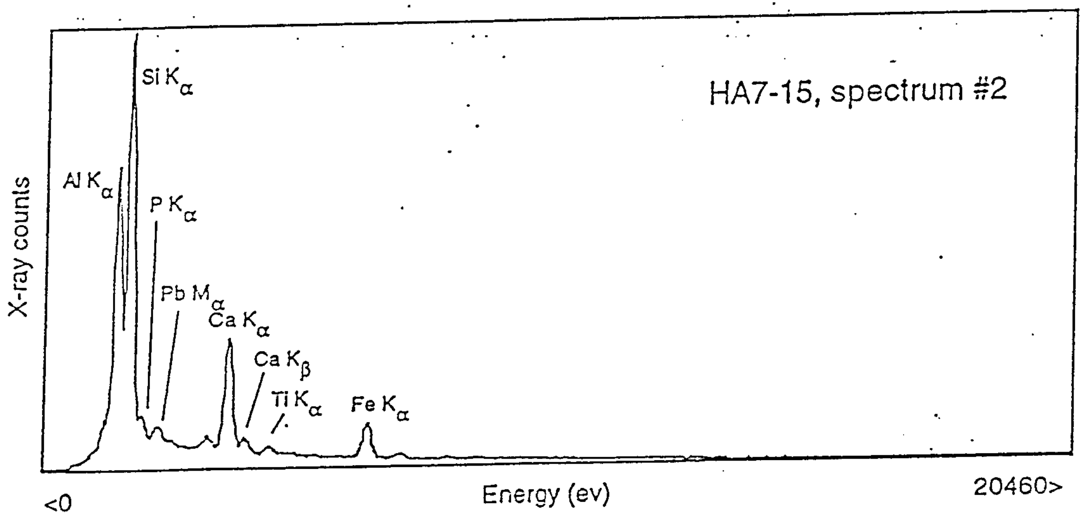


Figure A3. X-ray Energy Dispersive Spectra for Keesler AFB Soil Sample HA7-15.

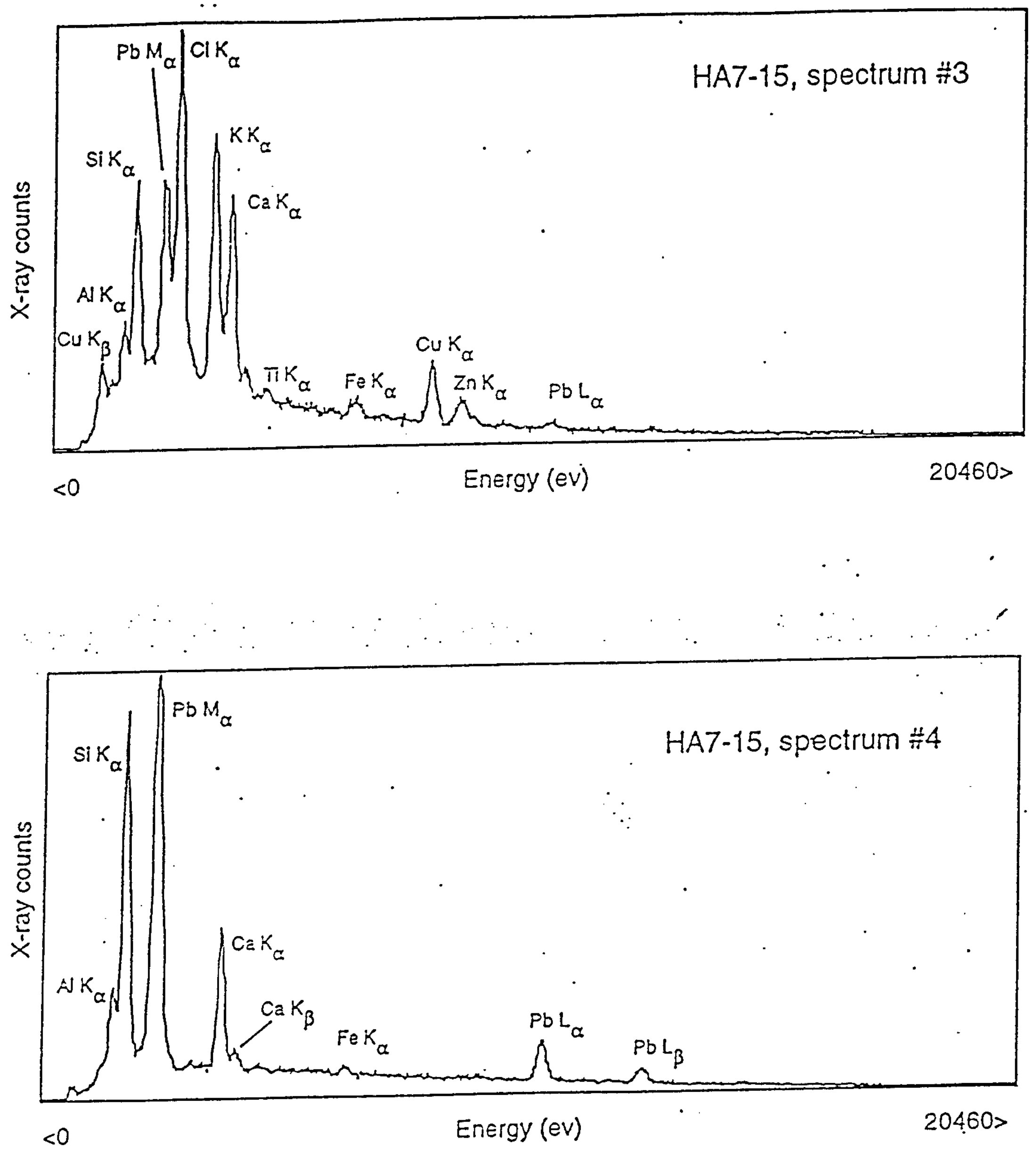


Figure A4. X-ray Energy Dispersive Spectra for Keesler AFB Soil Sample HA7-15.

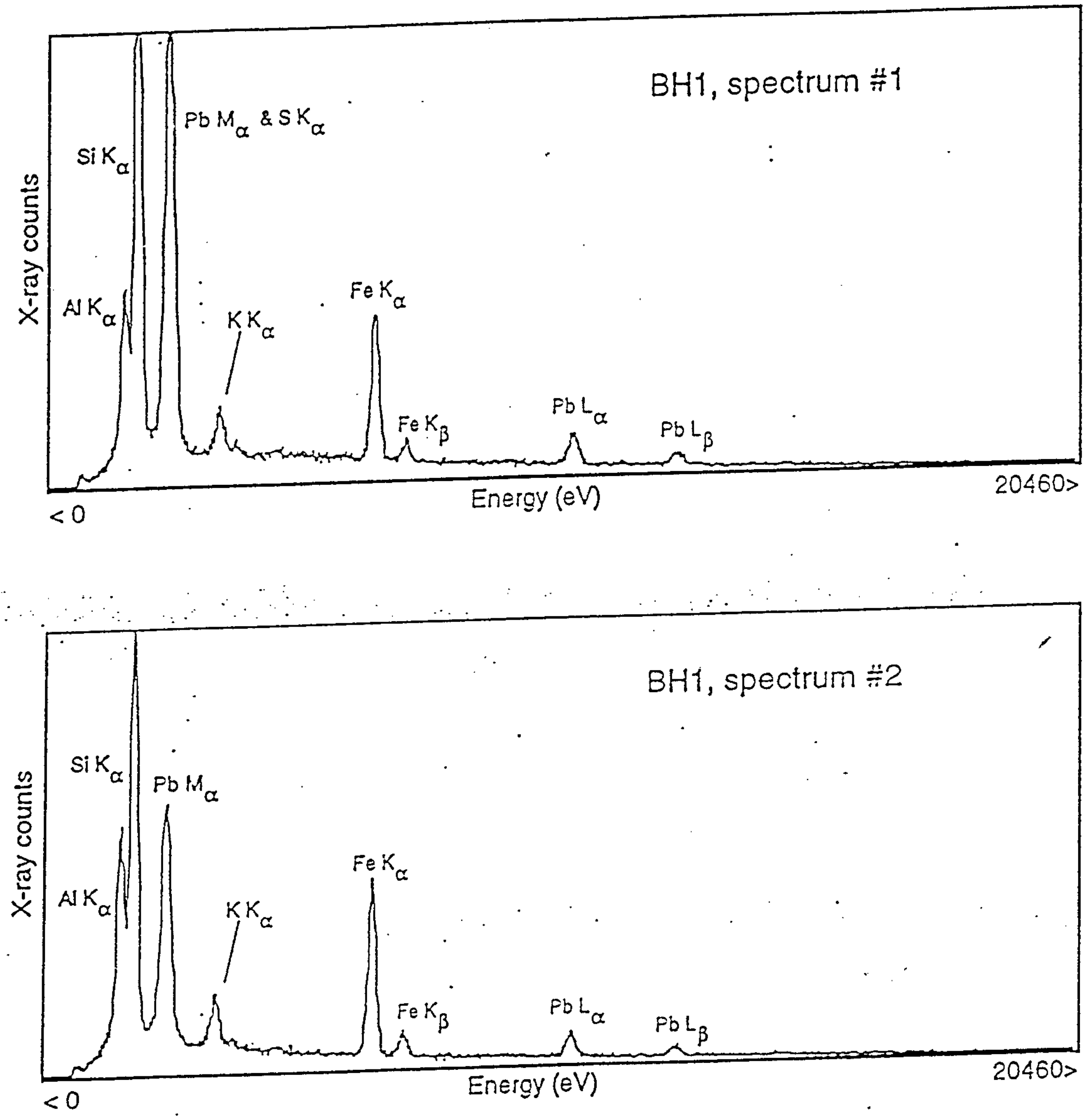


Figure A5. X-ray Energy Dispersive Spectra for Bunker Hill 1000 (BH1) mining soil.

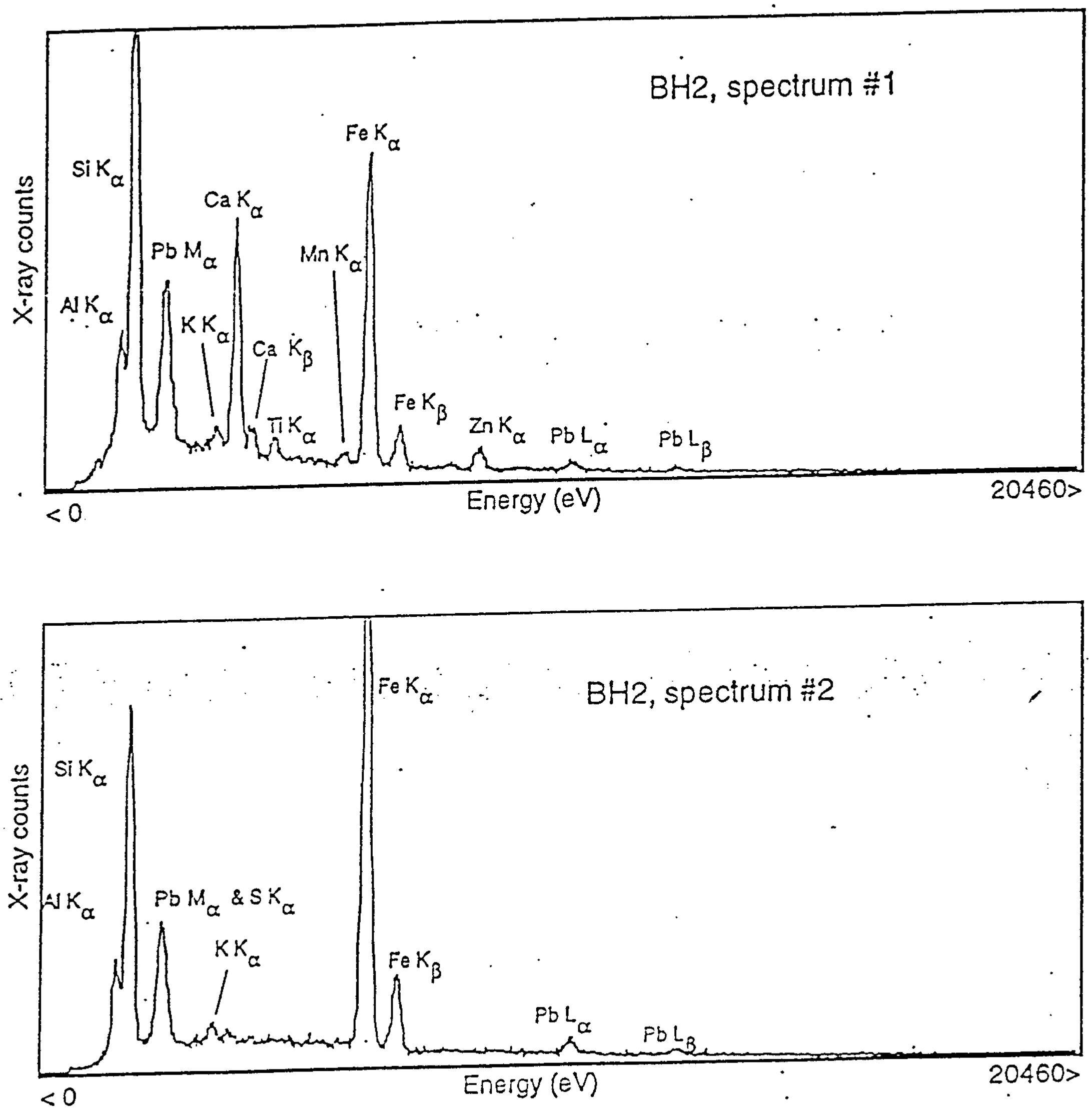


Figure A6. X-ray Energy Dispersive Spectra for Bunker Hill 1000 (BH1) mining soil.

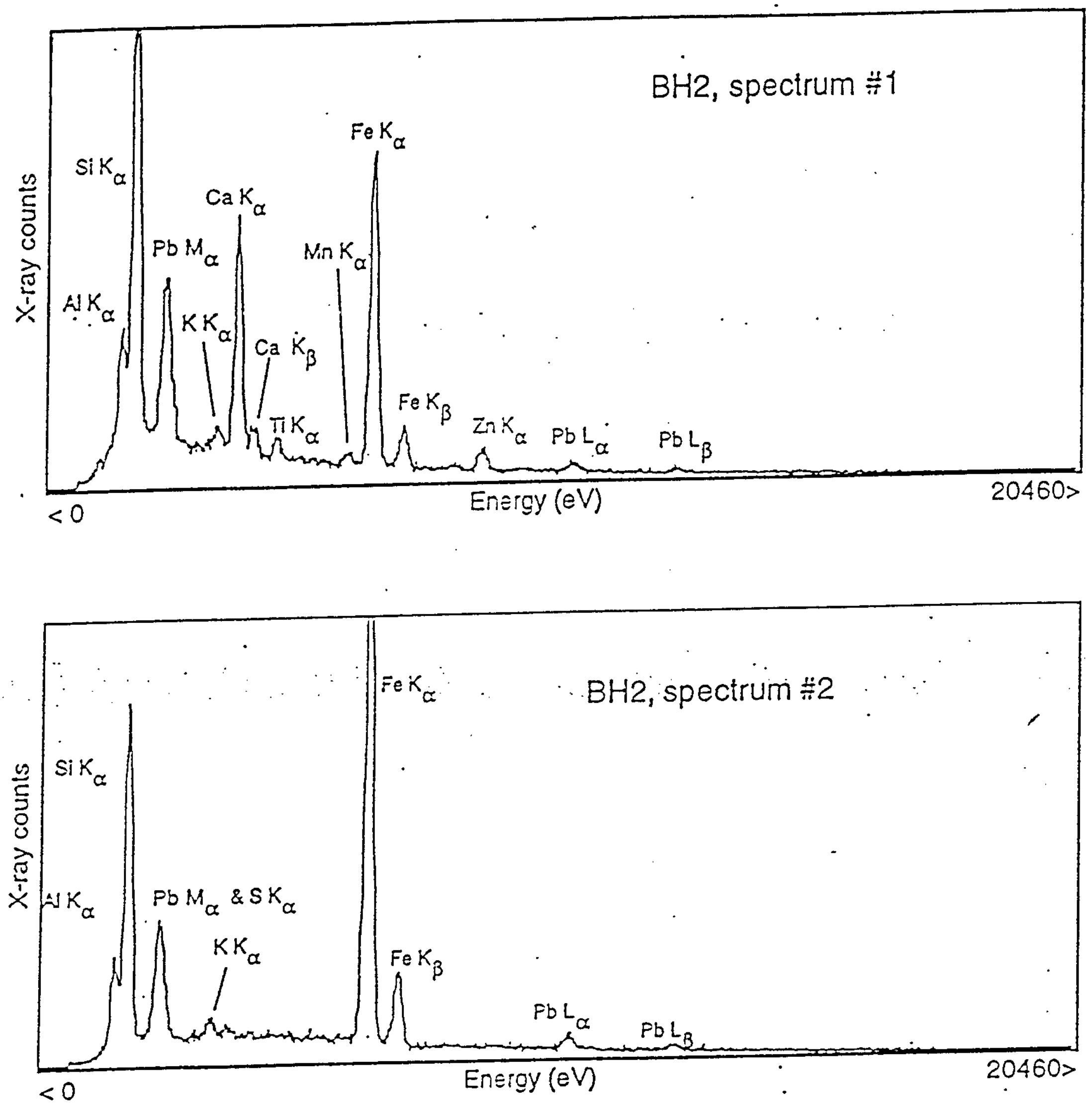


Figure A7. X-ray Energy Dispersive Spectra for Bunker Hill 2000 (BH2) mining soil.

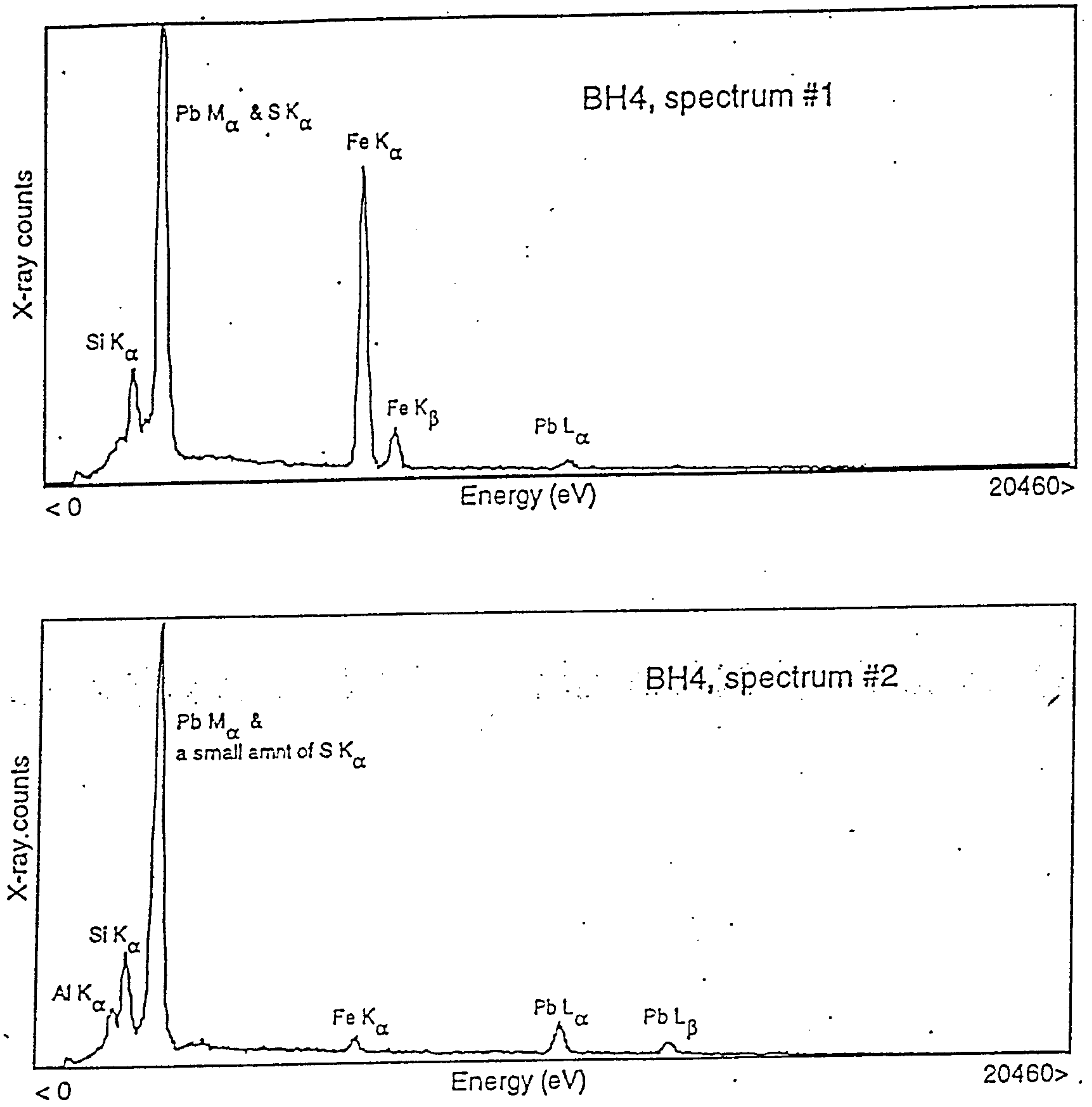


Figure A8. X-ray Energy Dispersive Spectra for Bunker Hill 2000 (BH2) mining soil.

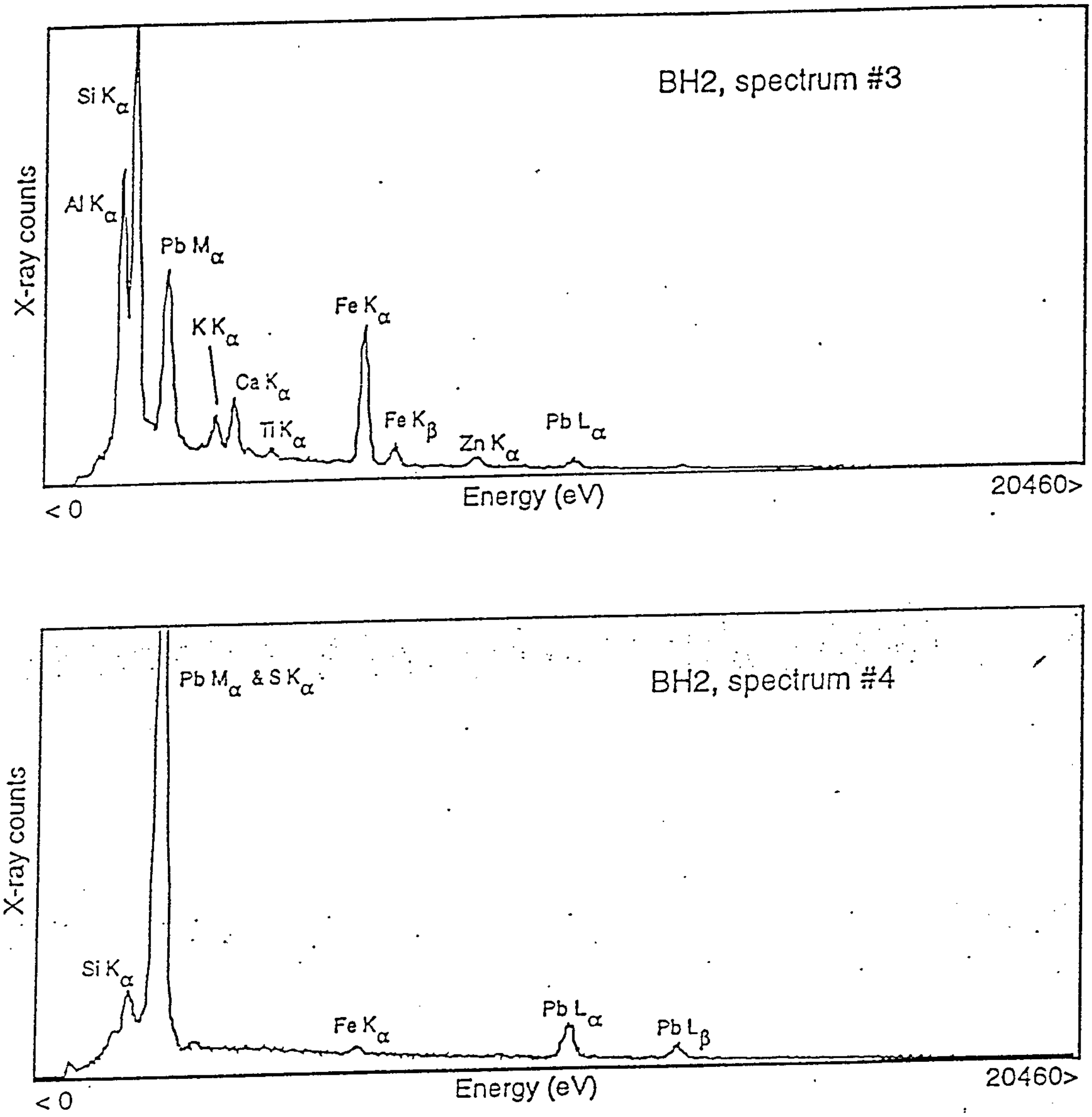


Figure A9. X-ray Energy Dispersive Spectra for Bunker Hill 4000 (BH4) mining soil.

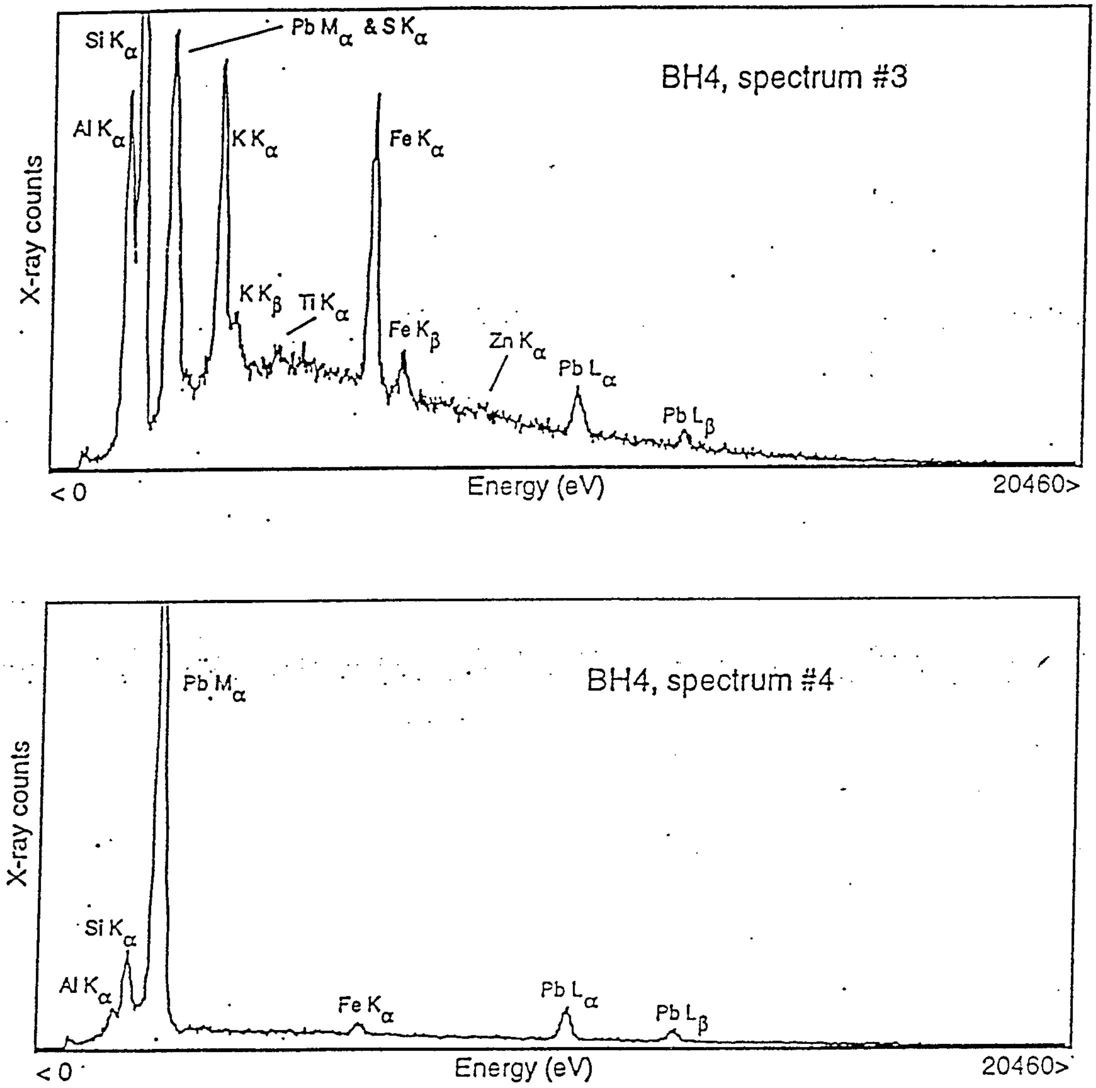


Figure A10. X-ray Energy Dispersive Spectra for Bunker Hill 4000 (BH4) mining soil.

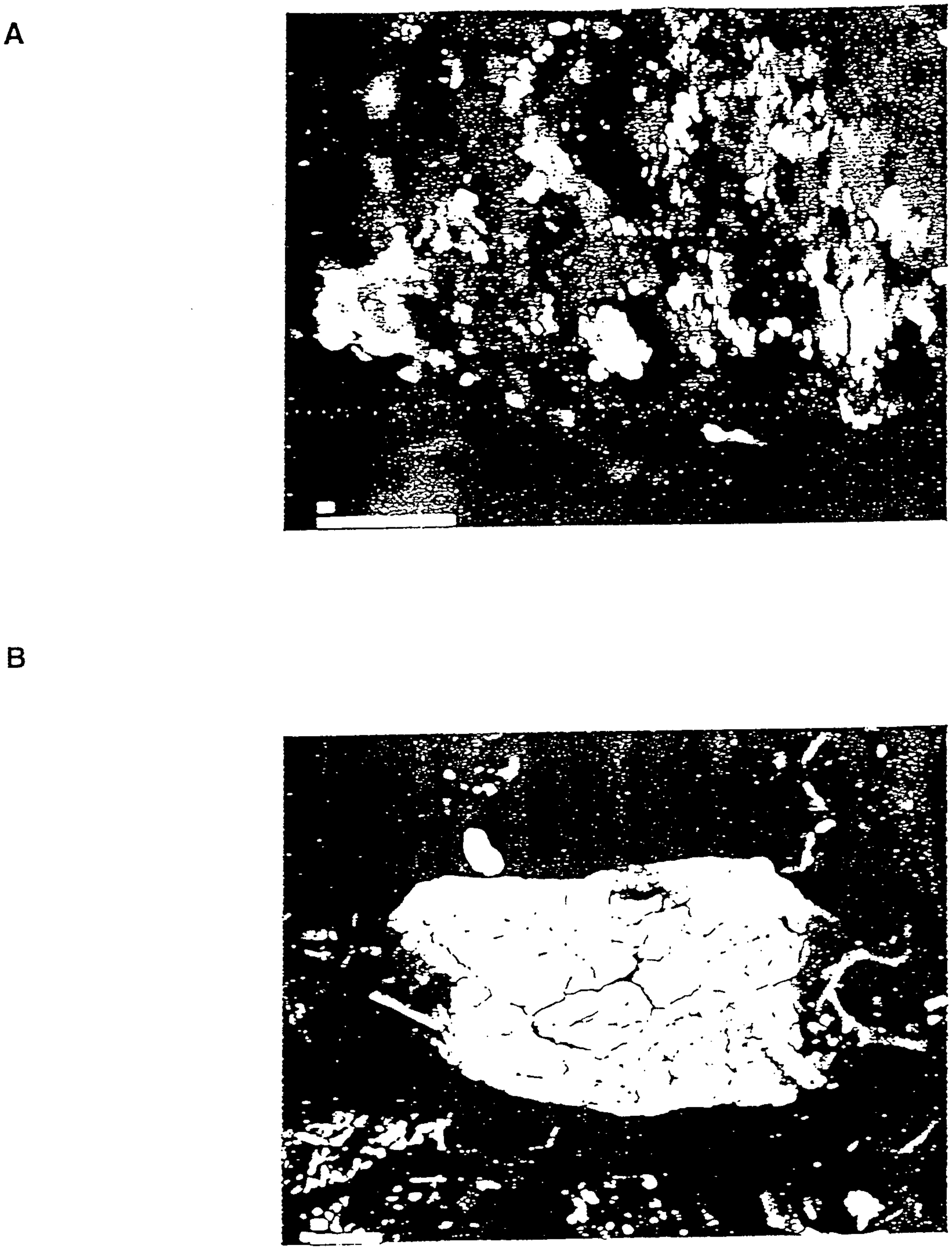


Figure A11. Back Scattered Electron (BSE) Photos of Pb-bearing Grains. (A) HA7-8, Spectrum #4. (B) Bunker Hill 2000 (BH2), spectrum #2. The Longer Scale Bar = 10 microns.