Chapter 5 – TREATABILITY STUDIES

5.1 Introduction

This chapter describes treatability studies that were conducted to further evaluate the technical and economic feasibility of applying the selected technologies to Site soils impacted by lead and arsenic.

Section 5.2 describes the objectives of the treatability studies; Section 5.3 describes the approach taken and summarizes the treatability studies conducted; Section 5.4 summarizes the pertinent results and provides an interpretation to be used in the selection of alternatives (Chapter 6) and their subsequent detailed analysis (Chapter 7). Section 5.5 summarizes the conclusions of the treatability studies and provides recommendations for additional treatability work.

5.2 Treatability Study Objectives

Extensive treatability studies were mainly completed prior to 2000/2001. They were mainly used to help understand lead/arsenic distribution and interactions with Site soils. The studies were also used to investigate ways to address high concentrations of lead- and arsenic-impacted soil. The 2000/2001 ISR actions removed the high concentrations of lead and arsenic soil (above “dangerous waste limits”).

Only small amounts of high concentrations of lead and arsenic soil now remain, after 2000/2001, and these soils are in the miscellaneous small RUs. Though the pre-2000/2001 treatability studies will not play a major role in selecting/evaluating preferred alternatives for final cleanup, since they were geared to high concentrations of soils, they are still presented in this Chapter. The treatability studies still provide background, understanding and insight into how remaining lead- and arsenic-impacted soils can be managed to meet RAOs.

Various treatability studies were conducted to aid in the evaluation of treatment technologies related to physical screening and/or soil washing with extraction. This group of technologies was identified in Chapter 4 as a key component in developing remedial alternatives (Chapter 6) and their subsequent detailed analysis (Chapter 7). These studies where also useful in the design and completion of the 2001 Wet Screening ISR Program. The focus of these studies was to obtain data to:

- Confirm the suitability of these technologies for Site-specific soils;
- Identify potential problems associated with these technologies for application at the Site; and
- Define additional treatability work that may be conducted prior to Site remediation.

Lead- and arsenic-impacted soil remediation technologies that take advantage of the concentration distribution of constituents between the different size fractions of the soil matrix were the primary technologies investigated. Typically, higher concentrations of metals are associated with the smaller grain size soil fractions. By physically segregating the soils into two or more fractions, the following would be obtained:

- A coarse fraction that contains metal concentrations below remediation or cleanup levels that can be returned to the Site as soil for backfill; and
- One or more fine fractions that contain metal concentrations above remediation or cleanup levels that will require further treatment.

Wet Screening and Classification processes were investigated for their ability to achieve physical segregation. Soil Washing with Extraction was examined for constituent extraction potential. Recycling to a Thermal Process was investigated to assess the potential for treating the finer separated soil fractions that would be expected to exceed the remediation or cleanup levels.

The principal objectives of the treatability studies were to:

- Determine the grain size distribution of soil present at the Site;
- Determine the constituent distribution by soil grain size;
- Determine the chemical nature of the constituent; and
- Evaluate volume reduction potential by removal of "clean" soil fractions.

Table 5-1 summarizes the relevant soil characterization parameters used to assess the viability of the above-referenced treatment technologies.

5.3 Treatability Study Approach

The treatability study program used comprehensive soil characterization and speciation studies and bench-scale treatability testing to obtain data on the fundamental physical and chemical properties of the impacted soils. An overview of the program and the pertinent results are summarized in Appendices C and D.

The soil characterization parameters, a description of how the parameters are used, and the specific test types are presented in Table 5-2. (More detailed definitions of the parameters and the testing procedures are summarized in Appendix B.) The soil characterization parameters are organized in Table 5-2 as follows:

Physical Properties that may impact materials handling (e.g., during excavation, stockpiling, treatment, and residuals management). These include particle size distribution and Atterberg limits (liquid limit, plastic limit, and plasticity index) that are used to determine the USDA soil classification. Other physical properties measured were moisture content and bulk density of both loose and packed soil.

Regulatory Analyses to determine regulatory classification of waste streams which provides information for management and disposal of treatment residuals in accordance with federal, state, and local regulations.

Chemical Analyses to gather information on soil chemistry, soil mineralogy, soil/constituent interactions, and the distribution, speciation, and mobility of the lead and arsenic constituents. The chemical analyses and the information they provide include the following:

- pH and Generalized Acid Neutralization Capacity (GANC) measure the alkalinity or acidity of the soil and indicate inherent buffering capacity;
- GANC and Reverse GANC (RGANC) are soil leaching tests that measure a soil's capacity to buffer an acid or a base. This information can be used to design solidification/stabilization design mixes. It can also be an aid in designing acid or base extraction treatment processes;
- Organic carbon and anions analyses indicate the potential to provide bonding sites for heavy metals;
- Soluble cations analysis indicates the potential for competition with the heavy metals for bonding sites; and
- Scanning Electron Microscopy (SEM) and sequential extractions determine the specific chemical form of the metal in the soil matrix and the bonding mechanism. This information may be used when chemical reactions such as metals dissolution (in soil washing processes) and metals precipitation (removal of metals from solvent used in a soil washing process) are included in soil treatment.

Because of constituent concentrations for soil samples vary both vertically and horizontally, samples were analyzed for total constituents prior to conducting treatability testing. Thus, treatability study sample results were representative of the bulk of the Site soils likely to require cleanup action.

Table 5-3 lists the treatability studies conducted in support of lead and arsenic remediation at the Site. A detailed soil characterization program conducted by Hazen Research Inc. (Hazen), at its facility in Golden, Colorado, represents the majority of the treatability study work. Constituent speciation work, physical screening studies, and bench-scale technology evaluations were performed by Battelle Pacific Northwest Laboratories, Hart Crowser, State University of New York, and Weyerhaeuser Analytical and Testing Services.

The following sections briefly describe each treatability study and summarize the results. In addition, the results are evaluated in terms of the physical parameters (soils handling properties), technical feasibility of the remediation alternatives, and chemical parameters.

5.3.1 Lead- and Arsenic-Impacted Soils Characterization Study - Hazen Research Inc.

This study involved soil samples collected from Site areas impacted by lead and arsenic, and included detailed characterization and speciation analysis of the lead- and arsenic-impacted soils. Soil sampling for the characterization study used a statistical procedure based on EPA SW-846 guidance, recognized technical literature on sampling and analysis, and the experience of the Project Team. The sampling procedure enabled recovery of representative composite samples of impacted soils from randomly sampled grids in areas of the Site known to contain elevated concentrations of lead and arsenic.

Complete results for the lead and arsenic characterization are detailed in the final reports prepared by Hazen Research (1993a through 1993f and 1994a through 1994c). Six composite samples of lead-impacted soil and three composite samples of arsenic-impacted soil were collected from different Areas of the Site. The characterization results are summarized in Tables 5-4 and 5-5 for lead and arsenic, respectively. A full description of the Hazen Research soil characterization studies for lead and arsenic, and a discussion of the results obtained, is provided in Appendix C.

5.3.2 Arsenic Wet Screening Study - Hart Crowser, Inc.

Arsenic treatability studies were performed by Hart Crowser to better define the distribution of arsenic concentration with respect to soil particle size through the use of particle size distribution testing and associated arsenic analysis of sized soil fractions. Samples were collected in the Reference Grid Area, and the NGRR area to supplement the results of the Hazen arsenic characterization study completed on samples from Areas 18 and 36 and the NGRR. A summary of the results is provided in Table 5-6 and further details of the treatability study procedures and results are presented in Appendix D.

5.3.3 Arsenic Speciation Analysis - Battelle Pacific Northwest Laboratory (PNL)

Battelle PNL performed limited arsenic speciation analysis on soil samples collected from Areas 5, 25, and 38, and in the NGRR area. The purpose of this study was to identify ionic species of arsenic and investigate the presence of arsenic forms in Site soils potentially impacted by acid production (Areas 5 and 25), the use of arsenic-based herbicides (NGRR), or arsenic-based paint/ink (Area 38). The results are summarized in Table 5-7.

5.3.4 Bench-Scale Soil Leaching Study – State University of New York, Buffalo

A screening of non-proprietary soil leaching chemistries was performed by the Department of Civil Engineering at the State University of New York at Buffalo (UB) (State University of New York at Buffalo, 1994). The efficacy of various soil washing extraction agents and leaching conditions were evaluated for removing lead from a lead-impacted soil sample (-8 to +200 mesh fractions) from Area 40 of the Site. The results of this study are summarized in Table 5-8.

5.3.5 Bench-Scale Soil Leaching Study - Weyerhaeuser Analytical and Testing Services

To investigate the potential for using non-proprietary leaching chemistries to remove arsenic from the Site soils, a leaching study was carried out at the laboratories of Weyerhaeuser Analytical and Testing Services (Weyerhaeuser ATS). Several leaching solutions were applied to -1/4 inch by +200 mesh fractions of combined soil samples from Area 18 and the NGRR area. The effects of pH and liquid:solid ratio were investigated as well as performance under single-stage batch and multistage countercurrent extraction regimes. The results of the study are presented in Appendix C.

5.4 Interpretation of Results

In this section, the results of the treatability studies are discussed by treatment technology using the parameters relevant to each technology as presented in Table 5-1. For each parameter, the results that are applicable to handling and remediation of Site soils are discussed.

5.4.1 Physical Screening/Soil Washing

The relevant characterization test results for physical screening/soil washing with dissolution technologies (as shown in Table 5-1) are silt/clay content, constituent distribution with regard to particle size, surface area calculations, Atterberg Limits, organic carbon, GANC/RGANC, MANC/RMANC, and Sequential Extraction for speciation analysis.

The silt/clay (less than 200 mesh particle sizes) content of the Site soils ranged between 6% and 15 % for the samples tested, well below the 40% upper limit generally considered likely to limit the effectiveness of soil washing processes. The sand (greater than 200 mesh and smaller than 1/4 inch particle sizes) content of the Site soils varies between 26% and 53% and the gravel (greater than 1/4 inch particle sizes) content varies between 38% and 66% by weight.

The lead content in the silt/clay fraction of the Site soils is substantial at between 27% and 67% of total lead in soil, which suggests that significant volume reduction of lead-impacted soil could be achieved by separating the fine material from the whole soil. Classification to separate soil at the 100 mesh cut point would represent recovery of about 90% of whole soil mass suitable for on-Site deposition in appropriate land use areas.

Wet screen particle size distribution test results and corresponding chemical analyses results for separated size fractions indicate that between 84% and 97% of the soil lead is concentrated in the sand and silt/clay fractions. These fractions represent between 40% and 62% by weight of the whole soil. These results indicate that recovery of the cobbles and gravel fraction (representing between 38% and 60% of the whole soil) as "clean" material could be readily achieved using conventional wet screening or soil washing to achieve segregation of Site soils into different size fractions.

The arsenic content in the silt/clay fraction of the soils is between 51% and 71% of total arsenic in soil (corresponding concentrations range between 186 and 2,550 mg/kg), which suggests that significant volume reduction of arsenic-impacted soil could be achieved by separating the fine material from the whole soil. Classification to separate soil at the 100 mesh cut point would represent recovery of about 90% of whole soil mass suitable for on-Site deposition in appropriate land use areas.

Particle size distribution test results for Site soils and corresponding chemical analyses results for separated size fractions indicate that between approximately 79% and 92% of the soil arsenic is concentrated in the sand and silt/clay fractions. These fractions represent between 27% and 56% of the whole soil. These results indicate that recovery of the cobbles and gravels fraction (representing between 44% and 73% of the whole soil) as "clean" material could be readily achieved using conventional wet screening or soil washing to achieve segregation of Site soils into different size fractions.

For water-based soil washing processes, the wet screening and Sequential Extraction test results indicate that, because of the low aqueous solubility of lead or arsenic from Site soils, little or no water treatment provisions would be necessary.

The surface area calculations for each of the soil size fractions indicate, as expected, that the majority of the total soil surface area is contained in the silt and clay (64% to 83%), with less in the sands (17% to 36%), and least in the cobbles and gravel (<1% to 2%).

In the case of Areas 7 and 18, the lead distribution by size fraction increases with reducing size fraction and increasing surface area; these results indicate that lead bonding and binding is mostly surface-related. The lead distribution for Areas 36 and 40 in the sand and silt/clay fractions does not proportionally follow surface area distribution; this indicates that lead is not only surface bound but is also associated with other particulate matter present in the soil matrix. In the case of Area 36 soils, SEM confirmed the presence of particulate lead. The presence of metallic lead suggests that density separation techniques may need to be incorporated into the design of a soil washing system.

The arsenic distribution by size fraction for the Area 36 sample increases with reducing size fraction and increasing surface area; these results indicate that arsenic bonding and binding is mostly surface-related.

The very low silt/clay content and results of the Atterberg Limits testing show that the Site soils are non-plastic and should be both amenable to processing by physical screening equipment and easy to handle with conventional earth-moving equipment.

The organic carbon content of the Site soils (0.6% to 6.9%) is below the 10% upper limit generally considered to reduce removal efficiency in a soil washing system because of contaminant-carbon bonding. The inclusion of an organic carbon removal unit operation should not be necessary.

The GANC/RGANC results show that the Site soils have little buffering capacity and will not require the addition of large amounts of acid (to mobilize lead species) or base (to mobilize arsenic species) in a chemically enhanced soil washing system to achieve the desired pH change.

The ELP results (0.02 to 0.06 mg/L) demonstrate very low lead solubility with synthetic acid rain. The wet screening and Sequential Extraction test results also demonstrate that the lead species are relatively insoluble in water. The lead was more soluble in acetic acid solutions, as demonstrated by TCLP, GANC, and Sequential Extraction test data. These results indicate that lead is essentially immobile under normal environmental conditions, but can be mobilized under more rigorous leaching conditions.

The MANC/RMANC equilibrium lead concentrations in the aqueous phase occur between additions of 2 to 40 equivalents of acid/kg soil and between additions of 2 to 40 equivalents of base/kg. One stage acidic and alkaline leaching at 20:1 liquids:solids ratio can remove 45% to 75% of the lead using 2N acetic acid, or 13% to 40% lead using 2N sodium hydroxide. This indicates that acidic leaching has potential for use in conjunction with wet screening and other physical (gravity, density, and high-energy attrition) treatment techniques. Even under severe leaching, a maximum of 75% lead removal is achieved because of the presence of some extremely leach-resistant forms of lead.

In the consideration of MANC/RMANC equilibrium arsenic concentrations, high acetic acid concentrations (approximately 14 equivalents of acid/kg soil) were required to leach arsenic, whereas RGANC indicated that about two base equivalents/kg soil were required for optimum leaching. One stage acidic/alkaline leaching at 20:1 liquids:solids ratio can remove 2% to 4% of the arsenic using 2N acetic acid, but amounts of between 74% and 80% can be removed using 2N sodium hydroxide. These results indicate that chemical leaching using alkaline reagents has potential for use in conjunction with wet screening and other physical treatment techniques. Conversely, mildly acidic conditions might be employed in a soil washing with dissolution treatment scenario to ensure that arsenic remains concentrated in the fines fraction, which could subsequently be stabilized.

In the sized fractions examined, Sequential Extraction data show that lead is predominantly present as carbonate, specifically adsorbed and ion-exchangeable forms, as well as being associated with iron and manganese oxides and organic material. This speciation information also indicates that further lead removal could be achieved in a chemically enhanced (acidic) soil washing or leaching treatment system.

Sequential Extraction data show that arsenic is predominantly present, in the sized fractions examined, in association with iron and manganese oxides and organic material. Speciation analyses performed on selected sized fractions (gravity separated as appropriate) using SEM confirmed the Sequential Extraction test results. The Battelle PNL speciation analysis also indicates that, in the areas of the Site sampled (Areas 5, 25, 38, and NGRR), arsenic is largely present as As(5). This speciation information supports the conclusion that chemically enhanced (basic) soil washing or leaching treatment could be used to liberate arsenic from the soils.

The results of the UB soil washing with dissolution study provide further support for considering a chemically enhanced treatment application. The study shows that strong mineral acid extractants (specifically, hydrochloric and perchloric acid) at approximately pH 1 were effective at significantly reducing (by greater than 60%) lead concentrations by approximately 1,400 mg/kg in the sand fraction of Site soils. TCLP lead values for treated samples ranged from 0.3 to 0.5 mg/L. Less acidic conditions (pH 3) were also effective if a chelating agent (such as EDTA) was added.

The results of the Weyerhaeuser ATS leaching study confirm the leaching data generated under the Hazen study and further demonstrate that sodium hydroxide caustic solutions are effective in removing arsenic from the Site soils. In single-stage batch extractions, solutions of sodium hydroxide at approximately pH 11.5 removed up to 57% of arsenic from sand fractions containing initial concentrations of around 100 mg/kg; sodium carbonate solutions gave similar results but required significantly higher reagent doses. A strong dependency on pH was shown in the leaching tests and there was no evidence that leaching performance was constrained by arsenic solubility. A batch extraction test examining relative leaching efficiencies between subfractions of the tested soil showed a slightly better performance for the larger subfraction. No significant improvements in overall leaching performance were observed in simulated countercurrent tests. Further investigation of washing process configuration, solids hold-up times, temperature, and aqueous extract treatment/recycling will need to be completed to decide if a leaching step should be included as part of a soil washing treatment application.

5.5 Conclusions and Recommendations

This section summarizes the conclusions from the various treatability studies relating to the viability assessment of physical screening/soil washing with dissolution.

5.5.1 Soil Characterization

The TCLP results for lead and arsenic obtained for the treatability samples indicate that most Site soils do not exhibit a RCRA hazardous toxicity characteristic associated with these metals.

Physical analysis data show that the Site soils are moderately well sorted (i.e., more coarse fraction and a relatively low silt/clay content), non-plastic, and classify as sand and sandy-loam. Excavation and materials handling of the soils should be relatively easy using conventional equipment and methods, and the soils should be amenable to processing by physical screening and mixing equipment.

The Site soils are essentially neutral and possess little acidic or basic buffering capacity. This is advantageous for both solidification/ stabilization and soil washing with dissolution processes in that the amounts of binder or leaching chemical needed to achieve the desired treatment performance will be minimized. The unamended soils will not be corrosive to excavation, materials handling, or processing equipment.

Based on speciation analysis data, soil lead is present mainly as carbonate, specifically adsorbed and ion-exchangeable forms, and in association with iron and manganese oxides and organic material. Lead constituents are present both in association with soil surfaces (surface bonding/binding) and as free metallic particles within the soil matrix. Arsenic speciation analysis data show that soil arsenic exists predominantly as arsenate (+5 valence state) and occurs mostly in association with iron oxides and the organic portion of the soil. Arsenic bonding and binding is primarily associated with the smaller soil particles with a high surface area per unit mass.

Leaching data show that both lead and arsenic are essentially insoluble and immobile under normal environmental conditions. Under both acidic and basic leaching conditions, soil lead can be leached (more readily mobilized under the former), although some extremely leach-resistant forms of lead are indicated. Soil arsenic can be readily mobilized under moderately basic leaching conditions but is difficult to remove at low pH. This is consistent with the information yielded by the lead and arsenic speciation analyses.

The Site soils have a low organic carbon content and so no interference or inhibitory affects associated with potential carbon-heavy metal bonding/binding would be expected for either solidification/stabilization or physical screening/soil washing with dissolution treatment.

5.5.2 Volume Reduction

For both lead and arsenic, significant proportions of these constituents were measured in the silt/clay fraction of the soil. Separation of the fines from the whole soil would be effective in concentrating a substantial proportion of the metals into a relatively small soil volume. This will potentially reduce the volume of significantly impacted soils requiring subsequent treatment or disposal.

A comparison of soil particle distribution and associated chemical distribution data with remediation and cleanup levels was made. The results indicated that recovery, as “clean soil”, of the cobbles and gravel fraction (40% to 60% of soil by weight) can be achieved by dry and wet screening, respectively. More aggressive soil washing and secondary treatment can achieve recovery of the sand, cobble, and gravel fractions (90% or more of soil by weight) as "clean" material.

5.5.3 Metal Dissolution/Removal

Strong hydrochloric acid or perchloric acid solutions at low pH (approximately pH 1) are effective at significantly reducing lead concentrations in the Site soils. Similar leaching performances can be achieved with these acids at more moderate pH (approximately pH 3) if a chelant (EDTA) is added to the leaching solution.

In the case of arsenic-impacted soils, strong sodium hydroxide and sodium carbonate solutions (approximately pH 12 or greater) are able to effectively remove arsenic in a single-stage batch extraction regime. Leaching performance does not appear to be constrained by arsenic solubility, and might be improved under a multi-stage countercurrent leaching process configuration.

The use of acidic/caustic leaching in conjunction with physical screening processes is indicated to have potential for reducing concentrations of lead and arsenic in the sand fraction of the soil or in the sands and fines combined. This approach merits further evaluation.

Table 5-1 - Soil Characterization Parameters by Treatment Technology

Soil	Treatment Technology	Test Types
Whole Soil and Fractions	Stabilization/Solidification	GANC/RGANC MANC/RMANC Total Carbon, Inorganic and Organic Carbon RCRA Appendix IX SemiVOCs TCLP (inorganic and semiVOCs) Moisture Content Speciation Analysis of Fractions
	Physical Screening/Soil Washing for Dissolution	Constituent Distribution with Particle Size Surface Area Calculations Silt/Clay Content MANC/RMANC during GANC/RGANC Organic Carbon Speciation Analysis of Fractions Atterberg Limits
	Smelting/Thermal Recovery	Total Constituent Concentration Constituent Distribution with Particle Size XRF Scan (mineralogy) Silica Content (by XRF) Moisture Content Total Carbon RCRA F039 Listed Metals

Abbreviated terms used in this table are defined in Appendix B.

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Table 5-2 - Soil Characterization Parameters by Category

Soil	Category	Information Use	Test Types
Whole Soil	Physical Handling	Provides information on how soil will behave during excavation and in treatment processes.	Surface Area Calculations (Lead only) Particle Size Distribution Soil Plasticity (Atterberg Limits) USDA Soil Classification Density (loose and packed) Moisture Content
	Regulatory	Provides information to enable regulatory waste code classification.	Total Constituent Concentration TCLP Constituent Concentrations RCRA Appendix IX Total Metal Concentration TCLP (inorganics and semiVOCs) RCRA Appendix IX Inorganics RCRA Appendix IX SemiVOCs pH
	Soil Chemistry	Provides information on contaminant/soil interactions to further general understanding of soil properties and used in evaluating treatment technologies.	Bonding/Binding Anions Soluble Cations Carbon (total/inorganic/organic) GANC/RGANC
	▸ Anions	Provides an indication of availability of bonding/binding sites for heavy metals (anions can combine with metals to form low solubility salts)	Sulfide Sulfate Phosphate Carbonate/Bicarbonates
	▸ Soluble Cations	Can compete with heavy metals for bonding/binding sites (ion-exchange sites, anions).	Calcium Sodium Magnesium Potassium Manganese Iron
	▸ Carbon Balance	Organic carbon can bond/bind with metals.	Total Carbon Inorganic (fixed) Carbon (by TGA) Organic Carbon (by difference)

Table 5-2 - Soil Characterization Parameters by Category

Soil	Category	Information Use	Test Types
Whole Soil, Continued	▸ Alkalinity/Acidity, Buffering Capacity	Provides indications of how soil will respond to acid/base changes.	pH Redox GANC/RGANC
	Mobility and Leachability	Provides information on mobility in, and availability to, the environment.	TCLP (inorganics and semiVOCs) Equilibrium Leaching Procedure (lead only) (SAR-F039 List Metals) MANC during GANC/RGANC GANC/RGANC
Soil Fractions	Regulatory	Provides information on metals of regulatory concern to enable proper management/disposal.	F039 List Metals
	Soil Chemistry	Provides information on contaminant/soil interactions to further general understanding of soil properties and used in evaluating treatment technologies.	Cation Exchange Capacity (CEC) (Lead only) Total Iron and Manganese Total Chloride
	Speciation	Provides information on what specific chemical forms of metals are present and how metals are bound within soil. Aids in determination of impact to environment and technology selection.	Sequential Extraction Scanning Electron Microscopy (SEM) X-Ray Diffraction (XRD) X-Ray Fluorescence (XRF) - Mineralogy

Abbreviated terms used in this table are defined in Appendix B.

Table 5-3 - Summary of Treatability Studies

Type of Study	Organization Performing Treatability Study	Location of Study	Target Constituent	Summary of Scope	Areas of Site Sampled
Soil Characterization	Hazen Research, Inc.	Golden, CO	Lead and Arsenic	Complete characterization (see Table 5-1 and Table 5-2)	7, 18, 36, 40, 18, 36, NGRR, Hot Spot Soils
Soil Washing/Leaching	Department of Civil Engineering, State University of New York	Buffalo, NY	Lead	Test various extraction agents and leaching conditions to remove lead	40
Constituent Speciation	Battelle Pacific Northwest Laboratories	Sequim, WA	Arsenic	Identify ionic and organic species of arsenic	5, 25, 36, NGRR
Wet Screening	Hart Crowser, Inc.	Seattle, WA	Arsenic	Determine distribution of arsenic between soil size fractions	18, 36, NGRR
Soil Leaching	Weyerhaeuser Analytical and Testing Services	Federal Way, WA	Arsenic	Test potential of non-proprietary leaching solutions for removal of arsenic	18, NGRR

Note: NGRR = Narrow Gauge Railroad Track

Additional Studies Performed but not considered during evaluation of technologies

Type of Study	Organization Performing Treatability Study	Location of Study	Target Constituent	Summary of Scope	Areas of Site Sampled
Solidification/ Stabilization	Center for GeoEnvironmental Science & Technology, University of Cincinnati	Cincinnati, OH	Lead and Arsenic	Evaluate ability of 3 types of binding mixes to stabilize lead and arsenic	36, 40

Table 5-4 Lead-Soil Characterization Study Summary of Test Results-Hazen Research [1]
Sheet 1 of 4

Whole Soil Procedures	Area 7 (Kettle)	Area 18 (Nitrator)	Area 36 (Lead Melt)	Area 40 (Pulverizer)	Area 40 (Glazemill)	Area 40 (Packhouse)
Sample Verification (Pulverized Head)						
Total Lead in mg/kg (avg. of three)	475	180	870	2,110	660	3,570
TCLP Lead in mg/L	1.7	0.3	4.6	1.3	1.2	21.4
RCRA Hazardous, D008	no	no	no	no	no	yes
Physical Materials Handling						
Particle Size Distribution in % (gravel, sand, silt)	56,32,12	38,53,9	61,32,7	43,42,15	60,32,8	53,37,10
Soil Plasticity (Atterberg Limits)	non-plastic	non-plastic	non-plastic	non-plastic	non-plastic	non-plastic
USDA Soil Classification	sand	sandy loam	sand	sand	sand	sand
Density (loose/packed) in g/cm^3	1.3/1.4	1.3/1.5	1.6/1.9	1.1/1.5	1.2/1.6	1.1/1.4
Moisture Content in %	12.2	9.8	5.0	20.5	11.7	17.0
pH (10% solids slurry)	4.4	6.0	6.3	7.3	5.4	5.8
Regulatory						
Total Lead in mg/kg (RCRA Appendix IX)	380	260	540	1,700	590	3,000
TCLP Lead in mg/L	2.0	0.3	4.7	1.4	0.9	18
RCRA Appendix IX Inorganics	none of concern	none of concern	none of concern	none of concern	none of concern	none of concern
RCRA Appendix IX SemiVOCs	none of concern	low level semiVOCs	low level semiVOCs	low level semiVOCs	none of concern	none of concern

Notes:
[1]Further description of the tests and interpretation of these results is provided in Section 5 text and in Appendix C.

Table 5-4 Lead-Soil Characterization Study Summary of Test Results-Hazen Research [1]
Sheet 2 of 4

Whole Soil Procedures	Area 7 (Kettle)	Area 18 (Nitrator)	Area 36 (Lead Melt)	Area 40 (Pulverizer)	Area 40 (Glazemill)	Area 40 (Packhouse)
Soil Chemistry						
Bonding/Binding Anions in mg/kg (total)	2,600	2,500	2,640	10,650	4,175	7,190
Soluble Cations in mg/kg (total)	81	24	77	261	66	94
Total/Inorganic/Organic Carbon in %	3.3/0/3.3	2.5/0.7/1.8	1.1/0.2/0.9	6.9/0/6.9	4.2/0/4.2	4.2/0/4.2
Net Acid/Base Potential in tons of $CaCO_3$/1,000 tons of soil	-10.9	-7.5	1.0	2.8	-24.4	-16.1
GANC/RGANC	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered
equivalents acid to reach pH<4	2	2	2	4	2	2
equivalents base to reach pH>10	2	2	2	2	2	2
Leaching and Mobility						
TCLP Lead in mg/L	2.0	0.3	4.7	1.4	0.9	18.0
Equilibrium Leaching Procedure						
leachate lead in mg/L	0.019	0.05	0.032	0.02	0.059	0.064
equilib. partition coefficient (K)	2.2E+04	1.0E+04	2.0E+04	8.1E+04	1.1E+04	6.3E+04
MANC/RMANC equilib. lead conc. (acid/base) in mg/L	15/7	4/3	33/8	48/14	15/13	90/25
Speciation						
Sequential Extraction	majority of lead in carbonate, specifically adsorbed, and exchangeable forms	majority of lead in carbonate, specifically adsorbed, and exchangeable forms	majority of lead in carbonate, specifically adsorbed, and exchangeable forms	majority of lead associated with carbonates, iron and manganese oxides, and organic material	majority of lead associated with carbonates, iron oxides, and organic materials	majority of lead associated with carbonates, iron and manganese oxides, and organic material
SEM/XRD	positive ID of lead sulfate and lead sulfide	positive ID of lead carbonate, lead oxide, and lead-manganese oxide	positive ID of lead carbonate, lead silicate, metallic lead, and lead-iron oxide	positive ID of lead carbonate, lead silicate, lead oxides,	positive ID of lead silicate, lead oxides, lead phosphate,	positive ID of lead oxides (manganese, tin, aluminum,

Notes:
[1]Further description of the tests and interpretation of these results is provided in Section 5 text and in Appendix C.

Table 5-4 Lead-Soil Characterization Study Summary of Test Results-Hazen Research [1]
Sheet 2 of 4

Whole Soil Procedures	Area 7 (Kettle)	Area 18 (Nitrator)	Area 36 (Lead Melt)	Area 40 (Pulverizer)	Area 40 (Glazemill)	Area 40 (Packhouse)
				and lead-iron oxide	and lead-iron oxide	and iron)

Notes:
[1]Further description of the tests and interpretation of these results is provided in Section 5 text and in Appendix C.

Table 5-4 Lead-Soil Characterization Study Summary of Test Results-Hazen Research [1]
Sheet 3 of 4

Whole Soil Procedures	Area 7 (Kettle)	Area 18 (Nitrator)	Area 36 (Lead Melt)	Area 40 (Pulverizer)	Area 40 (Glazemill)	Area 40 (Packhouse)
Soil Chemistry						
Cation Exchange Capacity in meq/100g	34.6	84.2	49.6	98.1	111.0	95.9
Chloride in mg/kg	100	<100	<100	500	100	260
Iron/Manganese in mg/kg	23,350/620	34,238/838	39,979/775	63,630/990	30,050/1,150	95,820/1,090
Regulatory						
F039-List Metals	As, Pb, Ba, Cr	As, Pb, Ba, Cr	As, Pb, Ba, Cr	Pb, Ba, Cr, Zn	As, Pb, Zn	As, Pb, Ba, Cu, Zn
Physical Screening/Soil Washing						
Silt and Clay Content in %	12	9	7	15	8	10
Lead Distribution by Particle Size % of total lead in gravel/sand/silt	16/29/55	3/30/67	10/63/27	5/56/39	13/48/39	3/58/39
Total Lead Conc. in mg/kg by Particle Size (gravel/sand/silt)	130/420/2,170	50/310/3,970	180/2,100/3,980	195/2,310/4,350	130/950/3,320	130/4,260/10,600
Surface Area Calculations % of total surface area in gravel/sand/silt	<1/17/83	<1/36/64	2/22/76	<1/18/82	1/23/76	1/20/79
Organic carbon in %	3.3	1.8	0.9	6.9	4.2	4.2
GANC/RGANC	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered
equivalents acid to reach pH<4	2	2	2	4	2	2
equivalents base to reach pH>10	2	2	2	2	2	2
MANC/RMANC equilib. lead conc. (acid/base) in mg/L	15/7	4/3	33/8	48/14	15/13	90/25
% Lead Leached under MANC/RMANC (acid/base)	60/29	44/30	75/18	45/13	45/40	50/14

Notes:
[1]Further description of the tests and interpretation of these results is provided in Section 5 text and in Appendix C.

Table 5-4 Lead-Soil Characterization Study Summary of Test Results-Hazen Research [1]
Sheet 4 of 4

Whole Soil Procedures	Area 7 (Kettle)	Area 18 (Nitrator)	Area 36 (Lead Melt)	Area 40 (Pulverizer)	Area 40 (Glazemill)	Area 40 (Packhouse)
Stabilization/Solidification						
GANC/RGANC	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered	unbuffered
MANC/RMANC Minimum Lead Concentration in mg/L/pH Range	<1/5.5 to 6.8	<1/4.6 to 6.1	<1/4.8 to 8.5	1/6.3 to 12.5	1/5.1 to 8.9	1/6.3 to 7.8
Total/Inorganic/Organic Carbon in %	3.3/0/3.3	2.5/0.7/1.8	1.1/0.2/0.9	6.9/0/6.9	4.2/0/4.2	4.2/0/4.2
RCRA Appendix IX SemiVOCs	none of concern	low level semiVOCs	low level semiVOCs	low level semiVOCs	none of concern	none of concern
TCLP Lead in mg/L	2.0	0.3	4.7	1.4	0.9	18
Moisture Content in %	12.2	9.8	5.0	20.5	11.7	17.0
Smelting/Thermal Recovery						
Total Lead in mg/kg	380	260	540	1,700	590	30,00
Lead Distribution by Particle Size % of total lead in gravel/sand/silt	16/29/55	3/30/67	10/63/27	5/56/39	13/48/39	3/58/39
Total Lead Conc. in mg/kg by Particle Size (gravel/sand/silt)	130/420/2,170	50/310/3,970	180/2,100/3,980	195/2,310/4,350	130/950/3,320	130/4,260/10,600
Silica Content in % (gravel/sand/silt)	-/69/59	-/-/33	-/-/45	-/56/28	-/-/28	-/50/29
Moisture Content in %	12.2	9.8	5.0	20.5	11.7	17.0
Total Carbon in %	3.3	2.5	1.1	6.9	4.2	4.2

Notes:
[1]Further description of the tests and interpretation of these results is provided in Section 5 text and in Appendix C.

Table 5-5 - Arsenic-Soil Characterization Study
Summary of Test Results
Hazen Research

Whole Soil Procedures	Area 18	Area 36	RR Track Area
Physical Materials Handling			
Particle Size Distribution (PSD) in % (Gravel/sand/silt)	66/26/8	60/30/10	52/39/9
Arsenic Distribution with PSD in % (Gravel/sand/silt/slimes)	12/28/35/25	18/30/47/5	7/22/63/8
pH (10% solids slurry)		6.2	
Regulatory			
TCLP Arsenic in mg/L (conducted at 4.9 pH)	<0.03	<0.07	<0.03
RCRA Hazardous, D004	No	No	No
Soil Chemistry			
Total Arsenic in mg/kg	41	29	353
GANC/RGANC	Unbuffered	Unbuffered	Unbuffered
Equivalents acid to reach pH<4	>14	>14	2
Equivalents base to reach pH>10	2	<2	2
Leaching and Mobility			
TCLP Arsenic in mg/L	<0.03	<0.07	0.03
MANC/RMANC minimum arsenic Concentration (acid/base) in mg/L: pH	0.007:3.8/ 0.05:5.0	0.007:3.7/ 0.035:8.8	0.045:3.2/ 0.28:5.2
MANC/RMANC equilibrium Arsenic concentration (acid/base) in mg/L	0.25/2.7	0.06/1.5	2/22
% Arsenic Leached under GANC/RGANC (acid/base)	3/75	4/80	2/74

Table 5-5 - Arsenic-Soil Characterization Study
Summary of Test Results
Hazen Research

Soil Fraction Procedures	Area 18	Area 36	NGRR Track Area
Sequential Extraction	Majority of arsenic associated with the organic fraction and, to a lesser extent, with the non-crystalline iron oxide fractions.	Majority of arsenic associated with the organic and non-crystalline iron oxide fractions and, to a lesser extent, with the crystalline iron oxide fraction.	Majority of arsenic associated with the crystalline iron oxide and organic fractions and, to a lesser extent, with the non-crystalline iron oxide fraction.
SEM	Very little arsenic detected, but associated mainly with iron oxide. Also associated with silicates, and present as iron-arsenic-phosphate.	Arsenic associated mainly with iron oxide (including suspected goethite); arsenic also detected in particles (containing Fe, Al, Ca, and Si) attached to carbon-charcoal particles and with lead-manganese-oxide.	Arsenic associated mainly with iron oxide and organic material. Also positive identification of iron-arsenic-phosphate, lead-arsenic-sulfate and potassium-iron-sulfate.
XRF	Presence of silica-alumina-iron matrix	Presence of silica-alumina matrix	Presence of silica-alumina-iron matrix

Table 5-6 - Arsenic Wet Screening Study

Summary of Test Results and Statistical Evaluation
Hart Crowser Labs

Soil Fraction Type	Screen Size	Mass Distribution by Soil Size Fraction in % by wt.	Mean Arsenic Concentration in mg/kg	Cumulative Mean Concentration in mg/kg
Summary of Arsenic Data for Grid Samples from Lead Reference Area				
Gravel	+1	18.00	7.46	7.46
	-1+1/2	26.00	8.67	8.26
	-1/2+1/4	16.70	9.87	8.68
Sand	-1/4+8m	8.70	17.29	9.86
	-8m+16m	4.50	30.45	11.23
	-16m+30m	5.00	45.66	13.43
	-30m+60m	7.60	58.21	17.19
	-60m+100m	3.60	84.05	20.01
	-100m+200m	2.50	120.47	22.50
Silt	-200m	7.30	181.90	32.44
Summary of Arsenic Data for Samples from Narrow Gage Railroad Track Area				
Gravel	+1	18.00	21.15	21.15
	-1+1/2	21.50	32.06	28.26
	-1/2+1/4	17.50	49.45	35.25
Sand	-1/4+8m	11.80	81.37	43.13
	-8m+16m	5.40	110.75	47.96
	-16m+30m	7.50	158.45	57.68
	-30m+60m	7.80	249.18	74.72
	-60m+100m	2.30	602.18	88.47
	-100m+200m	1.90	876.61	105.03
Silt	-200m	6.30	1,689.61	203.32

Table 5-7 - Arsenic Speciation Tests

Summary of Test Results

Sample ID	Arsenic Concentration in $\mu g/g$			
	As +3	As +5[1]	MMA[2]	DMA[3]
25-As-SP-1	<1.6	71.9 (>93.7%)	<1.6	<1.6
LR-20	<1.6	75.3 (>94.0%)	<1.6	<1.6
LR-60	<1.6	228 (>97.9%)	<1.6	<1.6
LR-104	<1.6	358 (>95.7%)	<1.6	12.9
5D-VS-34	2.2	500 (>98.9%)	<1.6	<1.6
38-As-SP-1	1.9	567 (>99.1%)	<1.6	<1.6

Notes:
[1]The values in parenthesis indicate the proportion of the As +5 species
[2]MMA = Monomethyl arsinic acid
[3]DMA = Dimethyl arsinic acid

Table 5-8 Summary of UB Soil Washing Evaluation (State University of New York)

Extractant	pH	Temp in °C	Liquid:Solid Ratio	Remaining Soil Lead in mg/kg (Number of Readings)	TCLP Lead in mg/L (Number of Readings)
HCl	1	25	20:1	611 ± 166 (3)	
HCl	1	25	20:1	941 ± 951 (3)	0.50 ± 0.50 (3)
HCl	1	25	10:1	444 ± 24 (5)	0.47 ± 0.14 (3)
HCl	1	25	5:1	579 ± 61 (5)	1.47 ± 1.74 (3)
HCl	2	25	20:1	703 ± 627 (3)	0.20 ± 0.00 (3)
HCl	3	25	20:1	1359 ± 77 (5)	
HCl	3	25	20:1	1223 ± 382 (3)	
HCl	3	50	20:1	1259 ± 66 (5)	
H_2SO_4	1	25	20:1	720 (1)	
H_2SO_4	3	25	20:1	1111 ± 110 (5)	
$HClO_4$	1	25	20:1	449 ± 96 (5)	0.33 ± 0.14 (3)
$HClO_4$	3	25	20:1	1228 ± 116 (5)	
HCl/0.5M NaCl	3	25	20:1	1170 ± 130 (4)	
H_2SO_4/0.5M NaCl	1	25	20:1	851 ± 97 (5)	0.60 ± 0.25 (3)
HCl/0.005M EDTA	1	25	20:1	607 ± 145 (5)	0.37 ± 0.29 (3)
HCl/0.01M EDTA	3	25	20:1	644 ± 53 (5)	0.67 ± 0.14 (3)
HCl/0.01M EDTA	3	50	20:1	1045 ± 171 (4)	1.17 ± 0.14 (3)
HCl/0.01M Salicylate	3	25	20:1	1248 ± 147 (4)	

Notes:
The soil extractions were completed in a 24-hour batch extraction.

Remaining soil lead concentrations are given as the mean ± 95% CL (number of readings), after 24 hours of batch washing, with measurement outliers omitted. Readings were considered to be outliers if their values were greater than the initial lead concentration of 1,401 mg/kg.

The maximum proportion of lead released by soil washing during these experiments was 68 percent, achieved with HCl as the extractant at a pH = 1, at 25 degrees centigrade, and a 10:1 liquids:solids ratio.

5.6 References for Chapter 5

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