United States
Environmental Protection
Agency

Office of
Research and Development
Cincinnati, OH 45268

EPA/540/R-502a
July 2004

EPA

MINE
WASTE
TECHNOLOGY
PROGRAM

EPA DOE Montana Tech Implemented by MSE Technology Applications, Inc.

Stabilization of Mercury in Waste Material from the Sulfur Bank Mercury Mine

Innovative Technology Evaluation Report

SITE

SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION

EPA/540/R-04/502
July 2004

Stabilization of Mercury in Waste Material from the Sulfur Bank Mercury Mine

Innovative Technology Evaluation Report

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency (EPA) under Contract Nos. 68-C5-0036 and 68-COO-179 to Science Applications International Corporation (SAIC). It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Lawrence W. Reiter, Acting Director
National Risk Management Research Laborator

Abstract

This report summarizes the findings of an extensive treatability study of three stabilization technologies for mercury immobilization on materials collected from the Sulfur Bank Mercury Mine (SBMM), located north of San Francisco, in Lake County, California. The SBMM site is believed to be contaminating the adjacent Clear Lake environment with mercury derived from historic mining practices at the site. The study was conducted as a joint effort between EPA's Superfund Innovative Technology Evaluation (SITE) Program and the Mine Waste Technology Program (MWTP). Two mercury contaminated materials were selected for treatment by three types of stabilization technologies.

The purpose of the study was to determine the effectiveness of the three stabilization technologies for immobilizing mercury in the waste rock materials and therefore reducing leachable mobile mercury in the effluent. Several mercury-bearing materials from the site were considered for testing. A material with high levels of leachable mercury was selected as the primary target of the study, and is referred to as "Mercury Ore". As a secondary objective, treatment effectiveness was evaluated on material that was lower in mercury concentration, but present in large quantities and is referred to as "Waste Rock".

Three stabilization technologies were evaluated as part of this study: (1) a Silica Micro Encapsulation (SME) process developed by Klean Earth Environmental Company (KEECO), (2) an inorganic sulfide stabilization technology (ENTHRALL®) developed by E&C Williams, and (3) a generic phosphate treatment.

The primary objective of this study was to determine the effectiveness of the three stabilization technologies (silica encapsulation, phosphate, and sulfide) in reducing the quantity of leachable mercury from SBMM material. Waste material evaluated in this study consisted of "mercury ore" from the south white gate pile and "waste rock" from the north yellow pile. The mercury ore was the primary test material due to its demonstrated ability to produce consistent and detectable levels of leachable mercury. The waste rock was included because it is a common material at the site, even though it yields lower levels of leachable mercury. In order to evaluate the performance of the three technologies, the leachable and mobile mercury (defined as the mercury in the <25µ filtered leachate fraction) from control columns receiving no treatment was compared to the leachable and mobile mercury in the treatment columns. Specifically, the objective was to achieve a 90% reduction in the total mass of mercury leached from each treatment relative to the control over a 12-week continuous column leaching study.

Leachability results from the no treatment control columns revealed that the predominant source of leachable mercury was found in the particulate fraction, i.e. approximately 96%. The phosphate treatment dramatically increased the levels of both the particulate and dissolved fractions (<0.45µm) over the course of the 12-week study. The dramatic rise in leachable mercury brought about by the phosphate treatment invalidates its utility as a remedial alternative for materials at the SBMM site. The E&C William's ENTHRALL® Technology did not appear to be effective in reducing the levels of mobile mercury in the mercury ore column tests. The total mass of mercury in both the particulate and dissolved fractions are statistically similar to the control. KEECO's Silica Micro Encapsulation Technology applied both in situ and ex situ, was effective in reducing mobile mercury (<25 µm) very close to the 90% reduction goal of the study. However, there was a significant increase in the mass mercury levels in the dissolved fraction (<0.45µm). The in situ applications exhibited a 198% increase relative to the control, and the ex situ exhibited a 238% increase.

Contents

Tables

Figures

Abbreviations and Acronyms

AQCR	Air Quality Control Regions
AQMD	Air Quality Management District
ARARs	Applicable or Relevant and Appropriate Requirements
ASTM	American Society for Testing and Materials
CAA	Clean Air Act
CCNY	City College of New York
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CSCT	Consortium for site characterization
CV	Coefficient of variation
CWA	Clean Water Act
DI	Deionized
DOE	U.S. Department of Energy
ECWI	E&C Williams Incorporated
EPA	U.S. Environmental Protection Agency
FS	Feasibility study
G&A	General and administrative
HSWA	Hazardous and Solid Waste Amendments
ICV	Internal calibration verification
ITER	Innovative Technology Evaluation Report
IM	Interim measure
KEECO	Kleen Earth Environmental Company
LCS	Laboratory control sample
L/hr	Liters per hour
mg/Kg	Milligrams per kilogram
mg/L	Milligrams per liter
mL	Milliliter
MS/MSD	Matrix spike/matrix spike duplicate
MWMP	Meteoric Water Mobility Procedure
MWTP	Mine Waste Technology Program
NA	Not analyzed
NAAQS	National Ambient Air Quality Standards
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPDES	National Pollutant Discharge Elimination System
NRMRL	National Risk Management Research Laboratory (EPA)
NSCEP	National Service Center for Environmental Publications
ND	Non-detectable, or not detected at or above the method detection limit
NPDWS	National primary drinking water standards
NTU	Nephelometric turbidity unit
OSHA	Occupational Safety and Health Administration
ORD	Office of Research and Development (EPA)
OSWER	Office of Solid Waste and Emergency Response (EPA)
PDI	Prosonic Drilling Company
ppb	Parts per billion
ppm	Parts per million
ppmv	Parts per million by volume
PPE	Personal protective equipment
PQL	Practical quantitation limit
PVC	Polyvinyl chloride

POTW	Publicly owned treatment works
QA/QC	Quality assurance/Quality control
QAPP	Quality assurance project plan
RI/FS	Remedial Investigation / Feasibility Study
RCRA	Resource Conservation and Recovery Act
RPD	Relative percent difference
RSD	Relative Standard Deviation
SARA	Superfund Amendments and Reauthorization Act
SAIC	Science Applications International Corporation
SBMM	Sulfur Bank Mercury Mine
SDWA	Safe Drinking Water Act
SEM/EDS	Scanning Electron Microscopy/Energy Dispersive Spectroscopy
SME	Silica Micro Encapsulation
SVE	Soil vapor extraction
SPLP	Synthetic Precipitation Leaching Procedure
SW-846	Test methods for evaluating solid waste, physical/chemical methods
SWDA	Solid Waste Disposal Act
SITE	Superfund Innovative Technology Evaluation
S.U.	Standard units
TCLP	Toxicity Characteristic Leaching Procedure
TER	Technology Evaluation Report
µg	Micrograms
µg/L	Micrograms per liter
µm	Micron
UCL	Upper confidence level
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
w/w	Weight to weight ratio
XRD	X-ray diffraction
XRF	X-ray fluorescence

Acknowledgments

This report was prepared under the direction of Mr. Edward Bates, the EPA Technical Project Manager for this SITE demonstration, and Mr. Roger Wilmoth, Director of EPA's Mine Waste Technology Program, both of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio. EPA review of this report was conducted by Diana Bless of USEPA and Dan McMindes of USACE. .

The demonstration required the combined services of several individuals from MSE-Technology Applications (MSE-TA), and Science Applications International Corporation (SAIC). Ms. Suzzann Nordwick served as the project manager for MSE-TA. Dr. Scott Beckman of SAIC served as the SITE work assignment manager for the implementation of treatability study activities and completion of all associated reports. The treatability study was performed at MSE-TA's facility in Butte, Montana. The cooperation and efforts of these organizations and individuals are gratefully acknowledged.

This report was prepared by Dr. Scott Beckman, Ms. Melissa Hammett, and Ms. Rita Stasik of SAIC. Ms. Stasik also served as the SAIC Quality Assurance (QA) Coordinator for data review and validation. Joseph Evans (the SAIC QA Manager) internally reviewed the report.

Executive Summary

Three innovative technologies for in situ stabilization of heavy metals were demonstrated in a large-scale treatability study performed on materials from the Sulfur Bank Mercury Mine, a superfund site in northern California. The treatability study was jointly sponsored by two EPA programs; the Mine Waste Technology Program (MWTP) and the Superfund Innovative Technology Evaluation (SITE) Demonstration Program.

The purpose of the study was to determine the effectiveness of these stabilization technologies for immobilizing mercury in sulfide mine waste materials such as those found at the Sulphur Bank Mercury Mine (SBMM) site and therefore reduce the potential for leaching and mobilizing mercury into the environment. The SBMM is a non-operating facility located on the South shore of Clear Lake in northern California where some of the highest mercury concentrations in the world have been recorded. Several mercury-bearing materials from the site were considered for testing. A waste material with high levels of leachable mercury (mercury ore) was selected as the primary target of the study. As a secondary objective, treatment effectiveness was evaluated on a waste material that was lower in mercury concentration, but present in large quantities (waste rock).

Stabilization technologies use chemical reagents to reduce the mobility of contaminants in a solid matrix. The three processes used in the treatability study are: (1) the Silica Micro Encapsulation (SME) process, developed by Klean Earth Environmental Company (KEECO) which encapsulates metals in an impervious microscopic silica matrix, thus preventing metals in the treated material from leaching into the environment, (2) Enthrall®, developed by E&C Williams, Inc., which uses an inorganic sulfide chemical to bind metals within the matrix, and (3) a generic phosphate treatment that forms insoluble phosphate salts containing the contaminant. Since metal contaminants cannot be destroyed, each of the selected technologies is targeted to inhibit the release of mercury from the mine materials into the environment.

The treatability study took place at the research facility of MSE in Butte Montana, from November 15, 2000 to April 29, 2001. The primary test procedure was an in situ kinetic column leach. The vendors each applied their reagent to four-kilogram splits of each of the two test materials that had been loaded into 3-foot PVC columns. The SME technology was applied ex situ as well, and then the treated material was loaded into the columns. To evaluate each technology's ability to reduce the amount of leachable mercury, single pass, low flow leaching was performed for twelve weeks, with weekly sampling for mercury and other constituents. The primary objective of the study was for each technology to achieve a 90% reduction in the mass of mobile mercury in the leachate over the twelve week period, as compared to untreated control columns receiving a water leach. Several secondary studies were performed along with the primary column study, including humidity cell testing to simulate extreme weathering conditions, and humic/fulvic acid leaching to simulate the effect of high molecular weight organic constituents from vegetative caps. Treated and untreated samples and leachates were also analyzed to determine other chemical characteristics and mineralogical changes due to the treatments.

Conclusions from the study are summarized below:

- Pre-demonstration leachability studies revealed that the dominant form of leachable mercury was in a particulate and mobile form. These studies indicated that leaching with a meteoric solution released particulates that remained suspended in solution and therefore could be mobile in a groundwater and/or surface water hydraulic system. Levels of dissolved mercury were low in these leaching studies. Based on these tests, a continuous column leaching test design was used to collect effluent samples over a 12-week period to evaluate leachable mercury in mobile (<25μm) and dissolved (<0.45μm) fractions from treated and control columns.

- The conventional phosphate treatment dramatically increased the levels of mobile mercury (<25μm fraction) over the course of the12-week study in the mercury ore columns. A 947% increase in the total mass of mercury leached occurred relative to the control.

- E&C Williams' sulfide treatment did not appear to be effective in reducing the levels of mobile mercury in the mercury ore column tests. There was no significant difference in the cumulative levels of mobile mercury in the effluent from the sulfide treatment relative to the control.

- KEECO's Silica Micro Encapsulation Technology was effective in reducing mobile mercury (<25 μm) very close to the 90% reduction goal of the study. However, the dissolved mercury portion (<0.45μm) of the mobile fraction increased by approximately 200% relative to the control.

- A leachability test using humic and fulvic acids on untreated mercury ore was performed to determine if these organic acids would accelerate the release of mercury from the waste material. A vegetative cap may be used to reduce meteoric water infiltration, and plant derived organic acids could impact mercury leachability. Leaching with humic/fulvic acids did not increase the generation of either particulate or dissolved mercury under the conditions of the test.

Section 1.0
Introduction

This section provides background information about the Superfund Innovative Technology Evaluation (SITE) Program and the Mine Waste Technology Program (MWTP), discusses the purpose of this Innovative Technology Evaluation Report (ITER), describes the Sulfur Bank Mercury Mine (SBMM) site, and describes the technologies that were applied in the treatability study on the SBMM materials. Key contacts are listed at the end of this section for inquires regarding the SITE and MWTP Programs, the technologies, and the site for which the treatability study was conducted.

1.1 Background

A treatability testing program was conducted to determine the effectiveness of in situ stabilization technologies on controlling the release of mobile mercury from the Sulfur Bank Mercury Mine in Lake County, California. Three stabilization technologies were evaluated during this study: (1) E&C Williams' Enthrall® sulfide based treatment, (2) Kleen Earth Environmental Company's (KEECO) Silica Micro Encapsulation (SME) process, and (3) a generic phosphate treatment. Pre-demonstration studies identified suitable materials from the site for testing, identified a potential mercury release mechanism, and evaluated several leachability protocols. Samples of two types of material from the site (mercury ore from the south white gate pile and waste rock from the north yellow pile) were collected and screened in the field, then taken to the research facility of MSE in Butte, Montana for demonstration testing. Kinetic column leaching tests were performed to determine the effectiveness of the treatments in reducing the generation of mobile mercury.

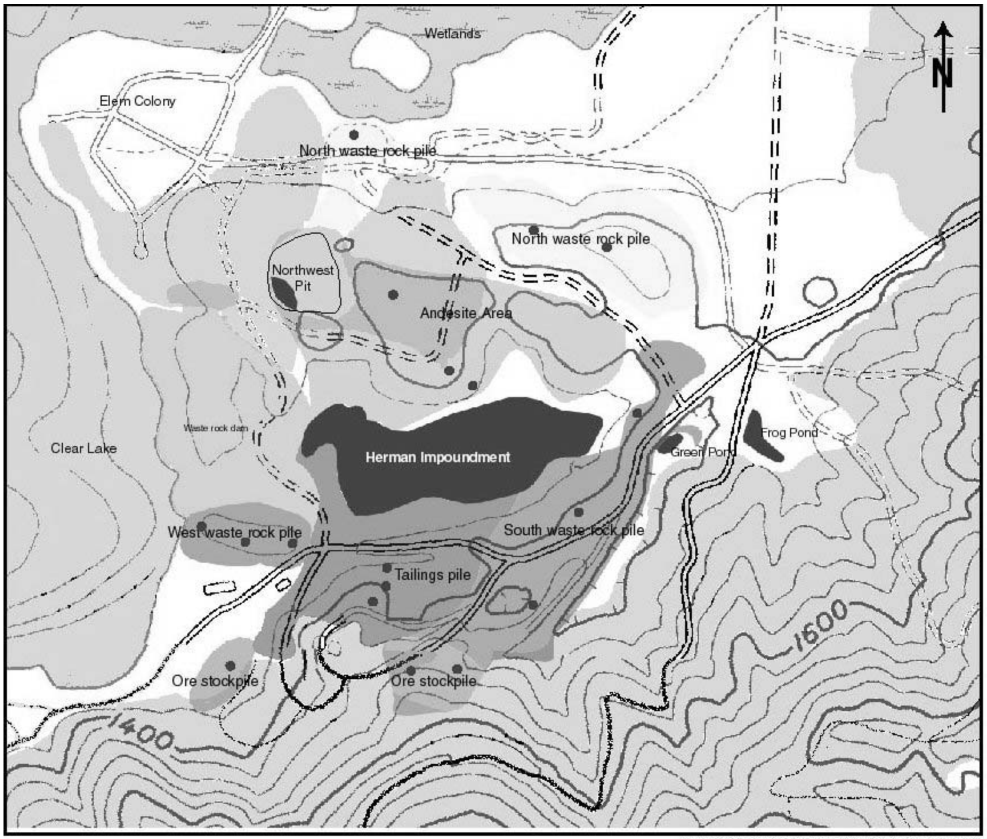
1.1.1 Description of the SBMM Site

The Sulfur Bank Mercury Mine (SBMM) is an EPA Superfund site, located on the south shore of the Oaks Arm of Clear Lake, in Lake County, California (Figure 1-1). With a surface area of 68 square miles, Clear Lake is the largest lake entirely in California and is a popular fishing, resort and watersport destination; thus the mercury contamination in the lake has caused great concern. Sulfur Bank was mined periodically from 1865 to 1957 with open pit mining beginning in 1915. In the late 1920's, heavy earthmoving equipment began to be used on a large-scale basis, which dramatically increased the environmental impacts of mining. Various mining activities over the years have deposited amounts of mercury in the Clear Lake ecosystem.

Several pits were excavated at the mine, the larger being Herman Pit, which is located a few hundred feet from the lake. Surface runoff, subterranean streams, surface seeps and groundwater have all played a part in filling the pit, which seeps through the waste rock dam into Clear Lake. Metal-laden acid mine drainage results from the interaction of surface and ground waters with sulfide bearing mine wastes, in and around the pit. Degradation of water quality in Clear Lake may have been caused largely by sulfate and acidity loading from the Sulfur Bank Mercury Mine, though the transport mechanisms remain unclear.

1.1.2 E&C Williams Enthrall® Technology (as provided by E&C Williams)

Enthrall® is a chemical stabilization process that uses inorganic sulfide to target heavy metals and/or cyanide in soil, liquid or sludge. The product, available in solid, liquid or granular form, has been developed for use in in-line treatment systems. The granular, pelletized form has also been developed that can be used as a reactive filter bed, which captures metals by forming sulfide bonds as the contaminated solution flows through the pellets. The treatment forms a permanent bond between the Enthrall® surface and heavy metals. Bonds remain resistant to leaching even though subsequent conditions may involve harsh pHs, as has been demonstrated by the Multiple Extraction Procedure that subjects materials repeatedly to an acidic environment. According to E&C Williams, a typical conventional treatment increases the volume of the treated material by 25 to 200%, whereas the ENTHRALL® addition often increases volume by only 5-10%. The smaller volume is advantageous during treatment, as less material must be handled. Additionally, the reduced quantity of treated material that must be transported or stored can significantly lower costs.



Source: USGS Topographic 7.5 minute quadrangle, Clearlake Oaks, California, 1993.

Figure 1-1*.* Features of the SBMM site.

The ENTHRALL® technology is applicable to in-line process streams and wastes containing heavy metals and/or cyanide and may be applied by either in situ or ex situ methods. The reagent may be applied to the surface and mixed in, or may be injected under pressure to achieve contact with deeper materials.

Successful application of the ENTHRALL® reagent must take place in a neutral to alkaline environment. When the calcium sulfide reagent is applied under acidic conditions, some hydrogen sulfide gas is produced, which reduces the effectiveness of metals stabilization.

No hazardous residuals are produced by the technology. In an in-line process the residual would be a nonhazardous form of the original potentially hazardous material, which could then be stored on site or disposed of in a Subtitle D landfill.

1.1.3 Kleen Earth Environmental Company Silica Micro Encapsulation (SME) Process (as provided by KEECO)

Klean Earth Environmental Company (KEECO) has developed a Silica Micro Encapsulation (SME) process, which encapsulates metals in an impervious microscopic silica matrix, thus eliminating the availability of the metals to have adverse human health or environmental effects. KEECO has developed three products for applying the technology to water (KB-1), solid waste (KB-SEA) and radioactive wastewater (META-LOCK). KB-SEA was used in this treatability study.

The SME process is a high-performance, low-cost technology for preventing and treating metal contamination in water and soils, as it uses silica, which is one of the most common and inert substances on earth. The durability of silica also contributes to the value of the treatment, which works by isolating the metals in question from contacting the environment. Metals cannot be destroyed, nor can they be broken down into other forms, so the most effective control method is to simply isolate them from contacting humans and the natural environment. KEECO's SME process differs from typical stabilization treatments in that the chemical formulation causes an electrokinetic reaction which facilitates transport of the metals towards the SME reactive components, thus enhancing contact with the target metals and reducing the amount of chemical required to achieve the desired results. The use of silica itself is another significant departure from more typical stabilization treatments.

The SME reagent is designed to be applied in situ by mixing a small amount, in either dry or slurry form, into the contaminated soil. Boulder-sized material would be coated with a slurry of the reagent. The volume of the material should only be increased by 1-2% due to the quantity of reagent added. If the reagent is applied dry, a small amount of water may be added to initiate the chemical reaction. A reaction period of 48 hours is recommended before initial testing for results. For areas of high metals concentration, a tilling device may be used to produce further contact between reagent and contaminated soil. This may be indicated in areas of high concentration and hydraulic transport rates.

SME is applicable to wastewater, sediment, sludge, soil, mine waste, radioactive wastewater and other complex media. Silica bridging between encapsulated particles in treated materials increases compressive strength over time, which can enhance the usefulness of the treated waste as backfill.

One problem that could be encountered with stabilization treatments is that weathering and exposure to changes in pH can break down the bonding and allow metals to be released. The long-term stability associated with SME treated wastes may indicate applicability for large in situ applications where treated materials will remain on site, exposed to the environment. The SME technology has been designed to treat metals-contaminated water and soils without producing any hazardous by-products.

Where the technology is applied correctly and in a manner that allows for thorough contact with the metal contaminants of concern, no hazardous wastes should be produced. Water treatments using the SME products produce a dense sediment or sludge that can be separated from the water and disposed of on-site or in a sanitary landfill. Treated soils and other solids can be left in place or used as backfill material.

The effectiveness of the SME process is somewhat dependent on the substrate pH. Highly alkaline substrates (such as unstable sludge from water treatment plants, or soils that have been amended with lime) having a pH greater than 8 may produce resistance to the reactive process. In such an environment, a pretreatment step to lower the pH by may be necessary prior to the addition of SME. In this case, an evaluation of the effectiveness and economics of the multi-step treatment would be required.

According to KEECO, the single most limiting factor in the effectiveness of the SME technology is contact with the metal-bearing particles. Where the chemicals cannot make contact with all the metal bearing substrate, for example in the in situ treatment of large waste rock or tailings piles, effectiveness would be limited. KEECO is in the process of designing deep subsurface injection methods to more effectively introduce the reagent, in an effort to overcome this inherent limitation of in situ treatment. SME is solely applicable as a stabilization technology and cannot be used as a reactive barrier.

1.1.4 Phosphate

Phosphate-based binders have been used successfully to reduce solubility of heavy metal contaminants, particularly lead, in soils. The reagents form bonds with metal ions to form insoluble metal complexes called pyromorphites. The kinetics of the reaction depends on the phosphate form in the reagent. Phosphates have been used in in situ remediation by land farming (plowing and grading), injection, and surface application and auguring.

During the design phases of the treatability study, there was an interest in testing phosphate as a binding agent for mercury. A generic phosphate reagent was obtained for testing. Phosphates stabilize metals by chemically binding them into new stable phosphate phases, such as apatites, and other relatively insoluble phases in the soil. Phosphates have been included in the reagent mixes for stabilizing lead during remediation of several Superfund sites.

Metals stabilized in apatite minerals are durable and resistant to leaching because the mineral structure is stable from pH 2 to 12 and up to 1000 degrees C, in liquids or solids and through geologic disruptions. Previous studies have indicated that as little as 1% (w/w) phosphate addition could remediate metal-contaminated soils.

Earlier studies have found phosphates to be effective at stabilizing copper, lead, zinc, cadmium, nickel, lanthanides and actinides (Chen et al., 1997). Generally, the process is applicable to inorganics, including radionuclides, but not to organic contaminants or pesticides.

As with all stabilization remediations, the success of the process is dependent on the reagent and the waste. Generally, site-specific treatability studies are required.

Additionally, long-term stability has not been identified for very many combinations, so durability studies may be required. Lead phosphate is toxic by inhalation, so the formation of that compound would also have to be evaluated. While phosphate-binding has been well documented for lead remediation, there is little information on mercury stabilization.

1.2 *Brief Description of the Superfund Innovative Technology Evaluation (SITE) and Mine Waste Technology (MWTP) Programs*

The SITE Program is a formal program established by the EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, demonstration, and use of new or innovative technologies to clean up Superfund sites across the country.

The SITE Program's primary purpose is to maximize the use of alternatives in cleaning hazardous waste sites by encouraging the development and demonstration of new, innovative treatment and monitoring technologies. It consists of three major elements:

- Demonstration Program,
- Consortium for Site Characterization Technologies (CSCT)
- Technology Transfer Program.

The objective of the Demonstration Program is to develop reliable performance and cost data on innovative technologies so that potential users can assess the technology's site-specific applicability. Technologies evaluated are either available commercially or close to being available for full-scale remediation of Superfund sites. SITE demonstrations usually are conducted at hazardous waste sites under conditions that closely simulate full-scale remediation conditions, thus assuring the usefulness and reliability of the information collected. Data collected are used to assess: (1) the performance of the technology; (2) the potential need for pre- and post-treatment of wastes; (3) potential operating problems; and (4) the approximate costs. The demonstration also provides opportunities to evaluate the long-term risks and limitations of a technology.

Existing and new technologies and test procedures that improve field monitoring and site characterizations are explored in the CSCT Program. New monitoring technologies, or analytical methods that provide faster, more cost-effective contamination and site assessment data are supported by this program. The CSCT Program also formulates the protocols and standard operating procedures for demonstration methods and equipment.

The Technology Transfer Program disseminates technical information on innovative technologies in the Demonstration and CSCT Programs through various activities. These activities increase awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of technology transfer activities is to develop interactive communication among individuals requiring up-to-date technical information.

The Mine Waste Technology Program (MWTP) is an interagency effort by the EPA and U.S. Department of Energy (DOE) focused on developing and proving technologies that provide solutions to the remedial problems of abandoned mines and the compliance issues of active mines throughout the United States. Excluding coal production, the mining industry produces between 1 and 2 billion tons of mine waste annually. The 1985 Report to Congress estimated the total noncoal mine waste volume in the United States at 50 billion tons. MWTP priorities include at-source control technologies, improvements of short-term technologies for the alleviation of extreme environmental problems and implementing resource recovery methods to help alleviate the costs of remediation.

1.3 The SITE Demonstration Program and Reports

Technologies are selected for the SITE Demonstration Program through annual requests for proposals. This solicitation ended in 1995. EPA Office of Research and Development (ORD) staff review the proposals to determine which technologies show the most promise for use at Superfund sites. Technologies chosen must be at the pilot- or full-scale stage, must be innovative, and must have some technological and/or cost advantage over existing technologies. Mobile technologies are of particular interest.

Once the EPA has accepted a proposal, cooperative agreements between the EPA and the developer establish responsibilities for conducting the demonstration and evaluating the technology. The developer is responsible for demonstrating the technology at the selected site and is expected to pay any costs for transport, operation, and removal of the equipment. The EPA is responsible for project planning, sampling and analysis, quality assurance and quality control, preparing reports, disseminating information, and provides arrangements for transporting and disposing of treated waste materials. Usually, results of Demonstration Programs are published in three documents: the SITE Demonstration Bulletin, the Technology Capsule, and the Innovative Technology Evaluation Report (ITER). The Bulletin describes the technology and provides preliminary results of the field demonstration. The Technology Capsule provides more detailed information about the technology, and emphasizes key results of the SITE demonstration. The ITER provides detailed information on the technology investigated, a categorical cost estimate, and all pertinent results of the SITE demonstration. An additional report, the Technology Evaluation Report (TER), is not formally published. The TER contains the raw data collected during the demonstration and provides a detailed quality assurance review of the data.

For the treatability study using KEECO's SME, E&C Williams' Enthrall®, and a generic phosphate technology, a SITE Capsule and ITER have been prepared; all for use by remedial managers in making detailed evaluations of the technologies for applications to specific sites and wastes. A TER is also submitted for this demonstration to serve as verification documentation.

1.4 Purpose of the Innovative Technology Evaluation Report (ITER)

This ITER provides information on a treatability study performed using KEECO's SME, E&C Williams' Enthrall®, and a generic phosphate treatment. This report includes a comprehensive description of the study and its results. The ITER is intended for use by EPA remedial project managers (RPMs), EPA on-scene coordinators (OSCs), contractors, and other decision-makers carrying out specific remedial actions. The ITER is designed to aid decision-makers in evaluating specific technologies for further consideration as applicable options in a particular cleanup operation. This report represents a critical step in the development and commercialization of a treatment technology.

To encourage the general use of demonstrated technologies, the EPA provides information regarding the applicability of each technology to specific sites and wastes. The ITER includes information on cost and desirable site-specific characteristics. It also discusses advantages, disadvantages, and limitations of the technology.

Each SITE demonstration evaluates the performance of a technology in treating a specific waste matrix. The characteristics of other wastes and other sites may differ from the characteristics of the treated waste. Therefore, a successful demonstration of a technology at one site does not necessarily ensure that it will be applicable at other sites. Data from the demonstration may require extrapolation for estimating the operating ranges in which the technology will perform satisfactorily. Only limited conclusions can be drawn from a single field demonstration.

1.5 Sources of Further Information

EPA Work Assignment Manager
Ed Bates
U.S. EPA
National Risk Management Research Laboratory (NRMRL)
26 W. Martin Luther King Dr.
Cincinnati, OH 45268
(513) 569-7774

Mine Waste Technology Program
Roger Wilmoth
U.S. EPA
National Risk Management Research Laboratory (NRMRL)
26 W. Martin Luther King Dr.
Cincinnati, OH 45268
(513) 569-7509

E & C Williams Project Manager
Charlie Williams
E & C Williams, Inc.
120 Varnfield Dr, Ste. A
Summerville, SC 29483
(843) 821-4200

KEECO Project manager
Amy Anderson
19023 36th Ave. West, Ste. E
Lynnwood, WA 98036
(425) 778-7165

Section 2.0
Technology Application Analysis

This section addresses the general applicability of stabilization processes to sites containing mercury contamination, with specific information regarding the technologies evaluated in the SBMM treatability study where appropriate. Since the report is based on a treatability study rather than a field scale demonstration, there is no actual treatment system to describe; however, the vendors were asked to conceive and provide cost estimates for a full scale application to two piles at the SBMM site. Details on the selected piles can be found in Section 3.2.

Stabilization technologies include a broad range of treatment options that are designed to immobilize contaminants in the existing material, rather than reducing or removing them. Stabilization processes depend on a chemical reaction between the reagent and the contaminant of concern to stabilize the contaminant within the matrix. All of the technologies in this treatability study are stabilization methods, each comprised of a unique chemical system. The technologies in the study are also innovative in that a reduced volume of reagent is required as compared to traditional stabilization processes. This is beneficial in that it reduces the amount of material that must be handled and stored during treatment, and generally produces treated material with a minimal increase in volume.

Limited information on mercury stabilization is available; therefore, the analysis is based on the body of data that is available, and on the more widely available information on stabilization treatments for other heavy metals, as well as information provided by the technology vendors who participated in the treatability study.

2.1 Key Features of the Stabilization Process

The primary components of a stabilization treatment system are the reagents and equipment used to mix it into the treatment matrix. In addition to the treatment reagent, the matrix characteristics and depth of the material and the application type (in situ or ex situ) would determine the equipment requirements. Unless ground or surface water contamination is an immediate concern (e.g. very shallow water table beneath treatment zone), monitoring can be as simple as auguring samples from the treated pile after the treatment has been performed in order to determine the success of the treatment.

The application design for ECWI's ENTHRALL® process would use a proprietary sonic drilling rig subcontracted from Prosonic Drilling Company, Inc (PDI) of Phoenix, Arizona. The reagent would be injected directly into the pile at 15 foot intervals, which should allow the reagent to thoroughly permeate the material.

KEECO's design calls for a modified ex-situ approach wherein a mixing facility would be constructed adjacent to each pile. The material would be hauled by dump trucks to the facility where it would be dumped onto a mixing pad, reagent would be mixed in by a front end loader and the material would be hauled back to the pile by dump truck and then replaced and compressed in place. Each mixing facility would be enclosed to prevent fugitive dust emissions.

2.2 Operability of the Technology

Stabilization processes are among the simplest of remediation technologies, consisting mainly of a chemical reagent and the mixing/drilling equipment required to apply it. The effectiveness of stabilization technologies is largely dependent on the degree of contact between the reagent and the contaminated matrix. Thorough mixing is desirable to ensure the maximum particle contact, though in in situ treatments, mixing may not be practical and application of the chemical would have to be accomplished by drilling and injection into the material. In such cases, care would have to be taken in designing the application to ensure complete contact between the reagent and the treated matrix. Existing environmental conditions are generally not a problem and may be incorporated into the process (e.g. natural moisture content of the matrix). In most stabilization technologies, the chemical reaction takes place quickly, making weather and temperature much less significant factors than in other methods with longer treatment times.

Ensuring thorough contact with contaminants in the matrix is easier in ex situ applications due to the ease of mixing when material is moved to the treatment locale, which can consist of moving to a lined pad near the area of contamination. In situ treatments are inherently more complicated, but developing technologies for this form of application is desirable because of the reduced cost, reduced contact with contaminants, and lowered risk of spillage and air contamination during transport of the material to a treatment facility.

The chemical reagents used in stabilization technologies are usually applied dry or are available in a concentrated form that can be mixed with water on site, thus minimizing the amount of chemical that must be transported. For smaller applications, where equipment is likely to be used for only a few days, portable generators and mixers can be rented, reducing capital investments. At large treatment sites it may be more cost effective to purchase equipment; however, the treatments designed by the technology vendors for the Sulfur Bank Mercury Mine site use either specialized equipment that would be subcontracted, or heavy equipment in such quantity that purchase would not be feasible. In addition to environmental remediation applications, stabilization treatment is also applicable to industrial waste products and to contaminated waters, as discussed in detail in Section 2.3.

2.3 Applicable Wastes

As discussed in the previous section, stabilization technologies are applicable to solid matrices such as contaminated soil or mine wastes. Stabilization treatment is also applicable to industrial waste products that are still in the production system and to contaminated waters, though this is more likely to be used in a contained system, as opposed to a natural environment, because the resulting contaminated sludge would have to be removed. Since the process works by binding an environmentally neutral element with contaminants in the environment, there are minimal hazardous byproducts. The process is also applicable in situations where subsurface utilities limit or preclude the use of technologies requiring excavation, though special care would have to be taken when drilling was used in the product application.

2.4 Availability and Transportability of Equipment

Stabilization technologies can be implemented anywhere the chemical can be delivered and a drill rig/mixing equipment can be used. Since all-terrain drill rigs are available, most locations would be accessible. KEECO's silica technology would be applied by mixing with front end loaders in a facility constructed on site for that purpose. Standard earth-moving, heavy equipment that is normally moved from site to site would be used. Application of the ENTHRALL® technology as used in the SBMM treatability study would require the use of a sonic drill rig. The rig is truck-mounted and easily transportable to the site.

2.5 Materials Handling Requirements

Materials handling for stabilization processes are generally limited to transporting the reagent to the site, and mixing and applying it to the contaminated matrix. There should be no residuals or waste products that have to be removed from the site, other than a small quantity of personal protection equipment (PPE), which could be removed from the site in a sealed drum, by a facility qualified to dispose of hazardous waste.

For an application such as the piles at SBMM, where the treatment matrix is unconsolidated rock, minimal site preparation would be required. The size of the piles can be measured, with the depth of the piles being estimated from pre-mining topographic maps. Where dumping records are not available, core samples may be taken to verify consistency of material in the piles, and some sampling should be done regardless of records to check for changes in the material since it was deposited.

Drilling services are generally subcontracted to a company that has both the required equipment (drill rigs, augers, samplers) and personnel trained in drilling operation. If work is to be performed on a hazardous waste site, drilling personnel must have the OSHA-required 40-hour health and safety training. Process monitoring would be required initially to ensure that the reagent was making full contact with the contaminated matrix, and samples of post-treatment material would be collected at intervals throughout the application to determine the success of the technology, and any modifications that were required.

ECWI would subcontract drilling and injection of the reagent for the SBMM project. All personnel working on site would be required to complete safety training. The SBMM treatment designed by ECWI calls for one weekly sample of treated material to be collected and analyzed for leachable mercury. This would ensure that sufficient reagent was being applied and that complete contact between reagent and contaminated material was being achieved.

KEECO's design includes two mixing facilities, each of which would be operated two shifts per day. Their sampling plan calls for one sample of treated material to be collected daily by each shift.

2.6 Range of Suitable Site Characteristics

Stabilization technologies can be applied at any site that is accessible to the drilling and mixing equipment. Electrical power and water would be required at most sites, but if necessary, a generator could provide electricity and water could be hauled in. Application of reagents would need to be done when temperatures were above freezing to avoid the reagent solidifying before full contact with the targeted contaminant was made.

2.7 Limitations of the Technology

The main limitation of stabilization technologies is that while the process is easily applied to most solid wastes, the success of the treatment depends on a very specific chemical reaction. To ensure complete stabilization, the reagent must be mixed into the soil thoroughly enough to ensure complete contact; therefore success is limited by mechanical access to materials. Very deep or relatively impermeable bodies of material would not be thoroughly treated without specialized equipment and application techniques, which could make in situ treatment difficult. The pH of the material being treated can limit the effectiveness of the reagent, but this can often be remedied by adding the appropriate buffering material to the reagent before it is applied.

In a diverse waste body, such as the piles found at SBMM, the majority of the material being treated is not necessarily the same as the relatively small amount of material that was sampled prior to treatment application. Heterogeneous matrices may require extensive testing to insure that the mode of treatment is applicable to the entire volume. If heterogeneity affects performance, than separate treatment scenarios may need to be developed for each component. This may impact cost and schedule.

As with any technology, results in the field often differ from lab scale results, so modifications to the process may be required during application. Stabilization treatments are generally designed to be one-time applications, but due to the variability of the reaction and potential interferences, additional applications may be indicated.

2.8 Applicable or Relevant and Appropriate Requirements (ARARS) for Stabilization Processes

The National Contingency Plan (NCP) of 1985, codified in Title 40 Code of Federal Regulations (CFR) Part 300, delineates the methods and criteria used to determine the appropriate extent of removal and cleanup for hazardous waste contamination. The NCP required compliance with Federal applicable or relevant and appropriate requirements (ARARs) in order to make use of other programs' or agencies' standards. The Comprehensive Environmental Responsibility, Compensation and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 codified and expanded the provisions.

This subsection discusses specific federal ARARs that are pertinent to the application of stabilization technologies, including the transport, treatment, storage, and disposal of wastes and treatment residuals. State and local regulatory requirements, which may be more stringent than those set by the federal agencies, must also be addressed by remedial managers. ARARs that apply to stabiliation remedial technologies have been promulgated in various regulatory acts, including: (1) the Comprehensive Environmental Response, Compensation, and Liability Act; (2) the Resource Conservation and Recovery Act; (3) the Clean Air Act; (4) the Clean Water Act; (5) the Safe Drinking Water Act, and (6) the Occupational Safety and Health Administration regulations. These six regulatory acts are discussed below; with specific ARARs that may be applicable to the stabilization process being identified in Table 2-1.

2.8.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The CERCLA of 1980, as amended by SARA of 1986, provides for federal funding to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or to the environment. SARA states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It directs EPA to do the following:

- use remedial alternatives that permanently and significantly reduce the volume, toxicity, or the mobility of hazardous substances, pollutants, or contaminants;

Table 2-1. Potential Federal and State ARARs for Stabilization Remediation Processes.

Process Activity	ARAR	Description	Basis	Response
Waste Characterization of Untreated Waste	RCRA: 40 CFR Part 261 (or State equivalent)	Standards that apply to identification and characterization of wastes.	Chemical and physical properties of waste determine the suitability of treatment by a stabilization/solidification process.	Chemical and physical analyses must be performed to determine if waste is a hazardous waste.
Waste Processing	RCRA: 40 CFR Part 264 (or State equivalent)	Standards apply to treatment of wastes in a treatment facility.	Applicable to stabilization processes only when applied in a waste treatment facility.	Compliance with requirements for operations, record keeping, and contingency planning.
	CAA: 40 CFR Part 50 (or State equivalent)	Regulations govern toxic pollutants, visible emissions and particulates.	Mixing reagent into soil could create particulate dust in the air.	Where materials being treated cause dust particulate, surface should be wetted, or dust containment facilities installed.
Determination of Cleanup Standards	SARA: Section 121(d)(2)(ii); SDWA: 40 CFR Part 141	Standards that apply to surface & groundwater sources that may be used as drinking water.	Applicable to stabilization processes only when runoff or seepage of solutions from treatment may contact surface and groundwaters.	Application must be designed to ensure no significant amounts of runoff or seepage into groundwater.
Waste Disposal	RCRA: 40 CFR Part 262	Standards that pertain to generators of hazardous waste.	Generated hazardous wastes would, in most cases, be limited to PPE, other contaminated supplies and possibly washwater.	Generators must dispose of wastes at facilities that are permitted to handle the waste. Generators must obtain an EPA ID number prior to waste disposal.
Worker Safety	OSHA: 29 CFR Parts 1900-1926; or State equivalent	Worker health and safety standards	CERCLA remedial actions and RCRA corrective actions must follow requirements for the health and safety of on-site workers.	Workers must have up to date training and medical monitoring; use of appropriate protective equipment is required.

- select remedial actions that protect human health and the environment, are cost-effective, and involve permanent solutions and alternative treatment or resource recovery technologies to the maximum extent possible; and
- avoid off-site transport and disposal of untreated hazardous substances or contaminated materials when practicable treatment technologies exist [Section 121(b)].

In general, two types of responses are possible under CERCLA: removal and remedial actions. Superfund removal actions are conducted in response to an immediate threat caused by a release of a hazardous substance. Remedial actions are governed by the SARA amendments to CERCLA. As stated above, these amendments promote remedies that permanently reduce the volume, toxicity, and mobility of hazardous substances or pollutants.

Stabilization technologies qualify for use in CERCLA remedial actions as the process may permanently reduce the mobility of the contaminants of concern. Most stabilization processes also reduce toxicity in the treated matrix by binding contaminants in a neutral compound.

On-site remedial actions must comply with federal and state ARARs, which are determined on a site-by-site basis. These regulations may be waived under six conditions: (1) the action is an interim measure, and the ARAR will be met at completion; (2) compliance with the ARAR would pose a greater risk to health and the environment than noncompliance; (3) it is technically impracticable to meet the ARAR; (4) the standard of performance of an ARAR can be met by an equivalent method; (5) a state ARAR has not been consistently applied elsewhere; and (6) meeting the standard for that particular ARAR, with respect to the degree of protection or reduction of risk afforded by it, would incur such costs that standard and remedial actions at other sites would be jeopardized. These waiver options apply only to on-site actions, and justification for the waiver must be clearly demonstrated.

2.8.2 Resource Conservation and Recovery Act (RCRA)

RCRA, an amendment to the Solid Waste Disposal Act (SWDA), was passed in 1976 to provide a framework for achieving environmentally sound management of both hazardous and nonhazardous wastes. Subtitle C of RCRA regulates the generation and handling of hazardous waste, with most of the regulations also being applicable to CERCLA activities. The Hazardous and Solid Waste Amendments (HSWA) of 1984 greatly expanded the scope and requirements of RCRA.

RCRA defines two types of hazardous wastes: characteristic and listed. Criteria for identifying characteristic hazardous wastes, given in 40 CFR Part 261 Subpart C, are: ignitability, corrosivity, reactivity, and toxicity. 40 CFR Part 261 Subpart D provides a list of wastes from specific and nonspecific industrial sources, which comprise the “listed” wastes. RCRA regulations do not apply to sites where RCRA-defined wastes are not present.

RCRA regulations define hazardous wastes and regulate their transport, treatment, storage, and disposal. These regulations are only applicable to stabilization processes if RCRA defined hazardous wastes are present.

In a typical stabilization application, hazardous wastes would be limited to the material being treated, and a small amount of personal protective equipment (PPE) that may have become contaminated during treatment. If wastes were determined to be hazardous according to RCRA, essentially all RCRA requirements regarding the management and disposal of this hazardous waste would have to be addressed by the remedial managers.

In order to legally generate any hazardous waste, the responsible party must obtain an EPA identification number. Other applicable RCRA requirements may include a Uniform Hazardous Waste Manifest (if the waste is transported off-site), restrictions on placing the waste in land disposal units, time limits on accumulating waste, and permits for storing the waste.

Requirements for corrective action at RCRA-regulated facilities are provided in 40 CFR Part 264, Subpart F and Subpart S. These subparts also generally apply to remediation at Superfund sites. Subparts F and S include requirements for initiating and conducting RCRA corrective action, remediating groundwater, and ensuring that corrective actions comply with other environmental regulations. Subpart S also details conditions under which particular RCRA requirements may be waived for temporary treatment units operating at corrective action sites and provides information regarding requirements for modifying permits to adequately describe the subject treatment unit.

2.8.3 Clean Air Act (CAA)

The CAA establishes national primary and secondary ambient air quality standards for sulfur oxides, particulate matter, carbon monoxide, ozone, nitrogen dioxide, and lead. It also limits the emission of 189 listed hazardous pollutants such as vinyl chloride, arsenic, asbestos and benzene. States are responsible for enforcing the CAA. To assist in this, Air Quality Control Regions (AQCR) were established. Allowable emission limits are determined by the AQCR, or its sub-unit, the Air Quality Management District (AQMD). These emission limits are based on whether or not the region is currently within attainment for National Ambient Air Quality Standards (NAAQS).

The CAA requires that treatment, storage, and disposal facilities comply with primary and secondary ambient air quality standards. Provided that the stabilization reagents are mixed into the soil matrix without generating excessive dust, there should be no clean air issues associated with the process.

2.8.4 Clean Water Act (CWA)

The objective of the Clean Water Act is to restore and maintain the chemical, physical and biological integrity of the nation's waters by establishing federal, state, and local discharge standards. If treated water is discharged to surface water bodies or Publicly Owned Treatment Works (POTWs), CWA regulations will apply. A facility desiring to discharge water to a navigable waterway must apply for a permit under the National Pollutant Discharge Elimination System (NPDES). When a NPDES permit is issued, it includes waste discharge requirements. Discharges to POTWs also must comply with general pretreatment regulations outlined in 40 CFR Part 403, as well as other applicable state and local administrative and substantive requirements. Stabilization technology applications involve minimal amounts of water, and should produce no excess solution; therefore, CWA criteria would not generally apply.

2.8.5 Safe Drinking Water Act (SDWA)

The SDWA of 1974, as most recently amended by the Safe Drinking Water Amendments of 1986, requires the EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorized national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The National Primary Drinking Water Standards (NPDWS) are found in 40 CFR Parts 141 through 149. There should be minimal effluent from the treated material during a stabilization process, so safe drinking water regulations would only apply where any effluent, if produced, could impact surface or groundwater drinking water sources.

2.8.6 Occupational Safety and Health Administration (OSHA) Requirements

CERCLA remedial actions and RCRA corrective actions must be performed in accordance with the OSHA requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of OSHA, which describes safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, must also be met.

All personnel who are working at a hazardous waste site are required to have completed an OSHA training course and must be familiar with all OSHA requirements relevant to hazardous waste sites. Workers at hazardous waste sites must also be enrolled in a medical monitoring program. An acceptable program must include: (1) a health history, (2) an initial exam before hazardous waste work starts to establish fitness for duty and as a medical baseline, (3) periodic examinations (usually performed annually) to determine whether changes due to exposure may have occurred and to ensure continued fitness for the job, (4) appropriate medical examinations after a suspected or known overexposure, and (5) an examination at termination.

For most sites, minimum PPE for workers will include gloves, hard hats, steel-toed boots, and Tyvek7 coveralls. Depending on contaminant types and concentrations, additional PPE may be required, including the use of air purifying respirators or supplied air. At the sites where stabilization treatments will be applied, the minimal list of PPE will usually be sufficient. Noise levels are not expected to be high, except during the operation of mixing and drilling equipment. During these activities, noise levels should be monitored to ensure that workers are not exposed to noise levels above a time-weighted average of 85 decibels over an eight-hour day. If noise levels were to exceed this limit, then workers would be required to wear hearing protection, however, hearing protection should be available for any level of discomfort from noise. The levels of noise anticipated are not expected to adversely affect the community, but this will depend on proximity to the treatment site.

Section 3
Economic Analysis

3.1 Introduction

The purpose of this economic analysis is to estimate costs (not including profits) for commercial treatment of mercury-contaminated material at the Sulfur Bank Mercury Mine in Northern California using the Enthrall® and SME technologies that were demonstrated in the treatability study. Since a field-scale demonstration has not been performed, best efforts to reasonably estimate costs have been based on past experience of the vendors and reasonable engineering assumptions. The cost figures provided in this economic analysis are considered “order-of-magnitude” estimates, and may significantly change if field testing is performed.

The technology vendors were asked to provide cost estimates based on twelve categories of costs that are associated with typical cleanup activities at Superfund sites. Where the vendor did not supply costs, an estimate has been included based on past SITE program experience, or generic treatment costs. The phosphate treatment was applied in the treatability study as a generic treatment, and based on the results, further experimentation and product modification would have to be performed before the reagent would be considered for use at the SBMM site; therefore, vendor costs for a full scale treatment using phosphate were not included in the estimates.

3.2 Cost Estimate Scope

The technology vendors were asked to provide cost estimates for treatment of two piles at the site, the North Waste Pile and the Waste Rock Dam. For purposes of the cost estimate, the mercury content in the piles was assumed to be the same as that in the mercury ore used in the treatability study.

The vendors were asked to estimate costs based on the following dimensions:

North Waste Pile:
Surface area = 894,000 square feet
Volume = 877,000 cubic yards
Estimated maximum depth = 75 feet
Calculated average depth = 26.5 feet

Waste Rock Dam:
Surface area = 1,034,000 square feet
Volume = 556,000 cubic yards
Estimated maximum depth = 70 feet
Calculated average depth = 14.5 feet

The costs associated with typical cleanup activities at Superfund sites have been broken down into 12 categories:

(1) Site Preparation
(2) Permitting and Regulatory Activities
(3) Capital Equipment
(4) Start-up and Fixed
(5) Labor
(6) Consumables and Supplies
(7) Utilities
(8) Effluent Treatment and Disposal
(9) Residuals Shipping & Disposal
(10) Analytical Services
(11) Maintenance and Modifications
(12) Demobilization/Site Restoration

The technology vendors were asked to estimate costs for treating the specified piles based on the above categories.

3.3 Factors Affecting Estimated Cost

Since the technologies have only been applied to SBMM materials in the small scale of the treatability study, rather than a field scale demonstration, it is understood that the costs presented here are estimates only, based on past experience of the vendors and engineering assumptions as specified in the following descriptions.

There are a number of factors that could affect the actual cost of treatment of mercury-contaminated material using stabilization technologies. Cost estimates in this report have been provided by the vendors based on the assumption that the mercury and other metals content is the same as that in the material that was treated in the treatability study. A larger sampling of the material in the piles would be required prior to an actual application and the results could indicate significantly different concentrations. Analytical evaluation of the actual materials to be treated may also indicate that modifications to the reagents are necessary, which could impact costs. The characteristics of the material may also be a factor. Estimates are based on “typical material” characteristics; however, the actual material may require special handling depending on particle size, stability and compaction. Should the initial sampling results vary widely, additional sampling points would be required in order to ensure that the proper reagents and ratios were applied.

3.4 Issues and Assumptions

This section summarizes the major issues and assumptions used in estimating the cost of implementing the Enthrall® and SME technologies at full-scale. The vendors were given the dimensions of the piles and told that the material would be assumed to match the mercury ore material. Additional assumptions were specified by ECWI and KEECO in presenting their costs.

3.4.1 Site Characteristics

The Sulfur Bank Mercury Mine is comprised of two pits and extensive piles composed of various materials. Cost estimates have been prepared for two existing piles at the site, but characteristics of the material in the piles were assumed to be the same as that in the mercury ore from the treatability study. The maximum depth at any point in the pile has been estimated based on pre-mining maps. Since the volume of both piles was estimated from maps, the actual volume could differ due to map scaling or errors, and changes in the heap topography over time.

For purposes of cost estimation, characteristics for a typical site material were assumed. These included the assumptions that the material is unconsolidated, with sizes ranging from fines to large gravels and that the rock can be completely treated by the methods described in the following vendor sections.

3.4.2 Design and Performance Factors

ECWI and KEECO each designed the application technique for their respective reagents. These processes are described in later sections with details of each vendor’s cost estimates. Both processes include monitoring or pilot testing to verify complete contact between the reagent and the contaminated material in order to optimize treatment performance. The products used in the treatability study are all designed to be a one-time application.

3.4.3 Financial Assumptions

All costs are presented in 2001 U.S. dollars without accounting for interest rates, inflation or the time value of money. Insurance and taxes are assumed to be fixed costs lumped into the Startup and Fixed Costs category (see subsection 3.5.4).

3.5 Basis for Economic Analysis

In this section, each of the 12 cost categories that reflect typical clean-up activities encountered at Superfund sites, will be defined and discussed. These 12 cost categories form the basis for the estimated costs submitted by the vendors and presented in sections 3.6.1 and 3.6.2.

3.5.1 Site Preparation

Since the material being treated is already in piles and will be treated on site, the site preparation for implementing the stabilization technologies would be limited to bringing the necessary equipment for application and monitoring to the site, and constructing usage and storage facilities. Storage facilities for chemicals and fuels would have to comply with environmental regulations governing the site. The SBMM site is already fenced so no additional security costs should be incurred.

3.5.2 Permitting and Regulatory Requirements

Several types of permits may be required for implementing a full-scale remediation. The types of permits required will be dependent on the type and concentration of the contamination, the regulations covering the specific location, and the site’s proximity to residential neighborhoods. Extensive studies have previously been conducted on contamination in Clear Lake, so pretreatment site characterization should also be minimal for permitting purposes.

If site characterization were required for permitting, the non-analytical costs incurred for receiving approval from the regulatory agency to install the treatment system would be included under the Permitting and Regulatory Activities category. These costs would include the preparation of site characterization reports that establish a baseline for the site contamination, the design feasibility study for the pilot system, and meetings with regulators for discussing comments and supplying related documentation for acquiring approval for installing and implementing the treatment.

Depending upon the classification of a site, certain RCRA requirements may have to be satisfied as discussed in section two of this report. Since the SBMM site is an active Superfund site, it is possible that the technology could be implemented under the umbrella of existing permits and plans. Certain regions or states have more rigorous environmental policies that may result in higher costs for permits and verification of cleanup. Added costs may result from investigating all of the regulations and policies relating to the location of the site, and for conducting a historical background check for fully understanding the scope of the contamination.

3.5.3 Capital Equipment

Capital equipment includes all equipment for the treatment process, whether it is purchased or rented. Different specialized equipment is required for each of the technologies as specified in the following vendor's cost estimates. For this particular project, all equipment costs were based on rental or subcontracting rates rather than purchases.

3.5.4 Startup and Fixed Costs

Startup and Fixed costs can include such variables as insurance, taxes, initiation of monitoring programs, contingency funds, and the cost of physically starting the treatment such as building facilities, transporting equipment, etc. In requesting cost estimates from the vendors for the SBMM piles, the list of cost categories was provided, but developing and categorizing costs was left up to the vendors. Physical startup costs have been included in the site preparation category, leaving insurance, taxes, etc. in the startup costs, where they were included in the vendor's estimate.

Often, insurance and taxes are estimated to be 10% of the total annual purchased equipment costs. Contingency costs that allow for unforeseen circumstances such as strikes, floods and price variations, are often estimated at the same cost as insurance and taxes.

3.5.5 Labor

Included in this subsection are the labor costs of implementing the technologies and the associated monitoring that would be required to verify the results of the process. Where labor is performed but accounted for in other categories, an explanation has been included in those categories. The hourly labor rates presented in this subsection are loaded, which means they include base salary, benefits, overhead, and general and administrative (G&A) expenses. Travel and per diem expenses are additional costs included in this section.

Monitoring requirements for this project are based on the assumption that the material characterization has already been done, and costs are required only for the tests that would be necessary to determine the degree to which the process is working, and to satisfy environmental monitoring requirements. Sampling labor would include collecting and appropriately packing samples for shipping to the analytical lab and then delivering the samples to the nearest shipping office.

3.5.6 Consumables & Supplies

The category of consumables and supplies consists of materials used in the treatment process and supplies bought to support the treatment effort. In the SBMM treatments, the reagent and diesel fuel account for the consumables and supplies would consist primarily of personal protective equipment (PPE) and miscellaneous supplies.

PPE is routinely used by individuals who are active in treatment application, sample collection, and during any activity in which there is a potential for being exposed to contaminated soil or groundwater. Expendable items would primarily include nitrile gloves and tyvek coveralls; and possibly spent respirator cartridges if the work is conducted in Level C or higher.

3.5.7 Utilities

Utilities are generally comprised of electricity and water. At the SBMM site, the equipment in both treatment scenarios is diesel fueled, so only a small electrical cost to supply lighting and possibly for a phone and facsimile hookup would be needed. A water source would be needed for decontamination and incidental activities; however those costs are considered negligible.

3.5.8 Effluent Treatment and Disposal

For these technologies there is no effluent produced; therefore, it is assumed that there will be no effluent treatment and disposal expense.

3.5.9 Residuals Shipping and Disposal

No residuals would be anticipated from an in situ stabilization process conducted according to the method used in the treatability study. For the modified ex situ process designed by KEECO, material is removed from the pile to an adjacent mixing facility where it is mixed with reagent. At this point in the treatment process, KEECO considers the treated material to be residuals and included the cost of returning the material to the original location in the residual handling costs. Disposal of small amounts of decontamination wastewater that may be generated from cleaning sampling equipment is considered negligible.

3.5.10 Analytical Services

All samples of treated material would be sent to an off-site analytical laboratory. The level of testing required to substantiate site cleanup was specified by each of the vendors in their respective treatment scenarios. Both vendors based costs on analysis of leachable mercury only. Unlike the treatability study, which determined success by percent reduction in comparison with a water-leach control, actual remediation projects focus on attaining a specific cleanup concentration target level.

3.5.11 Maintenance and Modifications

Remediation efforts often include installation of a treatment system that would require ongoing maintenance. Using heavy equipment to apply the reagent directly to portions of the material would perform both treatment scenarios designed for the SBMM site. Maintenance on the equipment would be performed as required and no significant amounts of maintenance should be required elsewhere on the project. Modifications would be determined by analytical results, and should only be necessary in the volume or technique of reagent application.

3.5.12 Demobilization/Site Restoration

Demobilization and site restoration are performed at the conclusion of the treatment project, and would therefore be a one time cost. Restoration of a mine site often includes capping and revegetation; however, this is beyond the scope of the treatment designs for the SBMM site. For these cost estimates, it was assumed that demobilization/site restoration would consist of returning the equipment to the appropriate locations, and dismantling the mixing facilities in KEECO's design. It should be noted that boreholes in ECWI's design are not cased wells and it was assumed that no abandonment procedures would be required.

3.6 Vendor Cost Estimates

This section presents the cost estimates provided by the technology vendors. The estimates were to be based on the twelve cost categories specified above. In sections where a cost was not estimated by the vendor, an estimate has been included based on available information.

3.6.1 E&C Williams Enthrall® Technology

ECWI designed an in situ treatment that was based on an application strategy related to the techniques used in the treatability study. In this method, a truck-mounted sonic drill rig would be used to drill into the pile and inject the ENTHRALL® reagent at depth intervals that were calculated to allow for complete permeation of the material. ECWI would provide the chemical reagent and serve as technical consultants, but would subcontract the actual drilling and injection to Prosonic Drilling Company, Inc (PDI) of Phoenix, Arizona. Drilling costs in this estimate are based on information supplied by PDI.

Based on previous experience, ECWI has estimated costs on the assumptions that application at each borehole will treat a radius of 15 feet, and that injection to the average depth of the pile will provide sufficient treatment. Two rigs would operate concurrently on the heap, with one tanker truck supplying reagent to both. The rig would drill to the specified depth, inject the reagent and pull out the shaft, leaving a dispensable drive point in each hole. The treatment design calls for two eight-hour shifts on each rig per day. It was assumed that boreholes could be left in the pile and would not require abandonment procedures. Prior to beginning full-scale application, on-site pilot injection holes would be required to test the design assumptions.

Costs were estimated by ECWI for each of the specified piles, based on the assumption that treatment of the piles would take place sequentially, requiring only one mobilization and demobilization cycle. The following cost estimate is based on the 12 cost categories described above, and was provided by ECWI, except where otherwise indicated.

(1) Site Preparation: There is minimal site preparation required for the working site since the drill rigs are mobile and designed for field work. Prior to beginning treatment at the site, ECWI personnel would obtain training in spill containment and remediation procedures at ECWI's expense, and would visit the site to determine requirements and costs to construct storage areas with secondary containment for diesel fuel and the chemical reagent. ECWI would provide poly storage tanks with secondary containment as working storage for the drilling/injecting teams at no charge to the project.

ECWI did not include a cost for the fuel and chemical storage and secondary containments in their estimate. Based on general information available from miscellaneous vendor publications a rough estimate for the fuel and reagent containers and secondary containments has been made at $40,000.

(2) Permitting and Regulatory Activities: PDI is licensed to work in California. Any additional required business licenses or permits would be the responsibility of ECWI, and they would have to be informed of such requirements in advance of a site application with sufficient lead time to procure the appropriate permits. As discussed in Section 3.5.2, permit requirements are very site specific, and may be modified by the existing status of the project as a superfund site. ECWI has not been to the site, or been informed of permitting requirements so a cost for this budget item was not included in their estimate.

RCRA and State regulations may have to be satisfied in addition to Superfund requirements. Since the site is an active Superfund site, it is possible that the technology could be implemented under the umbrella of existing permits and plans held by the site owner or other responsible party. Added costs may result from investigating the regulations and policies relating to the location of the site. Based on past experience with similar projects, the cost associated with permitting activities was estimated at $20,000.

(3) Capital Equipment: Major equipment for the treatment at SBMM would consist of two rotosonic drill rigs and a fluid tanker with pumping equipment, both to be supplied by PDI. Costs for use and operation of this equipment was provided on a per-diem basis. The cost per day for the rigs, including operators, is $5,300. The cost for the fluid tanker, including an operator who would transport and assist in injecting fluid is $750.00 per day. The combined total costs for capital equipment would be $1,633,500 according to the individual pile costs as follows:

North Waste Pile

The estimated time for set up, drilling, injection of reagent, moving between holes and tearing down is 160 man-days for the North Waste Pile, based on 12-hour day maximums. This equates to $848,000 for drilling equipment and $120,000 for the fluid tanker, totaling $968,000 in capital equipment costs.

Waste Rock Dam

For treatment of the Waste Rock Dam, the estimated time for set up, drilling, injection of reagent, moving between holes and tearing down is 110 man-days, based on 12-hour day maximums, which would amount to $583,000 for drilling equipment and $82,500 for the fluid tanker, totaling $665,500 in capital equipment costs.

(4) Start-up and Fixed Costs: This category typically includes mobilization costs and initial supplies to begin operations. Mobilization costs to transport the drill rigs and support equipment from PDI's office in Arizona to the site would be $25,000. Mobilizing ECWI's tanks and other equipment to the site would cost another $20,000, bringing the total to $45,000.

(5) Labor: The treatment design calls for two shifts per day. The term "days" in the labor costs refers to man-days consisting of 8 hours. Labor costs for the crews who run the rigs have been included in the subcontractor's costs for the rigs under capital equipment. ECWI would also provide labor, which would include ten full-time workers with regular supervisory visits from ECWI management. ECWI would also contract professional assistance, including geologists and project managers. A safety officer would be appointed for on-site processing periods, and ECWI would be responsible for ensuring that site personnel were current in the 40 Hour HAZWOPER training. ECWI considers the cost of safety training to be an overhead expense and not a cost the project would pay.

Workers would be employed to work 8-hour days at an hourly rate of $15 plus $80 per diem. [Note: An hourly rate of $15 hour (loaded) is considered low. Anticipate higher labor rates. Also, a supervisor will be required at a higher rate.] Three professionals would be hired at the rate of $150 per hour, but would only be needed for 2 hours a day, and would not be required for the entire duration of the project. The per diem rate for the professionals would be $100 per day. The combined labor total is $903,300, which breaks down as follows:

North Waste Pile

The required ten workers for 160 days would cost $320,000. Three additional professionals for two hours per day, plus per diem, for 100 days would add another $120,000 in consultation fees. The wages for the PDI drilling crew were included in the cost of the rig, which was listed under capital costs, but an additional per diem of $85.00 for each member of the four-man crew over the period of 160 days would add $54,400. Providing for shift travel for off-work days at $2,500 every ten days equals $40,000. The total labor costs would equal $534,400.

Waste Rock Dam

Ten workers for 110 days would cost $220,000. Three additional professionals would be needed for an estimated 70 days for two hours per day with per diem, which would add another $84,000 in consultation fees. The wages for the PDI drilling crew were included with the rig under capital costs, but an additional per diem of $85.00 for each member of the four-man crew over the 110 days period would add $37,400. Providing for shift travel for off-work days at $2,500 every ten days equals $27,500. The total labor costs would equal $368,900.

(6) Consumables and Supplies: Costs predominately consist of the chemical reagent. Additional costs also include diesel fuel, an expendable drive point for each borehole and a small quantity of other supplies necessary for administrative and safety concerns. The unspecified supplies would constitute a very minor cost and are not detailed here.

The required quantity of reagent has been determined by 1:10 w/w ratio of reagent to material. The weight of the material was calculated by multiplying the volume of each pile by a typical density for a mixed soil type, 1.5 tons/cubic yard. If the density of the material in the pile were determined to be higher, then more reagent would have to be applied to maintain the same ratio. The ENTHRALL® addition rate was determined from its weight of 9.2 pounds/gallon, which converts to 217.39 gallons per ton of reagent.

Diesel fuel usage was estimated at 100 gallons/day for a total of 110 days. Fuel costs are highly variable, but based on an anticipated maximum of $2.00/gallon, this brings the total diesel cost to $22,000.

The expendable drive points, which would be required for drilling and would be left in the borehole, cost $14 each. Based on the assumption that each borehole will treat an area with a radius of 15 feet, the number of boreholes that would be required to inject the reagent into each pile was calculated from the specified surface areas. The category total costs would be $57,008,477 for the reagent and $50,840 for other supplies and consumables.

North Waste Pile

Applying the ENTHRALL® reagent at a 1:10 w/w ratio to the 1,315,500 tons of material in the North Waste Pile would require 28,597,826 gallons which would cost $34,889,348. This equates to a reagent cost of $26.52 per ton of material. If the density of the material in the pile was determined to be higher than 1.5, more reagent would have to be applied to maintain the same ratio. Based on a density of 1.7 tons per cubic yard, the cost would be $39,541,261.

The surface of the North Waste Pile was specified as approximately 894,000 square feet. This would require 960 boreholes, each of which would be 25 feet deep based on the average depth of the pile being 26.5 ft. The cost of 960 expendable drive points, at $14 each, would be $13,440.

Waste Rock Dam

Applying the ENTHRALL® reagent at a 1:10 w/w ratio to the 834,000 tons of material in the Waste Rock Dam would require 18,130,435 gallons which would cost $22,119,130. This equates to a reagent cost of $26.52 per ton of material.

The surface of the Waste Rock Dam was specified as being approximately 1,034,000 square feet. This would require 1,100 boreholes, each of which would be 15 feet deep based on the average depth of the pile being 14.5 ft. The cost of 1,100 expendable drive points, at $14 each, would be $15,400.

(7) Utilities: Electricity and water are usually the primary utilities required for a remediation project. An overall electrical requirement was estimated at $500/month for four months, or $2,000. Incidental amounts of water would be required for cleaning and human usage, but the cost should be small and was not included in the estimate.

In order to have a night shift running, a light plant would need to be provided, and could be rented for $175 per day. A reduced cost for lighting may be achieved if the commercial power grid is accessible from the treatment site. Portable generators may provide electricity for incidental usage also, but access to the commercial power grid is preferred. Portable toilets should be provided for field workers, and can be rented for $65 a month, which would total $520 for the life of the project, treating both piles.

North Waste Pile

Utilities for the project were not separated by piles with the exception of light plant rental, which would cost

$14,000 for the 80 calendar days that would be required for the North Waste Pile.

Waste Rock Dam

Running the light plant on the Waste Rock Dam for the duration of treatment application, 55 days, would run approximately $9,652.

(8) Effluent, Treatment and Disposal: In this in situ application of the technology, no effluent requiring treatment or disposal would be generated.

(9) Residuals, Shipping and Disposal: As this is an in situ technology, no residuals requiring treatment or disposal would be anticipated.

(10) Analytical Costs: Further investigation of the site would be required in order to define required monitoring parameters. Assuming that mercury is the only constituent requiring analysis, and that TCLP or SPLP followed by cold-vapor analysis is to be performed, the cost for each sample including the fees for a one-week turnaround time should be approximately $200 for each sample. A flow model would be used to estimate the time for the reagent to permeate the material and for the treatment reaction to occur. Sampling of treated material would begin on a weekly basis when the model indicated that the treatment was complete. ECWI would be responsible for sample collection and for getting the analysis performed Copies of the analytical report would be sent from the laboratory to a designated third party for review and storage, while the originals would be maintained by ECWI until the treatment phase of the project was closed. Based on the $200 per sample, ECWI estimated the analytical costs to be approximately $10,400. This was based on approximately one year of weekly sampling, with one target metal of mercury and a one-week turnaround on results.

(11) Maintenance and modifications: Maintaining equipment owned by ECWI and PDI would be the responsibility of the respective owners. No modification of equipment is anticipated; however, modifications to the process may be found necessary in technique or reagent application, but these should not significantly impact costs. ECWI allocates approximately $25,000/year for maintenance.

(12) Demobilization/Site Restoration: ECWI estimated the cost of demobilizing their own equipment from Clear Lake back to Summerville, SC to be $20,000. Demobilizing PDI's rigs would cost approximately $25,000. No site restoration costs were estimated.

3.6.2 KEECO's SME Technology

KEECO refers to the approach that was designed for use at the SBMM site as a modified ex situ process, in that the material is removed from its location for treatment, but only to an adjacent on-site facility for the addition and mixing of the reagent. The costing is based on a design that includes building a mixing facility adjacent to each of the piles. Each facility would consist of a concrete mixing corral with raised side berms inside an enclosed portable building. Each facility was designed for an hourly throughput of 300+ tons per hour per facility and would be equipped with an air handling unit, reagent delivery silos and a water storage tank to wet the soils in order to prevent fugitive dusts during the mixing process.

Excavators and dump trucks would be employed to move the material from the pile to the mixing facility. The material would be dumped in the mixing facility where a measured amount of reagent would be applied from the silo. Water would be applied to control fugitive dusts as a front end loader mixed the reagent into the material. In KEECO's design, the treated material is considered "residual" and costs for returning it to the heap and compacting it after treatment has been performed are covered under the residuals category.

KEECO used a typical density for mixed soil types, 1.5 tons per cubic yard, to calculate the weights that were used in the cost estimate. The calculated weights are 1,315,500 tons, in the North Waste Pile and 834,000 tons in the Waste Rock Dam. The cost estimate provided by KEECO was based on the combined mass of the two piles; therefore figures are presented for treatment of 2,149,500 tons without differentiating time and effort between the two piles. The treatment time required to treat the entire mass is 247 working days, based on an average daily throughput of 8,700 tons per day.

The cost estimates for KEECO's application were based on the assumption that mixing operations would be scheduled to operate on a 16 hours (consisting of two 8-hour shifts) per day, five days per week basis. A daily use factor of 90 percent of the design capacity was used based on the simplicity of the operation and reliability of the standard equipment selected. Based on an expected daily throughput of 8,700 tons per day, it is estimated that the mixing operations will be completed in 247 working days (one year). An additional training period of five days prior to treatment beginning and ten days at the end for demobilization should also be included in the schedule.

The cost estimate provided by KEECO is based on a preliminary design, which was produced without the benefit of data from a pilot project; therefore, cost ranges presented in this estimate may be wider than would normally be expected in a fully developed cost estimate. It should also be noted that SME reagent use rates in this cost estimate were taken from the lab scale treatability study, whereas historically, field use rates are considerably lower than lab use rates resulting in reduced reagent costs.

The cost estimate has been developed according to the twelve categories specified in Section 3.2 above.

(1) Site Preparation: The primary preparation cost would be the construction of the mixing facilities, which was estimated at $420,000 each. The total site preparation costs for facilities at both piles would be $840,000.

(2) Permitting and Regulatory Activities: The cost for State and Federal air treatment permits for the mixing facilities is estimated to be $20,000 including labor for data review, estimating emissions and permitting fees. Construction permits were estimated to be $2,500 and permitting costs for onsite disposition of the treated material were estimated at $40,000. Costs for permitting, regulatory activities, monitoring and waste transportation and disposal are highly dependent on the site, and as such could be significantly higher than the estimated total of $62,500.

(3) Capital Equipment: Heavy equipment would be rented or leased for the project. The following equipment list includes monthly rental rates for each piece of equipment: 2 excavator/backhoes at $15,000, 2 10-KW generators at $1,000, 4 dump trucks at $4,000, 4 front end loaders at $14,000 and 1 water truck at $3,000. The total monthly equipment rental would be $107,000, bringing the total for the estimated 12-month project duration to $1,284,000.

(4) Start-up and Fixed Costs: This category includes transportation of personnel and equipment, safety training, working capital, insurance, monitoring, and a contingency fund. Transportation costs for 14 pieces of rental equipment were assumed to be $7,000. The transportation of personnel cost was based on the purchase of six $1,200 round trip airline tickets for a total of $7,200. The remaining project staff would be hired locally. Safety training would consist of a 40 hour HAZWOPER course, which each member of the site team would be required to complete. Based on a crew size of 32 persons, the estimated cost of the training would be $57,000. Total transportation and training costs are estimated at $71,200.

Working capital consists of the costs of borrowing capital for operating supplies, utilities, and labor necessary to keep the project running without financial constraints. Working capital for this project is estimated at $1,000,000, based on maintaining 2 months of payroll, and sufficient inventory for all other items. The cost of capital is assumed to be 9% of the working capital, making the estimated working capital cost $90,000 per annum. Insurance was estimated at $50,000 per year and a contingency factor should be included in the budget to cover unforeseen events, for which KEECO estimated $150,000 as an appropriate figure.

Environmental monitoring is assumed to be required for fugitive dust emissions from the mixing facility only, and was estimated to cost $6,000. The combined total of costs in this category is $367,200.

(5) Labor: It is assumed that treatment operations would be conducted over 247 days, working in two shifts, for a total of 16 hours per day, 5 days per week. Total labor cost for treatment is estimated to be $2,986,800. Table 3-1 gives a breakdown of the number and types of employees, expected pay rates and the number of hours that would be required for each type of labor.

Table 3-1. Labor Unit Costs.

Description	Number of Persons	Cost Per Hour	Total Hours	Total Cost
Site Manager	1	$90	2096	$188,640
Foreman	2	$55	4192	$230,560
Truck Driver	8	$40	16768	$670,720
Excavator Operator	4	$45	8384	$377,280
Front End Loader Operator	8	$45	16768	$754,560
Water Truck Driver	2	$40	4192	$167,680
Laborer	4	$35	8384	$293,440
SSHO	1	$65	2096	$136,240
Facility Operator	2	$40	4192	$167,680
TOTAL				**$2,986,800**

(6) Consumables and Supplies: The most significant cost in the treatment estimate is the chemical reagent. The material requires a 5% by weight add ratio. The estimated cost of $23,107,000 assumes that a temporary batch mixing plant would be established on site to defray excessive transportation costs. This also assumes that utilities are available to support the operation of a temporary batch mixing plant.

Diesel fuel is required to operate the earth moving equipment and generators. It was estimated that fuel consumption would be 50 gallons of fuel per piece of equipment per day. This amounts to 650 gallons of fuel per day. Using a rate of $1.40 per gallon, daily fuel cost was estimated to be $910. Assuming 247 operating days, total fuel costs were estimated to be $224,770.

Supplies consist of operating supplies and SME reagent. Operating supplies consist of items such as safety equipment, PPE, office supplies, custodial supplies, potable water and the like. Operating supplies were estimated at 1 percent of annual labor, or $29,600. Combining the three costs for consumables and supplies brings the category total to $23,361,370 for consumables and supplies.

(7) Utilities: Water is used to minimize fugitive dust emissions during operations. Assuming a water use rate of 2 percent of the volume being treated, and a cost of $2 per 1000 gallons, the total cost of water for the project would be estimated at $20,600. Electricity would be required, but incidental usage should not add significant costs.

(8) Effluent, Treatment and Disposal: The treatment process produces no effluent, however, cleaning PPE and equipment may produce wash water that requires decontamination. It was assumed in the cost estimate that this would be a small enough quantity that any associated costs could be absorbed into the overall project costs.

(9) Residuals, Shipping, & Disposal: Residuals from the SME process can include treated waste, waters and sludge and waste from decontamination activities. It was estimated that treated material could be moved from the treatment facility, replaced and compacted onsite for $3 per ton or $6,448,500 for the entire project. This figure includes the equipment and labor used to return the treated material to the pile (not included in the previous cost sections) as KEECO differentiated treatment from residuals handling in these costs. It is expected that the project would generate one drum of contaminated PPE each week. Assuming a disposal cost of $500 per drum, the disposal cost for PPE was estimated at $26,000. The total cost of residuals, waste shipping, handling and transport was estimated to be $6,474,500.

(10) Analytical Services: It was assumed that 4 composite samples would be taken each day: one per shift per facility. It was also assumed that the sample number would be increased by 10% to provide QA/QC samples. With an assumed cost of $90 per sample to analyze for leachable mercury, the estimated cost for analytical services is $97,800.

(11) Maintenance and Modifications: Maintenance costs vary with the nature of the wastes, and the time between failures of the equipment. For the purposes of this cost estimate, these costs were assumed to be 2% of the cost of facilities and equipment and were estimated at $38,480.

(12) Demobilization/Site Restoration: It was assumed that a total of 10 days would be required for demobilization activities. It was further assumed that the entire project staff would be involved in the demobilization effort. Demobilization efforts will include facility dismantlement, equipment decontamination, and transportation. It is assumed that demolition of the mixing pads would not be required. Costs for the demobilization effort were estimated at $157,000.

3.7 Cost Summary

Table 3-2 presents the summarized costs by category for treating the SBMM piles. The volume of material at the SBMM site is extremely high compared to most waste sites, resulting in very large figures in the cost estimates; however the cost per cubic yard of treated material by either technology is in the low end of the cost range for comparable stabilization technologies. A study conducted for EPA in 1997 entitled "Recent Developments for In Situ Treatment of Metal Contaminated Soils" reported that, according to vendors of stabilization technologies, in situ applications range from $20 to $40 per cubic yard for treatment under optimum conditions, ranging upwards to $200 to treat high concentrations at great depths.

The cost estimates were developed independently by the vendors (with additions as noted) and because of differences in exclusions and assumptions, cannot be used for direct cost comparisons, but do provide an overview of cost magnitudes and a breakdown into cost categories and percentages of total costs. KEECO included working capital and contingency financing in their startup costs, and ECWI did not include these in their estimate, but they would be relevant costs to any

Table 3-2. Cost Summary.

	ECWI		KEECO	
ITEM	**Category Cost***	**Percent of Total Cost**	**Category Cost***	**Percent of Total Cost**
Site Preparation	$40,000**	0.1%	$840,000	2.4%
Permitting and Regulatory	$20,000**	0.0%	$62,500	0.2%
Equipment	$1,633,500	2.7%	$1,284,000	3.6%
Startup and Fixed	$45,000	0.1%	$367,200	1.0%
Labor	$903,300	1.5%	$2,986,800	8.4%
Chemical Reagent	$57,008,000	95.3%	$23,107,000	64.7%
Other Supplies & Consumables	$50,840	0.1%	$254,370	0.7%
Utilities	$26,145	0.0%	$20,600	0.1%
Effluent Treatment & Disposal	$0	0.0%	$0	0.0%
Residuals and Waste Handling	$0	0.0%	$6,474,500	18.1%
Analytical	$10,400	0.0%	$97,800	0.3%
Maintenance & Modifications	$25,000	0.0%	$38,480	0.1%
Site Demobilization	$45,000	0.1%	$157,000	0.4%
Total Operating Costs	**$59,807,000**	100.0%	**$35,690,000**	100.0%
Cost per Ton	**$27.82**		**$16.60**	

*Costs rounded to a maximum of five significant digits.

**Costs for this category not provided by vendor; assumed value as described in Section 3.6.1.

project. The largest area of discrepancy, residuals handling, is a legitimate difference between the two processes, however, as the ENTHRALL® process would not generate residuals whereas handling treated material is a major element of KEECO's SME process.

It is clear for both treatments that the chemical reagent is the largest cost factor, at $26,700,000 (68% of total costs) for SME and $57,008,000 (93.5% of total costs) for ENTHRALL®. The vendors based their application ratios on the amounts used in the treatability study, and if it was determined that the quantity required for a field application was reduced, then associated reagent costs would also be lower. Neither vendor indicated any cost reduction for high volume usage.

The equipment cost of $1,633,500 for the Enthrall® treatment constitutes only 2.7% of the total, but is the second highest cost category. KEECO's process is unusual in that it requires residual handling to the extent that it is the second highest cost factor, lowering the equipment costs to the fourth highest category despite the $1,283,000 estimated cost.

Section 4.0
Treatment Effectiveness

4.1 Pre-demonstration Studies

Pre-demonstration studies were undertaken to: (1) attain a suitable test material with sufficient mercury leachability for treatability testing; (2) elucidate the mechanism(s) of mercury leaching to develop appropriate testing procedures; and (3) provide samples of material to vendors, along with the testing criteria, to optimize their processes prior to the large-scale treatability studies.

Leachability methods for solid waste were developed to simulate the leaching behavior of the material when subjected to specific solutions and conditions. For example, the Toxicity Characteristics Leachability Procedure (TCLP) and the Synthetic Precipitation Leachability Procedure (SPLP) were developed for simulating the leaching conditions for landfilled wastes. The Meteoric Water Mobility Procedure (MWMP) and the Humidity Cell Procedure were developed specifically to simulate the conditions encountered by mining waste. Each leachability procedure may provide different results, based on the leaching fluids used, duration, leachate preparation, and nature of the waste material.

In order to quantitatively evaluate the effectiveness of the stabilization technologies tested for the mercury contaminated SBMM material, it was necessary to identify both a suitable material and leaching protocol. The objectives for the study required a material with leachable levels of mercury so that a reduction of 90% from a control could be observed. Furthermore, the leaching protocol would need to simulate the generation of mercury from the SBMM material so that the stabilization technologies could appropriately control the types and levels of mercury being generated from the site.

4.1.1 SPLP Characterizations

Leachability characterizations of materials from several locations at the SBMM site using the SPLP method demonstrated generally low overall mercury leachability. Figure 4-1 is an aerial photograph of the SBMM depicting the locations of samples collected for SPLP characterization. Table 4-1 presents the SPLP results as well as the whole rock mercury values. The levels of leachable mercury generated by the SPLP method for the tested materials were too low to be used in this technology evaluation. SPLP leachability was low even for materials exhibiting high whole rock mercury values of 1,000 mg/Kg.

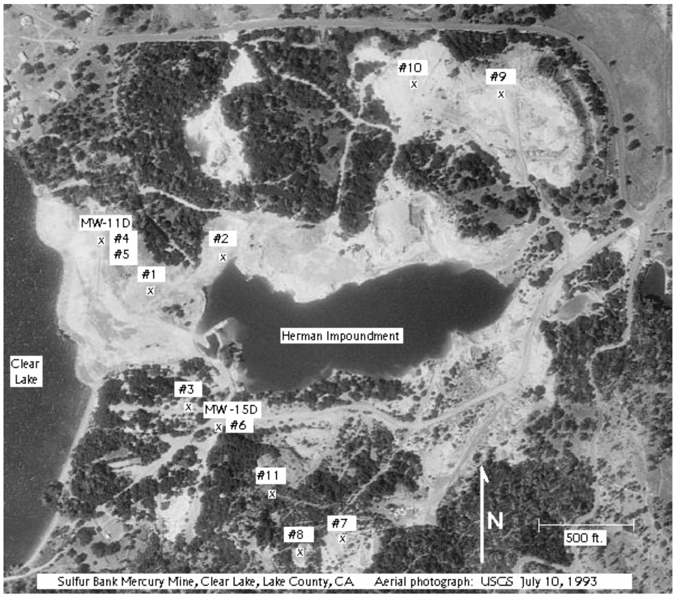


Figure 4-1. Locations of samples from SBMM site.

The lack of appreciable leachable mercury from SBMM materials despite high levels of whole rock mercury prompted additional studies to determine a suitable material and leaching protocol for the technology evaluation. Furthermore, the additional studies investigated possible mechanisms of mercury leachability from SBMM materials.

Table 4-1. SPLP Leachability Results from Various SBMM Materials.

LOCATION		Total Mercury	SPLP Mercury
#1	Waste Rock - Shoreline Material #1 (Middle Shoreline Pile)	762 mg/Kg	ND (0.2) µg/L
#2	Waste Rock - Shoreline Material #2 (Northwest Pit Shore)	37.5 mg/Kg	ND (0.2) µg/L
#3	Waste Rock - Shoreline Material #3 (West Shoreline Pile)	175 mg/Kg	ND (0.2) µg/L
#4	Drill Cuttings MW11D 0 to 25 feet	41.9 mg/Kg	ND (0.2) µg/L
#5	Drill Cuttings MW11D 25 to 45 feet	58.5 mg/Kg	ND (0.2) µg/L
#6	Drill Cuttings MW15D 0 to 20 feet	76.1 mg/Kg	1.39 µg/L
#7	Mercury Ore (South Hill White Pile)	1000 mg/Kg	19.9 µg/L
#8	Waste Rock (South Hill Waste rock Pile)	905 mg/Kg	10.5 µg/L
#9	Waste Rock (North Side Gray Pile)	35 mg/Kg	0.47 µg/L
#10	Waste Rock (North Side Waste rock Pile)	484 mg/Kg	9.84 µg/L

4.1.2 Leachability Studies

Roasted tailings from the site were used in a series of studies to determine mechanisms of mercury leachability. The roasted tailings are material derived from the retorting of the ore. This material was used because it exhibits consistent levels of whole rock mercury and constant particle size.

Replicate analyses using the SPLP method on the roasted material revealed consistent whole rock mercury values, but highly variable SPLP leachates (Table 4-2). Visual observations of the leachate from the SPLP extraction revealed a correlation between the visual turbidity of the sample and the concentration of mercury. This association prompted a more thorough evaluation of the relationship between leached particulates and extractable mercury.

Table 4-2. Replicate SPLP Analyses on Roasted Tailings

Replicate	**Total Hg** (mg/Kg)	**SPLP Hg** (µg/L)
SBMM-RF#1	25.7	60
SBMM-RF#2	26.6	195
SBMM-RF#3	37.8	487

The original roasted tailings material tested in triplicate was further studied. Triplicate samples of the roasted tailings were analyzed for total mercury (whole rock) and SPLP extractions. The extracts were filtered through a 0.7µm filter (standard for the method) and analyzed for SPLP Hg, pH, total solids, and turbidity. The remaining extract was filtered through a 0.45µm filter and analyzed for the same analytes, as well as a 0.2µm filter. The experiment resulted in the generation of nine leachate samples (triplicate analyses at three levels of filtration).

Results form the experiment (Table 4-3) indicates that total mercury was consistent between the three replicates (as observed in the original analysis). SPLP mercury at the standard filtration (0.7µm) was lower but exhibited much lower variability as compared to the original triplicate analyses. SPLP mercury at the 0.45µm and 0.2µm levels produced ND at the 1.0 µg/L level.

The results from the study suggested that leachable mercury is associated with particulates. Furthermore, there is a strong association between the turbidity in the sample and the level of filtration. Although the finer filters produced non-detect values, there is a correlation between the SPLP mercury and turbidity. The results from this experiment prompted an additional experiment to determine the relationship between particle size, turbidity, and leachable mercury.

Results from the test are presented in Table 4-4. There is a strong relationship between level of filtration, turbidity, and mercury content. Furthermore, the relationship between turbidity and mercury content is illustrated by plotting the mercury values for the filtered samples from both the SPLP and modified MWMP test (Figure 4-2). There is a high correlation between the turbidity of the sample and the mercury content of the leachate. This suggests that mercury in leachate samples is associated with particulates of various sizes, and is not predominately found in a dissolved state.

Table 4-3. Results of Triplicate SPLP Leaching Experiment

	Total Hg (mg/Kg)	Reporting Limit (mg/Kg)	SPLP (µg/L)	Reporting Limit (µg/L)	pH (SU)	Total Solids (mg/L)	Turbidity (NTU)
Replicate 1	24	0.049					
0.7µm			3.0	1.00	6.15	64	29.2
0.45µm			ND	1.00	3.26	48	7.24
0.2µm			ND	1.00	2.85	58	0.35
Replicate 2	23	0.052					
0.7µm			5.2	1.00	7.09	24	40.2
0.45µm			ND	1.00	3.63	24	0.58
0.2µm			ND	1.00	3.19	10	0.43
Replicate 3	22	0.049					
0.7µm			3.6	1.00	6.89	34	36.1
0.45µm			ND	1.00	3.85	26	0.59
0.2µm			ND	1.00	6.13	ND	0.49

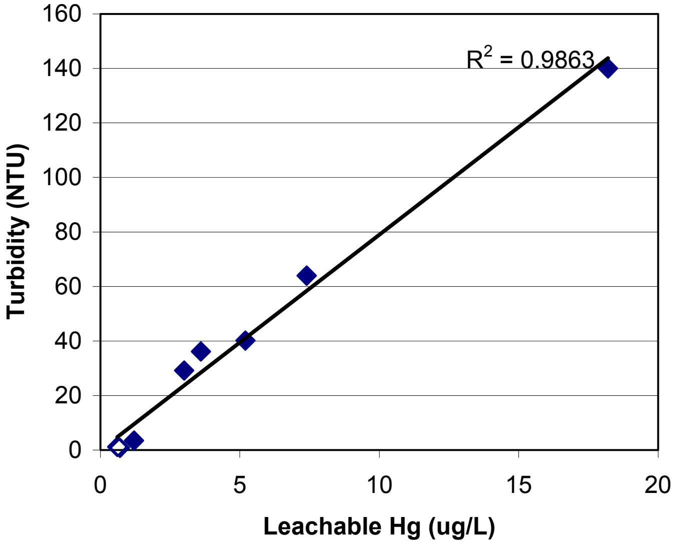


Figure 4-2. Turbidity and leachable mercury from SPLP and MWMP tests.

Table 4-4. Results from the Modified MWMP Leachate Test with Variable Filtration

Filtration Level	Hg µg/L	pH	Turbidity (NTU)
Unfiltered	402	4.07	362
25 µm	18.2	4.31	140
8 µm	7.4	4.25	64
2.5 µm	1.2	4.25	3.5
1 µm	0.7	4.25	0.76
0.7 µm	0.6	4.65	1.17

All filter blanks, Hg = ND
0.7 µm filter blank had turbidity = 0.28

4.1.3 Geochemical and Mineralogical Evaluation of Particulates

A mineralogical and geochemical study was performed at the City College of New York to characterize the particulate fractions generated during leaching and to identify potential mechanisms for release and transport.

Roasted tailings were placed in distilled water for three weeks without agitation. The water immediately became cloudy, and the degree of turbidity appeared to per sist unchanged throughout the three week period. Characterizations were performed both on fines that were suspended in the water and on particles re-suspended by stirring the mixture. Both the suspended particles and the particles re-suspended (stirred) are termed auto-released solids due to their ability to easily dissociate from the solid matrix.

The structure of auto-released solids was determined by using standard techniques for the x-ray analysis of clay-sized particles. Preliminary study of a randomly oriented sample demonstrated that the auto-released particles belong primarily to the clay mineral family. Glycolation treatment revealed that the auto-released particles contain chlorite-smectite interlayer clays. The clay thus possesses both a filled metal-hydroxide layer and a partially filled expandable interlayer.

Sieving and mounting procedures were used to estimate the quantity of mercury on particles of various sizes. The procedure involves entrapping mercury on sieves of varying sizes using a Mylar filter to fix the particles to the sieve material. The mylar-shielded samples were then analyzed using a Philips 1410 series x-ray fluorescence spectrometer and counting times of 400 seconds on both peak and background. The results are plotted as counts-above-background adjusted by weight using the relationship:

$$C_{adjusted} = \frac{C_{peak} - C_{background}}{W}$$

Where: C_{peak} is the number of counts on the mercury peak using a LIF200 crystal,

$C_{background}$ is the number of counts at ± 1 degree of the peak maximum, and

W is the microgram weight of the clay.

The adjusted counts indicate the distribution of mercury within the sample irrespective of the amount captured on a given sieve. Since the actual weight of sample is greater toward the larger sieve sizes, the relative error increases as the sieve-size decreases. The plot of this distribution (Figure 4-3) indicates that the bulk of the mercury is carried by the 10 to 20 micron clay fraction, but that a given amount of mercury is present in all sieve fractions, including the <0.45μm set. The results establish that clay is auto-released from roasted tailings.

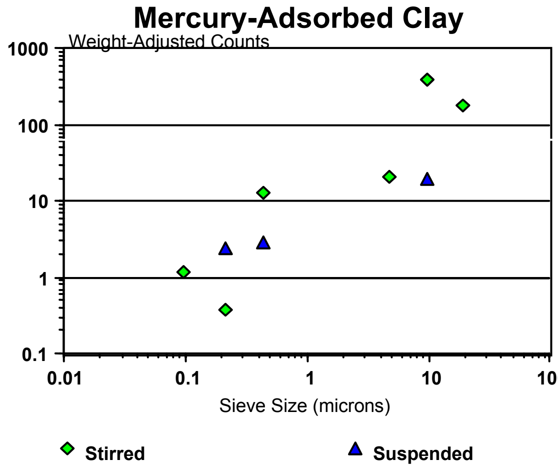


Figure 4-3. Mercury adsorbed on clay particles as indicated by the number of x-ray counts adjusted by the sample**.**

4.1.4 Extended Leachability Study

Three SBMM solid matrices were evaluated by a modified MWMP (Meteoric Water Mobility Procedure) over various time intervals to assess the change in leachability of mercury over time. The study was conducted to determine if dissolved mercury is generated when leaching times and exposure to aqueous solutions is extended. Conventional leaching procedures require only a 24-hour exposure to the leaching agent. The samples chosen for this exercise consisted of: (1) a roasted tailings composite, (2) waste rock (shoreline #1) form the middle shoreline pile, and (3) waste rock (# 10) from the north side waste rock pile. Whole rock mercury concentration of each matrix are 25 ppm for the roasted tailings, 762 ppm for the shoreline #1, and 484 ppm for the mine tailings #10.

The modified MWMP utilized a 1:1 ratio of solid material to leaching medium (deionized water) placed in a column-type apparatus and exposed to the leachate in a single pass manner over a 24-hour period. After each 24-hour period the leachate volume was collected and reapplied to the top of the column. The solution was passed back over the solids in the column until the end of the test period (for 72 hour tests) or for five days (Monday-Friday). For the 1, 2 and 4 week test periods, the solution was allowed to remain in contact with the solids over the weekend (with the column top covered), and then drained over 24 hours starting again on Monday.

The following tests were performed:

Matrix	# of Tests	Test Duration
Roasted tailings	5	24 hrs
		72 hrs
		1 week
		2 weeks
		4 weeks
Waste Rock (spl#1)	2	24 hrs
		2 weeks
Waste Rock (spl#10)	2	24 hrs
		2 weeks

The leachate from each test was split, with one-half of the sample set-aside for unfiltered analyses, while the second-half of the leachate sample was filtered through a 0.45µm filter. The leachate samples (unfiltered and filtered) were analyzed for the following analytes: mercury, sulfate, pH, turbidity, and total solids.

Analytical results from the study are presented in Table 4-5. For the roasted tailings, and as in previous studies, mercury appears to be associated with the particulate fraction (>0.45µm). For the unfiltered samples, mercury leachability is lower for the two week and 4 week samples. Mercury leachability, therefore, does not increase with longer leaching cycles, and actually decreases. For the filtered samples, mercury concentration is low and variable. There is no indication that extended leaching results in the generation of significant dissolved mercury.

Waste Rock spl#1 exhibited the highest leachable mercury concentration of the unfiltered samples. Although high particulate mercury concentrations were encountered, filtered mercury was low. The sample completely dissociated after five days into a hydrous clay, necessitating cessation of the leaching tests. The hydrous clay was submitted to CCNY for characterization. The sample was characterized as a mixture of two clays with properties similar to the auto-released clays from the first roaster fine study. Furthermore, the sample contained very high mercury content as measured by X-ray fluorescence. The complete dissociation of the sample and the presence of high mercury content in the clay fraction provide further evidence for a particulate transport mechanism.

Extended leaching of the waste rock spl #10 failed to provide significant concentrations of mercury in either the unfiltered and filtered fractions. There is some limited evidence that mercury content decreases over time in both fractions.

4.1.5 Conclusions from Leachability and Characterization Studies

The following conclusions are based on the results from the previously discussed studies:

- Mercury is found associated with particulates that auto-release from SBMM material and can remain suspended, and therefore mobile, in solution. There is no strong evidence from any of the leaching studies that a dissolved mercury fraction exists in the leachate.
- There may be clays in the material that are easily dissociable, contain mercury, and can be suspended and transported in an aqueous medium. Since the clays are expanded layer smectites, the mercury

Table 4-5. Results from the Extended Leachability Study

	Unfiltered					Filtered (0.45um)				
Sample	**Hg** (ug/L)	**pH**	**Sulfate** (mg/L)	**Turbidity** NTU	**Total Solids** (mg/L)	**Hg** (ug/L)	**pH**	**Sulfate** (mg/L)	**Turbidity** NTU	**Total Solids** (mg/L)
Roasted Tailings 24 hrs	20.0	6.86	9.7	434	333	3.30	7.26	10.2	19.4	NA
RoastedTailings 72 hrs	14.0	7.52	10	154	250	2.30	7.4	10.1	5.77	NA
Roasted Tailings 1 week	16.0	7.25	10.4	188	190	1.50	7.71	7.8	4.42	NA
Roasted Tailings 2 weeks	8.3	7.38	10.2	90.1	220	ND (1.2)	7.12	10.3	25.1	NA
Roasted Tailings 4 weeks	2.5	7.18	15.1	99.6	200	8.3	7.32	13.9	36.2	NA
Waste Rock (spl #10) 24 hrs **	96.1	3.11	7010	155	9110	2.20	3.13	5270	0.42	NA
Waste Rock (spl #10) 24 hrs	9.0	3.04	2630	4.9	3440	6.00	3.09	2350	0.52	NA
Waste Rock (spl#10) 2 Weeks	7.5	3.15	2360	8.15	3300	ND (2.5)	3.24	2210	0.1	NA

** spl #1 was observed to completely dissociate to a clay-mud after approx. 5 days
NA = Not Applicable
ND = Non detectable at level in parentheses
NR = Not Reported

may be bonded within the interlayers. These clays may be associated with the ore and rock, or may exist as discrete deposits that were segregated during the mining process.
- Mercury associated with the particulates may undergo further chemical and biological diagenetic changes in the groundwater and/or lake environment that release dissolved mercury during transport.
- The remedial solution may require technologies that can control the release of particulates from SBMM materials.
- The leaching protocol for the stabilization evaluation should simulate the generation of mercury-laden particulates from a solid matrix.

4.1.6 Pre-demonstration Kinetic Column Studies

A kinetic column configuration was investigated as a leaching protocol for evaluating the effectiveness of the stabilization technologies. In the kinetic column, leaching solutions are continuously passed over the material. For this evaluiation material from the south white gate pile ("mercury ore") and "waste rock" were tested. For the mercury ore material, whole rock mercury concentrations ranged from 300-1360 mg/Kg and SPLP mercury concentrations as high as 113 µg/L were encountered (Table 4-6). For the waste rock material, whole rock mercury concentrations ranged from 130 to 450 mg/Kg with leachable mercury below 10 µg/L in all three samples. Two kinetic column studies were initiated for each of the materials. For one set of experiments, leachant (15 L de-ionized water adjusted to a pH of 5) was applied to the column in flow-through mode

as a single-pass leach. The second set of experiments used approximately 15 liters of the solution in a recycle mode. Leachate was analyzed for mercury both as in an unfiltered sample and filtered through a 0.45µm filter. The results, presented in Table 4-7, indicated that: (1) the flow-through method generated higher and more consistent leachable mercury, (2) the unfiltered samples contained significantly higher levels of mercury, and (3) the mercury ore material generated significantly higher levels of leachable mercury. Based on these results a kinetic column leaching protocol using mercury ore material from the site and focusing on control of the particulate fraction would be relevant for evaluating the performance of the stabilization technologies.

Table 4-6. Mercury in Untreated Mercury Ore and Waste Rock

Matrix	**Total Hg** (mg/Kg)	**SPLP Hg** (µg/L)
Mercury Ore	751	37
	312	0.5
	1360	113
Waste Rock	447	1.5
	441	0.9
	130	5.6

4.2 Project Objectives

For all MWTP and SITE projects, specific objectives are defined in a Quality Assurance Project Plan (QAPP) prior to the initiation of treatability studies or fieldwork. The QAPP specifies the objectives to be achieved and provides experimental design. This section states the project objectives and summarizes each of the experiments performed as part of the treatability study.

4.2.1 Primary and Secondary Objectives

Objectives are subdivided into two categories: primary and secondary. Primary objectives are those goals of the project that must be achieved in order to adequately compare demonstration results with the claims made by the developer(s). The analytical results and field measurements required for achieving primary objectives are referred to as critical measurements. Secondary objectives are specified to obtain additional information of interest about the technology, but are not imperative for validating developer claims. The data and field measurements required for achieving secondary objectives are referred to as noncritical measurements.

Immobilization of mercury in material from the Sulfur Bank Mercury Mine (SBMM) was the goal of the treatments used in this treatability study. The objectives of the study are to evaluate the technologies' ability to achieve this end. Primary objective satisfaction was evaluated by treating "mercury ore" material from the site. The same testing process was applied to "waste rock" material to achieve secondary objectives. The actual testing procedures are described in their respective sections below. The success of the various treatments was evaluated by measuring the parameters as specified in Table 4-8.

Table 4-7: Kinetic Column Leachability Study

	Leach Time (days)	Hg in Mercury Ore Leachate (µg/L)		Hg in Waste Rock Leachate (µg/L)	
		Recirculating	Flow-through	Recirculating	Flow-through
Unfiltered	2	210	410	0.6	1.2
	9	210	530	0.3	2.1
	15	180	420	0.4	ND
	23	90	410	0.8	1.0
	29	93	270	0.1	ND
	38	140	390	0.2	0.2
<0.45µm Filtered	2	11	28	ND	ND
	9	11	9.0	ND	ND
	23	5.0	7.0	ND	ND
	29	2.0	9.0	ND	ND
	38	2.0	7.0	ND	ND

4.2.1.1 Primary Objective

The primary objective of the treatability study was to evaluate each technology's ability to immobilize, and therefore reduce the leachability, of mobile mercury in the SBMM mercury ore material. Mobile mercury is defined in this project as the mercury associated with the <25µm filtered fraction. Previously discussed studies revealed that particulates containing mercury are released from SBMM materials and can become suspended and therefore mobile in aqueous systems. The <25µm fraction was chosen based on the results from the previous studies. Success at immobilizing mercury was to be determined by comparison of the amount of mobile mercury (<25µm fraction) in each treatment columns leachate to the amount of mercury in leachate from untreated control columns. Each technology and control was tested in triplicate. After being loaded into columns and treated, the material was leached daily with fresh deionized water, adjusted to a pH of 5.0. The leachate was collected, measured, filtered and analyzed weekly for the critical parameters of dissolved and total mercury. The original design called for a minimum of eight weeks of leaching. This was extended an additional four-weeks for one of each type of column during the study.

Each technology was evaluated to determine the reduction in the cumulative mass of mercury in the <25μm filtered leachate, relative to the control column <25μm filtered leachates. The target reduction for the treatments was 90%. Mercury mass was calculated from leachate concentrations by multiplying the concentration in micrograms per liter by the volume of total sample collected each week (in liters), resulting tin the total micrograms leached from each column. Percent Mercury Reduction was determined from the difference between the amounts of mercury leached from treated columns and control columns as follows:

$$\frac{\text{Mercury Mass}_{(control)} - \text{MercuryMass}_{(treated)} \text{ x } 100}{\text{Mercury Mass}_{(control)}}$$

Where Mercury Mass is the summation of the average weekly mercury mass for each treatment or control over the 12-week test.

Mercury mass was determined for each column each week and then averaged for that week and summed to derive the total mass of mercury leached for each treatment or control. Leachate characteristics were also collected for turbidity, pH, redox potential, sulfate, sulfide, conductivity, alkalinity/acidity and the metals arsenic, iron and antimony. Primary and secondary objectives of the treatability study are summarized in Table 4-8. The table gives a description of the objective and the method by which each was evaluated.

Table 4-8. Treatability Study Test Parameters

Matrix	Parameter	Classification	Type	Purpose
Kinetic Test Column Leachates - mercury ore material, treated and untreated controls	Mercury-dissolved (<0.45μm)	Non-critical	Analytical	Primary objective: evaluating leachable Hg reduction
	Mercury-mobile (<25μm)	Critical	Analytical	
	Leachate volume	Critical	Field	
	Metals (As, Fe, Sb)	Non-critical	Analytical	Secondary objective: Evaluate leachate quality after treatment of primary test matrix
	Sulfate	Non-critical	Analytical	
	Sulfide	Non-critical	Analytical	
	Alkalinity	Non-critical	Analytical	
	Acidity	Non-critical	Analytical	
	Turbidity	Non-critical	Field	
	pH	Non-critical	Field	
	Conductivity	Non-critical	Field	
	Redox potential	Non-critical	Field	
Mercury ore material prior to leaching, treated and untreated	SPLP (Hg/As/Sb/Fe)	Non-critical	Analytical	Secondary objective: evaluate impact of treatment on conventional leachability
	X-ray diffraction	Non-critical	Mineralogical	Secondary objective: evaluate mineralogical changes of solids after treatment
	X-ray fluorescence	Non-critical	Mineralogical	
	SEM/EDS	Non-critical	Mineralogical	
	Humidity Cell Test	Non-critical	Analytical	Secondary Objective: assess weathering effects on treated material
Mercury ore material after leaching, treated and untreated control	X-ray diffraction	Non-critical	Mineralogical	Secondary objective: evaluate mineralogical changes of solids after leaching
	X-ray fluorescence	Non-critical	Mineralogical	
	SEM/EDS	Non-critical	Mineralogical	
Kinetic Test Column Leachates Waste rock material, treated and untreated controls	Mercury-dissolved	Non-critical	Analytical	Secondary objective: evaluate Hg reduction in second matrix
	Mercury-mobile	Non-critical	Analytical	
	Leachate Volume	Non-critical	Field	
	Metals (As, Fe, Sb)	Non-critical	Analytical	Secondary objective: Evaluate leachate quality after treatment of secondary test matrix
	Sulfate	Non-critical	Analytical	
	Sulfide	Non-critical	Analytical	
	Alkalinity	Non-critical	Analytical	
	Acidity	Non-critical	Analytical	
	Turbidity	Non-critical	Field	
	pH	Non-critical	Field	
	Conductivity	Non-critical	Field	
	Redox potential	Non-critical	Field	
Waste rock material, prior to leaching, treated and untreated	X-ray diffraction	Non-critical	Mineralogical	Secondary objective: evaluate mineralogical changes of solids after treatment
	X-ray fluorescence	Non-critical	Mineralogical	
	SEM/EDS	Non-critical	Mineralogical	
	SPLP	Non-critical	Analytical	Secondary objective: evaluate impact of treatment on conventional leachability
Waste rock material after leaching, treated and untreated control	X-ray diffraction	Non-critical	Mineralogical	Secondary objective: evaluate mineralogical changes of solids after leaching
	X-ray fluorescence	Non-critical	Mineralogical	
	SEM/EDS	Non-critical	Mineralogical	

4.2.1.2 Secondary Objectives

Secondary objectives are designed to provide information, in addition to the critical parameters, for evaluating the effectiveness of technology applications. The secondary objectives are:

Assess Mercury Contaminant Reduction in Treated Waste Rock Test Material: The same kinetic column leach test that was described for the primary mercury ore material was also run on the waste rock material, with results being evaluated in the manner described above. The waste rock material columns were not run in triplicate, but were run in duplicate for the control and single for the treatments.

Evaluate Leachate Quality After Treatment and During Column Testing: During and at the end of the column leach tests, filtered samples were analyzed for parameters in addition to mercury, in order to assess changes in the leachate chemistry. Samples were analyzed for the additional metals: arsenic, iron, and antimony, as well as pH, redox potential, sulfate, sulfide, conductivity, alkalinity/acidity, and turbidity. This analysis was done on both mercury ore and waste rock column effluents.

Evaluate Mineralogical Changes in the Treated Material: Samples of the mercury ore material were collected after reagents had been applied, but before leaching was begun for the evaluation of the mineralogical changes that may have occurred during treatment. Mineralogical analyses included x-ray diffraction, x-ray fluorescence and optical mineralogy.

Humidity Cell Test Protocol Using the Mercury Ore Material: Mercury ore material that had been treated but not leached was subjected to the Humidity Cell Test procedure. Leachate from the test was evaluated for both dissolved (<0.45µm) and mobile mercury (<25µm), and again reductions were evaluated by comparison to leachate from controls cells. Two control cells and one cell for each technology were run.

Evaluate Treated Materials for Conventional (Static Test) Leachability: After the reagents had been applied, but prior to the start of kinetic leach testing, samples of the treated and untreated (control) material were evaluated to determine the leachability of mercury and other metals in a static test protocol. Routine leachability testing is most commonly performed using the Synthetic Precipitation Leaching Procedure (SPLP) method 1312 as described in SW846, which is a one-time contact over a 24 hour duration. Both of the material types were subjected to SPLP leaching, which was performed on each of the treated materials and an untreated control sample. Resulting leachates were analyzed for mercury, antimony, arsenic, and iron.

4.3 Experimental Design

Several tests were designed to achieve the project objectives. In order to assure that the critical mercury ore material was homogenous so that each test unit (column or humidity cell) received equitable material, splits were carefully prepared. As it was collected in the field, the mercury ore material was screened to pass a 0.5-inch mesh. The material was transported to MSE's research facility where it was thoroughly mixed and split into batches of 5-6 kilograms. Each batch was split to obtain a 300 to 500 gram sample for mercury analysis. The requirement for successful homogenization of samples was a Relative Standard Deviation (RSD) of ≤25% for whole-rock mercury content. The analysis of the 32 split batches yielded a mean of 1,969 mg/Kg Hg, with a standard deviation of 313, resulting in an RSD of 16%, indicating successful homogenization.

4.3.1 Column Studies

The primary objective was achieved by performing column leach studies on the mercury ore material. Each column consisted of a 3-foot 4-inch section of clear schedule 40, 3-inch diameter PVC pipe, fitted with a cap on the bottom. A drain in the cap connected to 0.25-inch tubing. Columns were prepared by filling the first two inches with 1/8-inch stone to provide a drain layer. After the treatment on material in the columns was completed, two more inches of the 1/8-inch stone was added to the top surface to disperse the liquid being dripped onto the column.

For the ex situ application, four batches of mercury ore material were treated with KEECO's KB Sea dry reagent. Half of a batch (~2000 grams) was spread out in a bin and half of the dry reagent was sprinkled on top of it. The other half of the material and reagent were added in the same manner and the entire amount was thoroughly mixed together by hand turning. A total of 195.46 grams of KEECO's KB Sea dry reagent was added to each batch. Four kilograms from each of three batches was loaded into columns. The fourth batch was reserved for physical and chemical investigations, SPLP and humidity cell testing on treated material.

The three in situ treatments on mercury ore material were each applied to four columns, again to provide triplicate samples and an additional quantity of treated material for physical and chemical investigations, SPLP and humidity cell testing. In situ application was accomplished by loading the material into the columns in "lifts" of approximately 5 to 7 inches, with first and last lifts having somewhat more variability in depth. As each lift was placed, a liquid form of the reagent was added by the use of a garden sprayer, which allowed the solution to be injected into the material. This procedure was repeated until four kilograms had been treated in each column.

E&C Williams provided the ENTHRALL® reagent in a concentrated form, which was diluted with three parts deionized water to one part product. The four treatment columns with mercury ore material were each loaded in seven lifts. A total of 300 ml treatment solution was applied to each column as described above.

Phosphate treatment was provided in liquid form and was diluted with one part deionized water to three parts phosphate. Four columns were loaded with mercury ore material and treated in six lifts, as described above and 300 ml of the diluted phosphate was applied to each column.

KEECO's KB-1 product was applied to the mercury ore material for the in situ treatments. The reagent was applied as-supplied, with 1,184 ml being applied to each 4,000 gram column load. The first and last lifts were 3 inches deep, with intermediate lifts being 6 to 6.5 inches thick. Again, four columns were treated in this manner to allow for leachability testing in triplicate and enough treated material for further testing.

Since testing on the waste rock material was secondary to testing on the mercury ore, a less intensive regimen was prescribed. Columns were loaded and treated as above for leachability testing, but instead of treating an entire column to provide SPLP and laboratory analysis, a small amount of material was treated. A 500-gram sample of material was placed in a 500-ml sample jar and treated with the same ratio of reagent to material as was used in the columns with mercury ore material.

Two columns were loaded with waste rock material and treated with E&C Williams' ENTHRALL® process as described above. As with the mercury ore material, each column was loaded with 4,000 grams of material and treated with a total of 300 ml ENTHRALL® solution. A 500-gram portion of the material was treated with 37.5 ml ENTHRALL® for SPLP and laboratory analysis. The phosphate product was demonstrated on the waste rock material in the same manner, with the same quantities being applied. Products were diluted as described for mercury ore material above.

The KEECO treatments on the waste rock material were only tested in one column each. For the ex situ application, 217.84 grams of KB-Sea was mixed into 4,000 grams of waste rock material, and loaded into a column. A 500 gram portion was treated with 27.23 grams of reagent for lab analysis. In situ treatment of the waste rock material was performed by loading the column in lifts, as previously described, and applying KB-1 reagent to each lift. The initial and final lifts were three inches deep, with intermediate lifts being 6-6.5 inches thick. A total of 1,305 ml of KB-1 was applied to the column.

Three columns were each loaded with 4,000 grams of mercury ore material and two columns were loaded with the same amount of waste rock material. These were the experimental controls for the testing that was to follow.

Kinetic leach testing was then used to determine the success of the treatments. Deionized-distilled water, pH adjusted to 5.0, was applied at a constant rate of 0.09 L/hr, with leachate being collected weekly. The original design called for leaching to continue for a minimum of 8 weeks. The entire volume of effluent was collected and mixed weekly. After recording the volume, the effluent was taken to the lab where measurements of turbidity, pH, conductivity and redox potential were taken. Approximately 3 to 4 liters of leachate was then filtered through a 25μm filter for analysis of mobile mercury and through a 0.45μm filter for dissolved mercury analysis. Unfiltered samples from weeks 1, 4 and 8 were analyzed for total mercury to provide data on the relationship between total, dissolved and mobile mercury. Where necessary to satisfy secondary parameters, additional analysis was also performed, as detailed below.

After the initial eight week leach period, the columns were allowed to rest for four weeks. This was intended to simulate a drying period during which oxidation reactions would naturally occur in a dump or pile. If the mercury leachability was due to chemical reactions, there should have been a peak in mercury when leaching was restarted. Following the rest period, one column of each treatment type and one control was leached for another four weeks.

The column studies on the waste rock material were similar to the mercury ore column studies with the exception that the KEECO treatments were tested on only one column each and E&C Williams' columns and the phosphate columns were run in duplicate. The waste rock material control columns were also run in duplicate. Application rates and sampling were identical to the study on the mercury ore material.

In addition to mercury analysis, weekly samples were analyzed for sulfate, sulfide, alkalinity and acidity to satisfy secondary objectives. Sample splits for weeks 1, 4 and 8 were also analyzed for the metals antimony, arsenic and iron.

4.3.2 Humidity Cell Tests

"Humidity cell" testing, detailed in ASTM D 5744-96, is a protocol designed to meet kinetic testing regulatory requirements for mining wastes and ores. In this test method, the sample is subjected to alternate periods of dry air, moist air and water leaching in an effort to simulate the weathering process that the ore would undergo in a natural environment. The rigorous conditions applied in the test design subject the material to potential worst-case scenarios in that the extreme changes from moist to dry air and complete wetting of the ore.

For the treatability study, humidity cell testing was performed on the mercury ore material only. A 1,000 gram aliquot of each of the treated materials and the untreated material was placed in each cell. To perform the initial leach, one liter of deionized water was slowly added to each in a manner that would avoid hydraulic agitation. The flooded sample was allowed to sit for one hour, and then the cell was drained overnight into a sample collection vessel. Dry air was then introduced into the cell at a rate of two to three liters per minute for three days. This was followed by a wet air purge for the following three days. Wet air was created by using a humidifier with DI water at a temperature of 30± 2°C. The wet air was supplied for three days at approximately the same rate. The first week's testing was completed by a Deionized water leach, as described above. The cycle of dry-air purge, wet-air purge and water leach was repeated weekly for a total of seven weeks after the initial water leach. Leachate was collected and analyzed for dissolved and mobile mercury, pH and turbidity, sulfate, sulfide and acidity/alkalinity.

4.3.3 Mineralogical and Geochemical Tests

Mercury ore and waste rock samples were analyzed for mineralogical parameters by optical microscopy, x-ray diffraction (XRD) and x-ray fluorescence (XRF) in the Department of Earth and Atmospheric Sciences at the City College of New York (CCNY).

X-ray diffraction is a technique for gathering information about the structural state, including the degree of crystallinity of the materials in a sample. At the CCNY lab, the samples were pulverized in an agate mortar and pestle and mixed with a lanthanum boride standard. The samples were then mounted on a quartz non-reflecting holder and step-scanned at 0.02 degrees two theta over the appropriate range at 40kv/20 milliamps with a counting time of 1-4 seconds per step. For unit cell refinements, peak locations were obtained using a Philips APD package for single peak fits, or by a modified Pearson-VII peak fitting or related algorithm. Upon correction for peak position error, reflections were analyzed for unit cell parameters using either a Philips unit cell program or an in-house program that provides estimations of cell axes and angles and standard errors. For mineral identification, peak positions were obtained using the Philips APD package for fitting all spectral positions.

Samples were prepared for analysis by x-ray fluorescence by pulverizing under methanol in an agate mortar and pestle to a grain size of less than 50 microns. The pulverized material was then mixed in a 40:60 (rock:flux) ratio with lithium tetraborate and fused at 1000 degrees centigrade for 20 minutes. The material was then poured onto a hot aluminum plate and pressed into a pellet, approximately 0.6 inches in diameter. The pellets were epoxyed into one inch cylindrical holders leaving a glass face exposed. The glass is polished to a smooth face using silicon carbide polish, then corundum, and finally diamond micro-polish. For quantitative analysis, an automated Philips 1400 series x-ray fluorescence spectrometer was used under standard conditions, typically 50kv 50 ma for 50-100 seconds. Oxide values were determined using linear least squares corrections of data. Semi-quantitative XRD was also performed on samples that had been pulverized as above, then dispersed in distilled water and collected on 0.2 or 0.4 µm polycarbonate filters. The dried filters were then pressed into borax holders at about 20 tons pressure. The samples were analyzed using the spectrometer and compared to linear least squares corrections based on USGS pellets and standard analyzed minerals.

4.3.4 Humic/Fulvic Acid Tests

All natural environmental systems contain some amount of decomposed plant and animal matter called humus. The soluble portion of humus is called humic acids, and is further broken down into three fractions: humic acid, ulmic acid and fulvic acid. Humic acid is a long chain molecule, high in molecular weight, dark brown and soluble in alkaline solutions and is insoluble in water, acids, ethanol and acetone. Fulvic acid is a short chain, low molecular weight molecule. It is soluble in acid, alkali and water and is waste rock in color.

Mercury and methyl mercury bind strongly to soil and sediments by forming strong complexes with organic substances, including humic acids. Previous studies have indicated that humic and fulvic acids dissolve mercury from cinnabar in the environment, and subsequently release it into aqueous systems. Vegetative caps can be used on tailings and piles to inhibit the downward migration of meteoric waters through evapo-transpiration, and help stabilize the pile from erosion and collapse. A vegetative cap may produce these organic acids, which could then seep down and mobilize mercury in the underlying material.

In order to determine whether this would be a concern at SBMM if a vegetative cap would be considered, a supplemental test was added to the original experimental design. The additional test for humic/fulvic acid leachability was a modification of the MWMP described earlier. The design used glass columns 50 cm tall and 2.5 cm in diameter. Five identical columns were loaded with untreated mercury ore material. Three of these columns were leached with a synthetic dissolved organic carbon mixture consisting of 20 mg/L of humic acid and 10 mg/L of fulvic acid in deionized water. To ensure complete dissolution of the acids, the pH of the solution was brought to 9.0 with a sodium hydroxide addition, and then adjusted to a pH of 6.0 by adding acetic acid. The remaining two columns were leached with deionized water adjusted to a pH of 6.0 as a duplicate control. The 1:1 ratio from the MWMP was maintained, so the design called for the columns to be slowly leached with one solution volume equaling one material volume over each 24-hour period. The columns were loaded with 150 grams of material.

Leachate was collected on days 3 and 7 and then weekly for weeks 2, 3 and 4. The entire volume of leachate was collected, mixed and filtered. Each sample was analyzed after filtration through 25μm and 0.1μm with additional filtration at 0.45μm performed on day seven and week four. Turbidity and pH were measured immediately after each sample was filtered.

4.4 Results

Results are presented in this section for each set of tests.

4.4.1 Kinetic Column Study Results

The column studies were the primary leaching method to evaluate the effectiveness of the stabilization technologies on SBMM material. In particular, column tests using the mercury ore material were used to evaluate the primary objective, i.e. 90% reduction in the cumulative mass of mercury leached from the <25μm fraction relative to the control columns. Column study results will be presented individually for the mercury ore and waste rock material.

4.4.1.1 Column Studies on Mercury Ore Material – Primary Objective

Overall, the column studies using the mercury ore material enabled a quantitative evaluation of treatment effectiveness. Variability between the triplicate columns was low and detectable levels of mercury were encountered in all effluents from the control and treatments.

Evaluation of the primary objective for each technology consisted of summing the total mass of mercury leached from the <25μm fraction (volume *x* concentration) from an average of the triplicate columns over the 12-week test and comparing to the mass of mercury leached from the control column. For definitional purposes, this fraction is considered the "mobile" fraction based on previous studies that demonstrated the potential for particulate (colloidal) transport. In addition to calculating the mobile fraction, the "dissolved" fraction was determined by using data from the <0.45μm analyses, as well as calculating the "particulate" fraction as the difference between the <25μm and <0.45μm fractions.

Table 4-9 presents a summary of the total mass (in micrograms) of mercury leached for each treatment and the control over the 12-week testing period on the mercury ore material. The table shows the mercury mass of the <25μm filtered (mobile), the <0.45μm (dissolved), and calculates the particulate fraction (as the difference between the <25μm and <0.45μm fractions). The last column shows the calculation for the % difference in mass of mercury of the mobile fraction for each treatment relative to the control column. Figure 4-4 is a graphical presentation of the data presented in Table 4-9. The graph shows the mobile fraction leached and illustrates the contribution of the particulate and dissolved fractions.

Table 4-9. Total Mass Mercury Leached from Mercury Ore Columns Over Twelve Weeks

Treatment	**Mass Hg (µg) Leached** <25µm (Mobile)	**Mass Hg (µg) Leached** <0.45µm (Dissolved)	**Mass Hg (µg) Leached** 0.45µm to 25µm (Particulate*)*	**% Difference Relative to Control** <25µm Fraction (Mobile)
Control	12,509	488	12,021	
Phosphate	131,018	74,211	56,808	947%
E&C Sulfide	13,836	731	13,105	11%
KEECO In Situ	1,532	1,452	80	-88%
KEECO Ex Situ	1,723	1,650	72	-86%

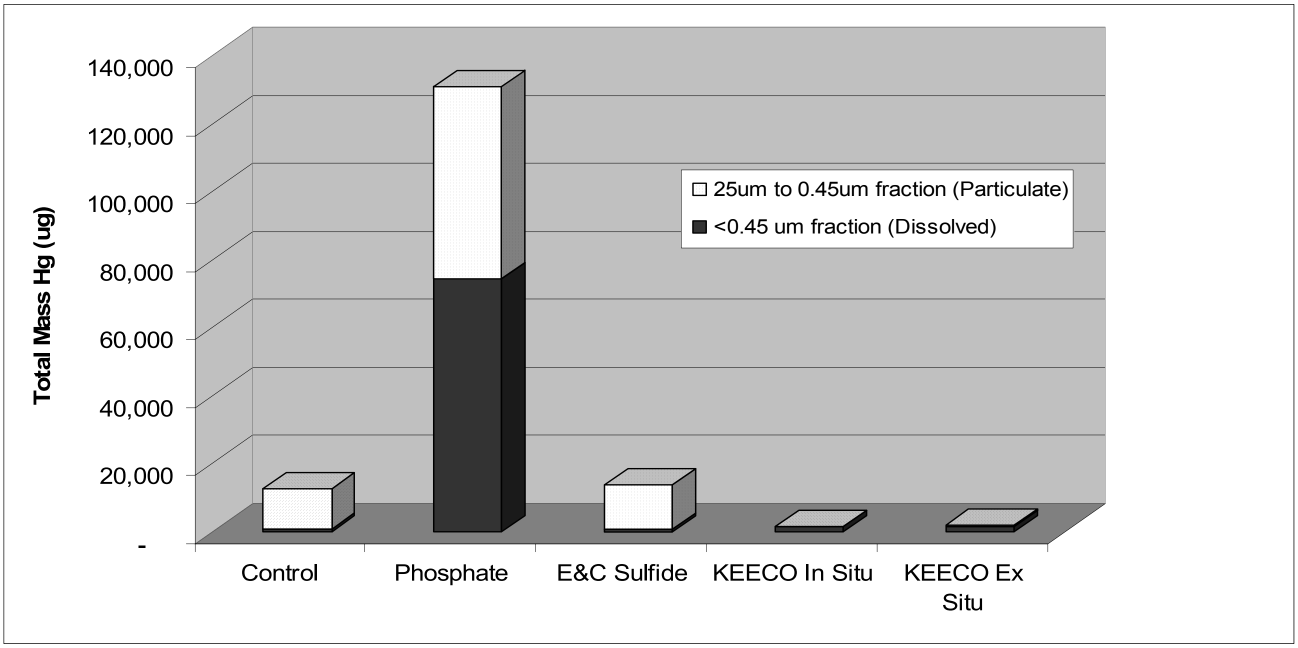


Figure 4-4. Comparison of the total mass mercury leached from the mercury ore columns.

Table 4-10 presents the leachability data for each week of the 12-week test period. The table shows the mass of mercury (in micrograms) leached from the control and treatment columns during each week of leaching for both the particulate fraction (25µm–0.45µm) and the dissolved fraction (<0.45µm).

A discussion of the results from the control columns and each set of treatment columns are presented and discussed relative to the primary objectives. Observations of the technology's performance and applicability to SBMM material are made when appropriate.

Table 4-10. Mercury Ore Leachability Results By Week

Week	Treatment	Average Whole Rock Hg Concentration (mg/Kg)	Mercury Mass Removed (µg)	
			Particulate 25µm -0.45µm	**Dissolved** <0.45µm
Week 1	Control	1888	1276.3	14.6
	Phosphate	1830	48623.0	66318.0
	E&C Williams ENTHRALL®	1867	506.6	12.4
	KEECO SME In Situ	2101	19.8	92.1
	KEECO SME Ex Situ	2066	6.1	16.0
Week 2	Control	1888	671.7	15.1
	Phosphate	1830	2933.1	3078.3
	E&C Williams ENTHRALL®	1867	495.7	19.2
	KEECO SME In Situ	2101	14.6	149.5
	KEECO SME Ex Situ	2066	1.5	193.7
Week 3	Control	1888	891.4	37.7
	Phosphate	1830	584.3	1563.1
	E&C Williams ENTHRALL®	1867	1054.3	38.2
	KEECO SME In Situ	2101	0.00	194.8
	KEECO SME Ex Situ	2066	0.00	266.4
Week 4	Control	1888	1477.5	52.9
	Phosphate	1830	738.8	954.5
	E&C Williams ENTHRALL®	1867	1668.0	85.1
	KEECO SME In Situ	2101	23.3	177.2
	KEECO SME Ex Situ	2066	33.5	222.0
Week 5	Control	1888	1559.3	67.3
	Phosphate	1830	592.4	509.4
	E&C Williams ENTHRALL®	1867	1392.5	106.1
	KEECO SME In Situ	2101	3.5	140.6
	KEECO SME Ex Situ	2066	0	170.5
Week 6	Control	1888	11196.0	40.7
	Phosphate	1830	657.5	359.0
	E&C Williams ENTHRALL®	1867	1688.8	99.7
	KEECO SME In Situ	2101	5.0	137.2
	KEECO SME Ex Situ	2066	5.8	155.1
Week 7	Control	1888	1050.3	56.9
	Phosphate	1830	NA	NA
	E&C Williams ENTHRALL®	1867	1761.0	86.7
	KEECO SME In Situ	2101	6.4	110.5
	KEECO SME Ex Situ	2066	1.9	129.0

NA = Not Analyzed

Table 4-10 continued. Mercury Ore Leachability Results By Week

Week	Treatment	Average Whole Rock Hg Concentration (mg/Kg)	Mercury Mass Removed (µg)	
			Particulate 25µm -0.45µm	Dissolved <0.45µm
Week 8	Control	1888	935.3	27.8
	Phosphate	1830	425.8	220.4
	E&C Williams ENTHRALL®	1867	1375.5	64.9
	KEECO SME In Situ	2101	8.8	101.5
	KEECO SME Ex Situ	2066	16.4	111.2
Week 9	Control	1888	915.0	55.5
	Phosphate	1830	912.6	452.4
	E&C Williams ENTHRALL®	1867	1248.5	60.5
	KEECO SME In Situ	2101	0.00	119.9
	KEECO SME Ex Situ	2066	4.4	128.5
Week 10	Control	1888	823.0	22.7
	Phosphate	1830	489.4	188.9
	E&C Williams ENTHRALL®	1867	707.2	31.2
	KEECO SME In Situ	2101	1.3	80.4
	KEECO SME Ex Situ	2066	0.0	93.9
Week 11	Control	1888	705.3	43.4
	Phosphate	1830	422.1	261.3
	E&C Williams ENTHRALL®	1867	620.6	56.2
	KEECO SME In Situ	2101	0.0	77.0
	KEECO SME Ex Situ	2066	0.0	84.7
Week 12	Control	1888	519.8	53.2
	Phosphate	1830	428.8	305.5
	E&C Williams ENTHRALL®	1867	586.1	70.6
	KEECO SME In Situ	2101	6.8	71.6
	KEECO SME Ex Situ	2066	6.0	79.5

NA = Not Analyzed

4.4.1.1.1 Control Column

Mercury leachability from the control columns was calculated as a comparative benchmark for the treatment columns as well as to elucidate potential leaching properties of the mercury ore material. The total mass of mercury leached from the control in the <25µm fraction was 12,509 µg over the course of the 12-week period. This was derived from the average of the three replicate columns. Overall, variability between the three columns was low with an average coefficient of variation (CV) of 30%. The CV is calculated as the standard deviation over the mean (as a percent), and is a normalized measure of the parameter's variability. The <0.45µm fraction exhibited a total mass mercury of 488 µg, and also exhibited a relatively low coefficient of variation of 36%. The calculated total mass mercury in the particulate fraction (25µm to 0.45µm) was 12,021 µg.

Detectable levels of mercury were encountered in all weekly effluent fractions with mass means (of the three columns) ranging from 573 µg to 1,627 µg for the <25µm fraction, and 14.59 µg to 67.31 µg for the <25µm fraction.

Figure 4-5 depicts the mass of mercury leached (particulate and dissolved) from the control columns (average of the three columns) over the 12-week test period. Overall, there are much greater levels of particulate-associated mercury in the leachate over the entire test period as compared to the dissolved mercury. After the fifth week of leaching, particulate mercury steadily decreased to week 12. The four-week rest period between weeks eight and nine did not significantly increase the mass of leachable mercury in either the particulate or dissolved fractions, suggesting that chemical oxidative processes are not enhancing mercury leachability with a water rinse.

The pH of the effluent over the course of the 12 weeks was relatively constant with a mean of 4.16 (CV=6.25%) and ranged from 3.54 to 4.52. The Eh of the solutions indicated oxic conditions throughout the test with a mean of 455 and a range from 384 to 500. There are no correlations between either the pH and leachable mercury or Eh and leachable mercury under the leaching conditions of this test.

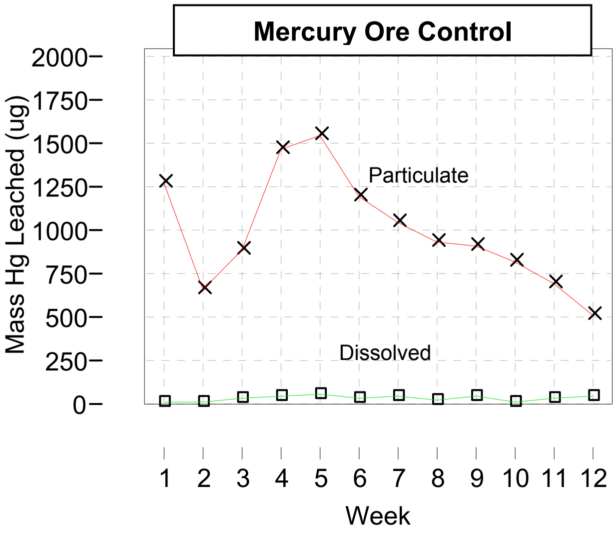


Figure 4-5. Dissolved and particulate leached Hg (mass) from mercury ore control columns.

As observed in the pre-demonstration studies, it does not appear that the <0.45µm fraction contains truly dissolved mercury. A plot of the turbidity vs. mercury concentration (Figure 4-6) of samples filtered through the 0.45µm filter reveals a general linear relationship. This suggests that the mercury from the control column leachates is associated with sub-micron particles, such as clays, which can transport the mercury as a colloidal suspension. This may have important implications in the transport and fate of mercury in the SBMM-Clear Lake system.

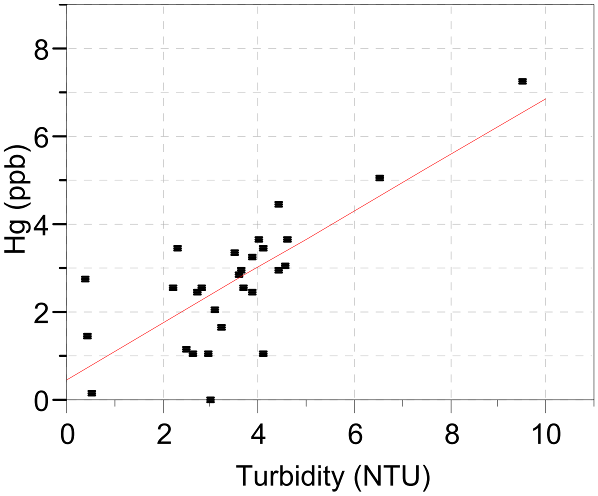


Figure 4-6. Turbidity vs. Hg for the <0.45µm fraction – mercury ore control columns.

4.4.1.1.2 Phosphate Treatment

The total mass mercury leached from the phosphate columns was compared to the control columns to evaluate the primary objective. The total mass of mercury leached from the phosphate treatment in the <25µm fraction was 31,018 µg over the course of the 12-week period. This represents a significant increase in leachability of 947% relative to the control. The overall variability between the three columns was low with a CV of 22%. The <0.45µm fraction exhibited a total mass mercury content of 74,211 µg over the 12-week test period. The overall variability between the three columns was low with a CV of 24%. The weekly average mass of mercury ranged from 646 µg to 114,941 µg for the <25µm fraction, and 189 µg to 66,318 µg for the <0.45 µm fraction. The calculated total mass of mercury in the particulate fraction (25µm to 0.45µm) was 56,808 µg.

The phosphate treatment dramatically increased the levels of both the particulate and dissolved fractions over the course of the12-week study. Figure 4-7 depicts the leachability profile over time for both the particulate and dissolved fractions. The mass of mercury leached was extremely high during the first two

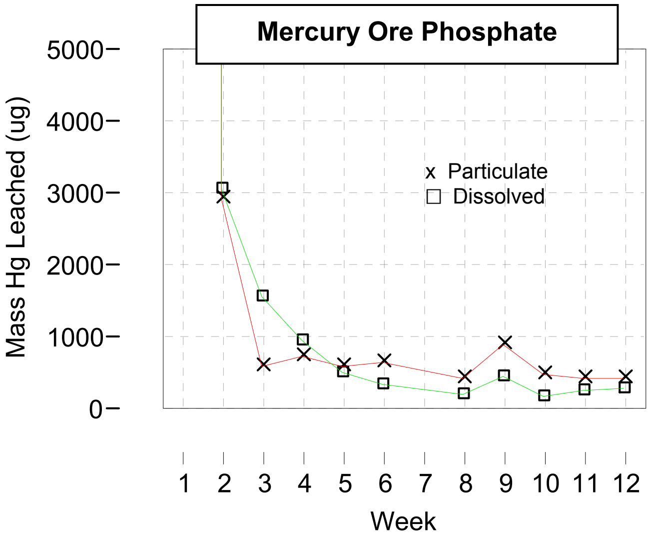


Figure 4-7. Dissolved and particulate leached Hg (mass) from mercury ore phosphate columns.

weeks, so these values are not shown on this graph in order to maintain scale for subsequent weeks. Although approximately 88% of the total leached mercury in both the dissolved and particulate fractions was leached out in the first week, significantly higher levels of mercury were still leached from the phosphate treatment during subsequent weeks as compared to the control. For example, from weeks 2 through 12 the total mass mercury leached from the phosphate treatment's dissolved fraction was 7,893 µg as compared to 473 µg from the control over the same period.

The pH of the solutions averaged 6.7 (6.38 to 6.87) and exhibited very low variability (CV=2%). The pH of the phosphate effluents was higher than the control. The average Eh of the solutions was slightly lower (338) than the control but still exhibited oxic leaching conditions. The Eh ranged from 166 to 420.

As with the control column, there is evidence that the mercury in the <0.45µm fraction is associated with sub-micron particles. This suggests that the phosphate treatment accelerated the breakdown of the mercury ore material matrix and facilitated the release of particulates. Therefore, it does not appear that the increase in mercury brought about by the phosphate treatment is due to true dissolution. The phosphate treatment greatly exaggerated the processes releasing mercury from the solid matrix.

The dramatic rise in leachable mercury brought about by the phosphate treatment invalidates its utility as a remedial alternative for materials at the SBMM site. Additional investigations could be carried out to determine the cause of the increased leachability for the purpose of identifying potential mechanisms that may be responsible for mercury leachability from SBMM (if occurring) and other mercury-bearing materials.

4.4.1.1.3 E&C Williams Sulfide Treatment

The total mass mercury leached from the sulfide treatment columns was compared to the control columns to evaluate the primary objective. Total mass mercury leached from the sulfide treatments averaged 13,835 µg in the <25µm fraction over the course of the 12-week study. This represents a slight, and statistically insignificant, increase in the leachable mercury. The overall variability between the three replicate columns was low, exhibiting a CV of 14%. The total mass of mercury in the <0.45µm fraction was 731 µg over the 12-week testing period, and exhibited low variability between the three replicate columns (CV=30%). The range of weekly mass mercury values was 515 µg to 1,847 µg for the <25µm fraction, and 12.41 µg to 106 µg for the < 0.45µm fraction. The calculated particulate fraction (25µm to 0.45µm) was 13,105 µg.

The mass of mercury leached over the 12-week period is depicted in Figure 4-8. As illustrated in the figure, the overall pattern and magnitude of mercury leachability is similar to the control. Furthermore, as in the control columns, it appears that the leachable mercury in the <0.45µm fraction is associated with sub-micron particles.

The average pH in the effluent over the course of the 12-week test was 4.01 (3.26 to 4.41) and exhibited a low CV of 8%. The Eh of the solutions indicated oxic conditions with an average value of 469 and a range of 469 to 507.

The E&C William's ENTHRALL® technology did not appear to be effective in reducing the levels of mobile mercury in the mercury ore material column tests. The total mass of mercury in both the particulate and dissolved fractions are statistically similar to the control. Furthermore, the temporal pattern and magnitude of mercury leaching between the control and sulfide treatment are similar. In addition, the association of mercury with particulates is very similar to the control. E&C Williams provides an explanation for their technology's performance in Section 4.51.

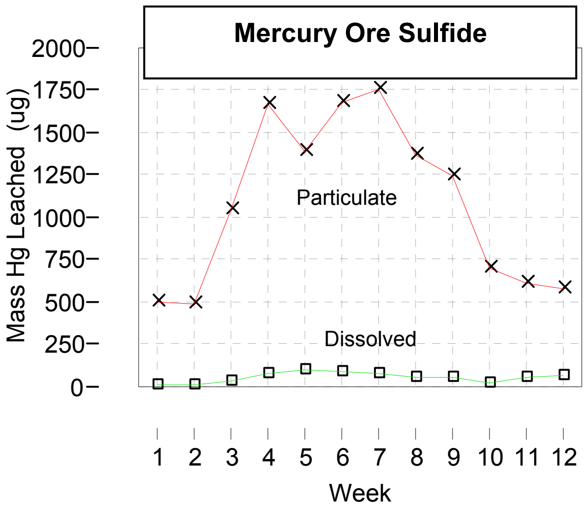


Figure 4-8. Dissolved and particulate leached Hg (mass) from mercury ore sulfide columns.

4.4.1.1.4 KEECO In Situ and Ex Situ

Both of the KEECO treatments (in situ and ex situ) will be discussed in this section, since performance results for both modes of treatment were similar. The total mass mercury leached from each of the KECCO treatment columns was compared to the control columns to evaluate the primary objective. Figures 4-9 and 4-10 present the temporal mass mercury leachability results for the in situ and ex situ columns, respectively. Note that the overall level of mercury leached was much lower than the control and other treatments, but unlike the other tests, the mass of mercury was much higher in the <0.45µm fraction (dissolved) than in the 25µm – 0.45µm fraction (particulate).

In general, both modes of application performed similarly in terms of levels and timing of mercury leaching. The total mass mercury leached in the <25µm fraction from the in situ and ex situ columns was 1,532 µg and 1,723 µg, respectively. This represents a reduction in leachability of 88% (in situ) and 86% (ex situ) as compared to the control. The overall variability between the three replicate columns for both applications was very low, 17% for the in situ and 12% for the ex situ. Weekly total mercury mass ranged from 76 µg to 201 µg for the in situ columns, and 22 µg to 265 µg for the ex situ columns. The <0.45µm fraction exhibited total mass mercury of 1,452 µg for the in situ, and 1,650 µg for the ex situ. This represents an overall increase in mercury for that fraction as compared to the control. Weekly mass mercury ranged from 71.55 µg to 195 µg for the in situ treatment and 16 µg to 266 µg for the ex situ treatment. Overall variability was very low with a CV of 16% for the in situ and 15% for the ex situ. The calculated total mass mercury in the particulate fraction (25µm to 0.45µm) was extremely low, i.e. 80 µg for the in situ treatment and 72 µg for the ex situ treatment.

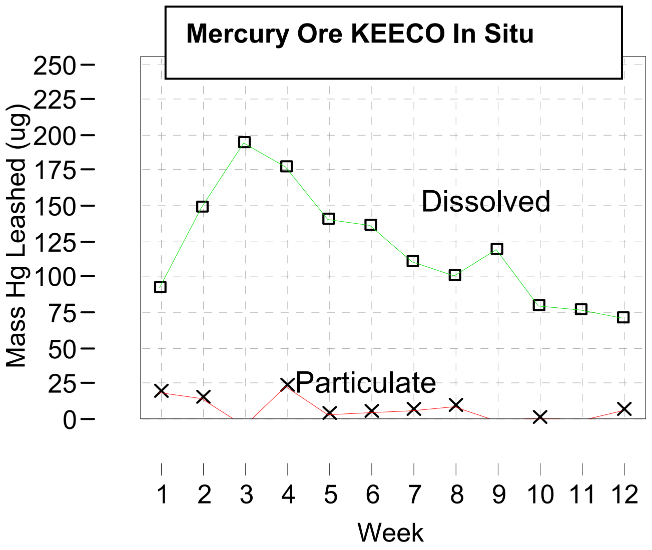


Figure 4-9. Dissolved and particulate leached Hg (mass) from mercury ore KEECO in situ columns.

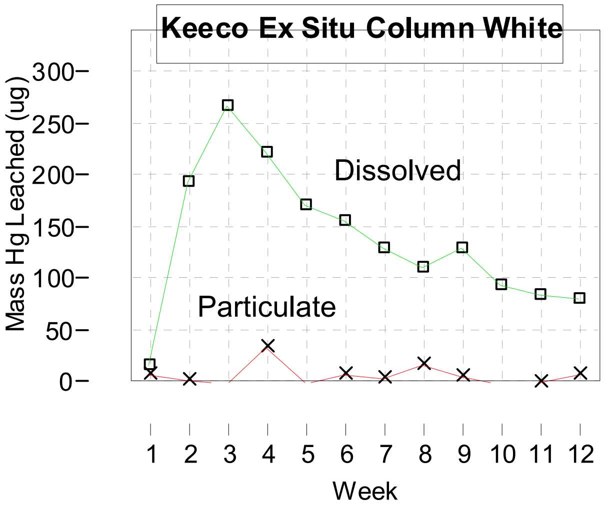


Figure 4-10. Dissolved and particulate leached Hg (mass) from mercury ore KEECO ex situ columns.

KEECO's Silica Micro Encapsulation Technology applied both in situ and ex situ, was effective in reducing mobile mercury (<25µm) very close to the 90% reduction goal of the study. Furthermore, the process was very effective in reducing the generation of mercury associated with the particulate fraction (25µm to 0.45µm). Both the in situ and ex situ treatments achieved a 99% reduction in particulate-associated mercury relative to the control. However, there was a significant increase in the mass mercury levels in the dissolved fraction (<0.45µm). The in situ applications exhibited a 198% increase relative to the control, and the ex situ exhibited a 238% increase. The form of mercury in this fraction for the KEECO treatment appears to be in a truly dissolved state as compared to the nano-particulate nature of the <0.45µm fraction from the control columns. This is based on the relationship between mercury concentration and turbidity in the <0.45µm fraction for the KEECO treatments and control as depicted in Figure 4-11. For the control (and for the other treatments), there is a general linear relationship in which the samples with higher mercury concentrations exhibit higher turbidity (presence of particles). It is postulated that the mercury in these effluents are associated with sub-micron particles (such as clays) that carry the mercury in the interstitial layers. The KEECO effluents from the <0.45µm fraction exhibit higher mercury with little or no turbidity, indicating that the mercury is not associated with sub-micron particles and is in a truly dissolved state.

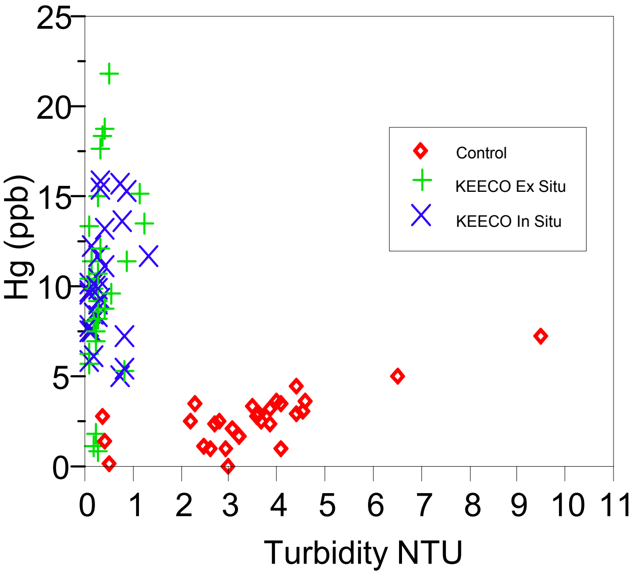


Figure 4-11. Turbidity vs. Hg for the <0.45µm fraction – mercury ore, KEECO and control columns.

The increase in the dissolved mercury concentration (relative to the control and other treatments) may be due to the elevated pH in the KEECO effluents. Figure 4-12 depicts the pH results from the KEECO effluents and the control effluents over the 12-week test period. As illustrated in the graph, the pH of the control effluents maintained a near constant pH of around 4 over the course of the study. Both of the KEECO treatments effluents' pH was elevated relative to the control, starting out at approximately 12 and stabilizing to around 9. Furthermore, after an initial drop after the first two weeks, the pH did not decrease over the duration of the study. This indicates that the KEECO treatments permanently modified the geochemical properties of the mercury ore material. The increase in dissolved mercury due to the elevated pH is supported by an Eh/pH leaching study on SBMM material[1]. The study demonstrated that alkaline conditions favored the dissolution of mercury. The maximum solubility occurred between a pH of 10 to 10.5. Furthermore, the addition of iron (in the form of ferric nitrate) inhibited the solubility of mercury at all pHs.

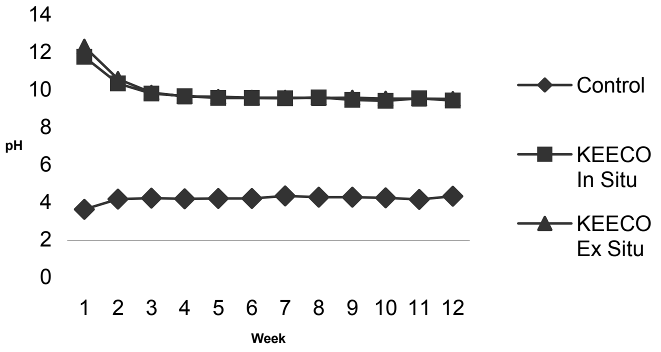


Figure 4-12. pH of KEECO and control column effluents – mercury ore material.

The data from the column studies suggests that two mercury mobilization/immobilization processes are occurring due to the KEECO treatments. The treatment was effective in inhibiting the generation of particulate associated mercury, which under the leaching conditions in the control test, is the dominant mercury mobility mechanism. The control of the generation of particulate associated mercury is probably due to the physical stabilization and binding of the matrix. However, due to the elevated pH brought about by the treatment, a chemical reaction dissolved a portion of the mercury. It

---

[1] Characterization and Eh/pH Based Leaching Tests of Mercury-Containing Mining Wastes from the Sulfur Bank Mercury Mine, Lake County, California. EPA/600/R-02/032, September 2001.

is important to note that the amount of mercury dissolved by the KEECO treatment is still significantly less than the mass of particulate mercury leached from the control. The KEECO treatment may have bound the matrix, thereby reducing the overall reactive surface area available for mercury dissolution. It is suggested that in order to inhibit the dissolution of mercury due to elevated pH, the vendor should consider iron amendments as part of their process for this material.

4.4.1.2 Waste Rock Column Studies

Results from the columns studies on the waste rock material are presented in Table 4-11. The whole rock mercury concentration in the waste rock was approximately one-half the levels in the mercury ore material, yielding lower levels of leachable mercury as compared to the mercury ore material. However, the levels of leachable mercury in the particulate fraction from the mercury ore material control columns were two orders of magnitude greater than from the waste rock control columns. This indicates that the waste rock may be less prone to releasing particulates when exposed to a leaching solution. The average pH from the waste rock control column leachates was 3.36 (3.06 to 3.61) and was lower than the pH from the mercury ore column controls (4.16). The Eh of the leachate solutions indicated oxic conditions throughout the 8-week period (mean=522, range 485-573).

Although there was significantly less mercury in the leachate from the waste rock column studies, the tests revealed similar technology performance results. The large number of non-detect values in the tests makes quantitative assessments and numerical comparisons difficult. However, a semi-quantitative discussion of each technology application follows.

A demonstrated in the mercury ore material columns, the phosphate treatment greatly increased the levels of mercury from the waste rock material (as compared to the control) in both the particulate (25µm to 0.45µm) and dissolved (<0.45µm) fractions. Since the phosphate treatment increased the level of mercury in the <0.45µm fraction (relative to the control), it was possible to evaluate the relationship between mercury concentration and turbidity. As depicted in Figure 4-13, there is a relationship between the mercury concentration and turbidity, indicating that leachable mercury in the waste rock material may also be associated with sub-micron particles. Therefore, it is concluded that the mercury generated from the waste rock material is associated with particulates. The pH of the weekly leachate samples averaged 4.99 (3.71 to 5.61), which was lower than the average from the mercury ore columns (6.7). The average Eh (383) indicated oxic conditions throughout the test and was similar to the average Eh of the mercury ore column leachates (338).

There appears to be minimal differences between the leaching characteristics of the E&C Williams Sulfide treatment and the Control for the waste rock material. However, the E&C Williams treatment may have slightly reduced leachable levels of mercury in both the particulate and dissolved fractions. This is indicated by the greater numbers of non-detect levels of mercury encountered in the E&C Williams treated waste rock material relative to the control. The pH from the weekly effluents averaged 3.25 (3.15 to 3.39), which was similar to the pH of the control effluents, and lower than the average weekly effluent of the treated mercury ore material (4.01). Eh conditions indicated oxic conditions throughout the testing period (mean of 534).

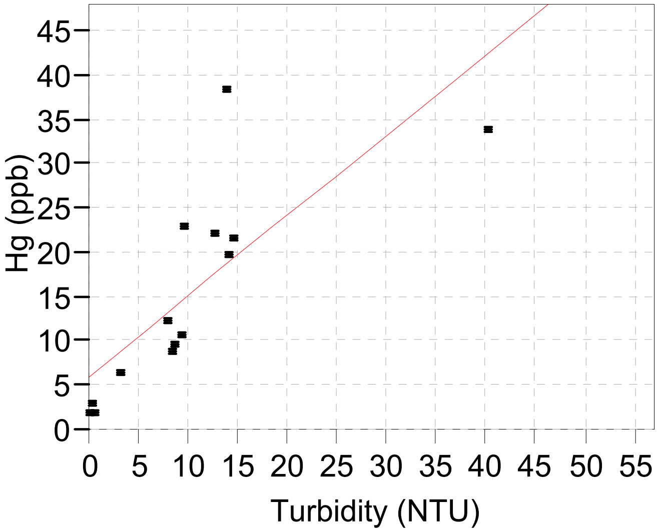


Figure 4-13. Turbidity vs. Hg for the <0.45μm fraction waste rock phosphate column.

The leachability characteristics of the KEECO treatments on the waste rock material performed similarly to the mercury ore material. As in the mercury ore material tests, the KEECO treatments reduced the levels of particulate-associated mercury in the leachate. However, due to low levels of overall particulate generation in the control columns, the magnitude of this reduction cannot be quantitatively assessed. As observed with the mercury ore material, the KEECO treatment increased the levels of dissolved mercury demonstrated by an increase in the mass of mercury

Table 4-11. Weekly Average Mass Mercury Leached from Waste Rock Columns

Week	Treatment	Average Whole Rock Hg Conc. (mg/Kg)	Mercury Mass Removed (µg) Particulate 25µm -0.45µm	Mercury Mass Removed (µg) Dissolved <0.45 µm
Week 1	Control	864	43.6	11.2
	Phosphate	889	411.7	35.8
	E&C Williams ENTHRALL®	976	55.9	19.5
	KEECO In Situ	776	16.3	60.2
	KEECO Ex Situ	900	1.3	23.8
Week 2	Control	864	3.3	2.4
	Phosphate	889	2772.2	172.1
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	18.3	75.0
	KEECO Ex Situ	900	0.0	58.6
Week 3	Control	864	1.9	ND
	Phosphate	889	4533.7	320.7
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	7.7	57.4
	KEECO Ex Situ	900	0.0	65.3
Week 4	Control	864	0.0	2.0
	Phosphate	889	2990.2	383.4
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	14.2	50.6
	KEECO Ex Situ	900	0.0	57.7
Week 5	Control	864	2.2	2.9
	Phosphate	889	1888.8	311.4
	E&C Williams ENTHRALL®	976	7.8	ND
	KEECO In Situ	776	6.3	42.4
	KEEC) Ex Situ	900	2.8	45.8
Week 6	Control	864	ND	ND
	Phosphate	889	514.9	128.2
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	1.5	42.7
	KEECO Ex Situ	900	1.4	43.2
Week 7	Control	864	ND	ND
	Phosphate	889	NA	NA
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	3.1	33.2
	KEECO Ex Situ	900	0.0	35.8
Week 8	Control	864	ND	ND
	Phosphate	889	1623.2	229.1
	E&C Williams ENTHRALL®	976	ND	ND
	KEECO In Situ	776	6.1	33.9
	KEECO Ex Situ	900	5.8	28.8

ND = Not Detected
NA = Not Analyzed

generated in the <0.45µm fraction. Due to the low turbidity in the leachate from the <0.45µm fraction (Figure 4-14), it appears that the mercury is truly dissolved and not associated with sub-micron particles. As seen in the mercury ore column tests, the KEECO treatment significantly increased the pH of the leachates from the waste rock material relative to the control. This pH increase may be responsible for the increase in dissolved mercury relative to the control.

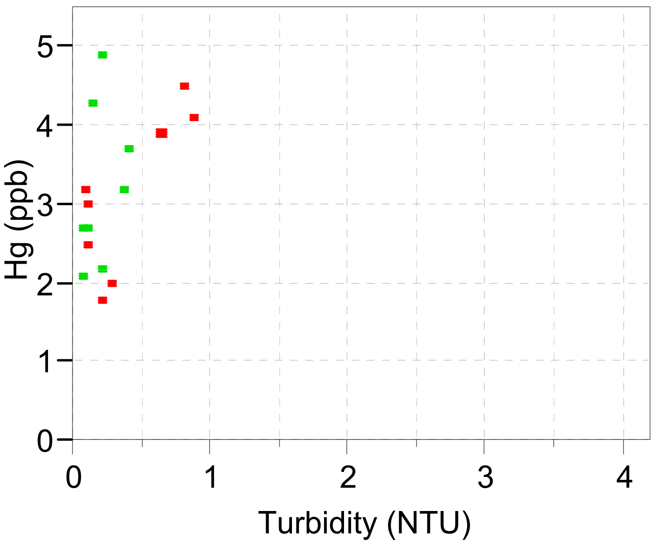


Figure 4-14. Turbidity vs. Hg for the <0.45µm fraction waste rock, KEECO columns.

4.4.2 Humidity Cell Tests

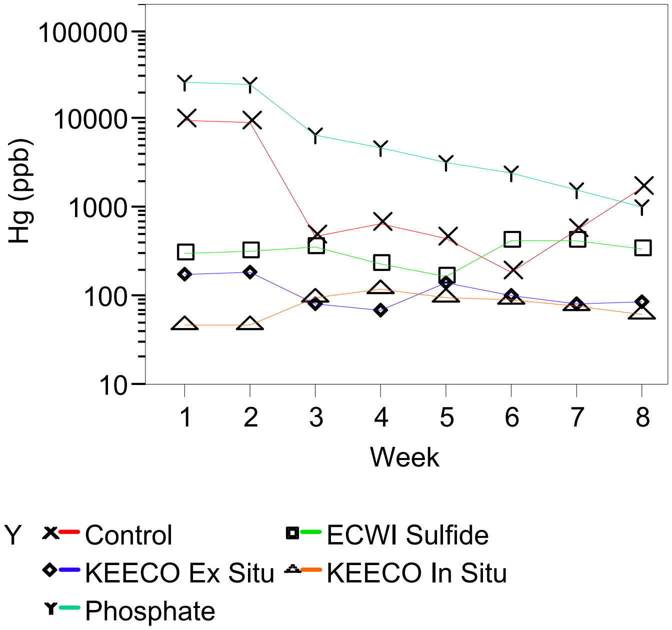


Figure 4-15. Results from Humidity Cell tests on mercury ore material - <25µm fraction.

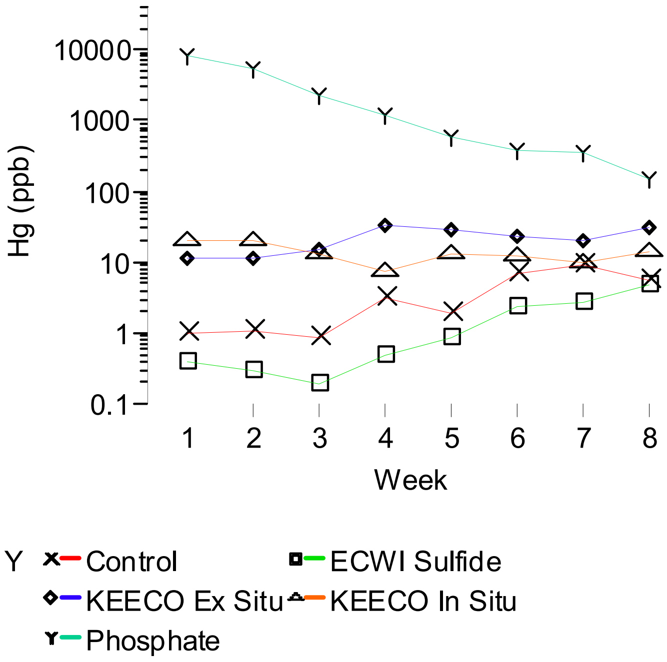


Figure 4-16. Results from Humidity Cell tests on mercury ore material - <0.45µm fraction

Results from the humidity cells on the mercury ore material generally agree with the column studies from both the mercury ore and waste rock materials. Figures 4-15 and 4-16 present the weekly results for the controls and each treatment for the <25µm and <0.45µm fractions, respectively. Note that due to the wide range in mercury concentrations, the Y-axis is presented on a logarithmic scale. As demonstrated in the previous tests, the phosphate treatment significantly increased the levels of mercury in the leachate relative to the control. Based on the humidity cell results, the E&C Williams sulfide treatment reduced the concentration of mercury in both the <25µm and <0.45µm fractions relative to the control. For the KEECO treatments, there is a reduction in the concentration of the <25µm fraction relative to the controls, and an increase in the <0.45µm fraction relative to the controls. This is consistent with previous findings in which the KEECO treatments (relative to the controls) reduced the levels of particulate associated mercury, but increased the amount of dissolved mercury in the leachate. As in the column tests, the KEECO process increased the pH of the effluents relative to the control columns. This increase in pH may be responsible for the increased levels of dissolved mercury (<0.45μm fraction). However, the KEECO process greatly reduced the generation of particulate-associated mercury, thus causing an overall reduction in the levels of mobile mercury (<25μm).

4.4.3 Synthetic Precipitation Leaching Procedure (SPLP)

SPLP tests were performed on un-treated and treated mercury ore material to evaluate the performance of the technology and to compare this widely used leaching procedure to the results of the column and humidity cell tests. Results from the SPLP tests are presented in Table 4-12**.**

Table 4-12. SPLP Results for Mercury Ore and Waste Rock Material

Sample	**Mercury Ore** (μg/L)	**Waste Rock** (μg/L)
Control 1 (untreated)	479	5.5
Control 2 (untreated)	6260	0.4
Control 3 (untreated)	224	
Control 4 (untreated)	2090	
Control Mean	***2263***	***2.95***
Phosphate 1	11900	3200
Phosphate 2	13100	
Phosphate Mean	***12500***	***3200***
Sulfide 1	2650	9.7
Sulfide 2	404	
Sulfide Mean	***1527***	***9.7***
KEECO In Situ 1	5	
KEECO In Situ 2	10	
KEECO In Situ Mean	***7***	Not Analyzed
KEECO Ex Situ 1	5	2.2
KEECO Ex Situ 2	10	
KEECO Ex Situ Mean	***7***	***2.2***

The SPLP results on the untreated mercury ore material (control) exhibit a wide range of values and are much higher than previously performed SPLP tests on material from the site. The SPLP results on the untreated waste rock material are low. The average SPLP value for the untreated mercury ore material is almost 1,000 times greater than the waste rock untreated material even though the whole rock mercury concentration of the mercury ore material is only two times higher than the waste rock material. Column and humidity cell leachability was also higher for the mercury ore material relative to the whole rock mercury as compared to the waste rock, but not as great as encountered in the SPLP tests. The high SPLP values in the mercury ore material may be due to the agitation during leaching which may be dislodging more mercury-bearing particles in the mercury ore material relative to the waste rock. This may be the case if the mercury in the mercury ore material is associated with fractures, which would be more prone to contact with leaching solutions under agitation.

As demonstrated in both the column and humidity cells, the SPLP results indicate a significant increase in mercury leachability after phosphate treatment for both the mercury ore and waste rock materials. For the sulfide treatment, the SPLP results do not indicate a statistically significant reduction in mercury leachability relative to the control for either the mercury ore or waste rock material. For the KEECO treatments, there is a significant decrease in mercury leachability relative to the control for the mercury ore material. Due to low and variable leachable mercury in the waste rock control, there is no demonstratable leachability reduction for this material.

Due to the high variability associated with leachability results from the SPLP test on the materials studied in this investigation, SPLP testing may not be a reliable measure of mercury leachability or technology performance. This may be due to the heterogeneous association of mercury in the materials, the agitation of the matrix during testing, and the relatively small sample size used for testing. If SPLP testing is used, several replicates may need to be analyzed and/or larger sample sizes may be used in order to minimize the variability.

4.4.4 Humic/Fulvic Acid Leaching Tests

A modified meteoric water mobility procedure (MWMP) continuous leaching test using a humic/fulvic acid solution (treatment) and a deionized (DI) water control was performed to determine the effects of plant derived high molecular weight organic acids on mercury leachability in mercury ore material from the SBMM site. A total of 5 columns were tested, three with the organic solution (containing humic and fulvic acids) as triplicate test columns and the other two columns as the DI water control columns. The MWMP utilized a 1:1 ratio of solid material to leaching medium (humic/fulvic acid or deionized water) placed in a column-type apparatus and continuously leached over a 4-week period. Samples were collected for mercury and other characteristics twice during the first week and on a weekly basis over the next three weeks. Leachate volumes were measured for each sample so that the mass of mercury leached could be calculated. The treatment solution contained 10 mg/L humic acid and 5 mg/L fulvic acid, adjusted to a pH of 6. The control solution consisted of DI water adjusted to a pH of 6. All samples were filtered through either a 25µm or 0.1µm filter to determine the relative amounts of mobile (<25µm) and dissolved (<0.1µm) associated mercury. Table 4-13 presents the results from the humic/fulvic acid leaching tests for the <25µm and <0.1µm fractions. A 0.1µm filter was selected for these studies (as compared to the 0.45µm in previous studies) to characterize more of the truly dissolved fraction. For each leaching interval the total mass in µg was calculated, as well as the average µg/day. The total mass of mercury (µg) was calculated for each treatment and control.

Table 4-13. Results From the Humic/Fulvic Acid Leaching Tests

	<25 Micron Fraction									
	HA/FA 1		HA/FA 2		HA/FA 3		Control 1		Control 2	
Days	ug	ug/day	ug	ug/day	ug	ug/day	ug	ug/day	ug	ug/day
1 to 3	114.89	38.30	16.06	5.35	150.55	50.18	83.26	27.75	114.74	38.25
4 to 7	75.33	18.83	67.94	16.99	151.28	37.82	97.09	24.27	109.95	27.49
8 to 14	42.44	6.06	120.29	17.18	249.73	35.68	509.86	72.84	212.55	30.36
15 to 21	50.55	7.22	100.87	14.41	129.50	18.50	86.35	12.34	134.53	19.22
22 to 28	77.91	11.13	33.64	4.81	197.93	28.28	120.46	17.21	88.14	12.59
Total	361.12		338.80		878.98		897.02		659.91	

	<0.1 Micron Fraction									
	HA/FA 1		HA/FA 2		HA/FA 3		Control 1		Control 2	
Days	ug	ug/day	ug	ug/day	ug	ug/day	ug	ug/day	ug	ug/day
1 to 3	0.58	0.19	0.89	0.30	1.28	0.43	5.41	1.80	4.29	1.43
4 to 7	0.75	0.19	1.38	0.34	12.37	3.09	11.69	2.92	13.72	3.43
8 to 14	2.88	0.41	2.94	0.42	13.93	1.99	43.32	6.19	67.67	9.67
15 to 21	4.43	0.63	19.65	2.81	9.91	1.42	11.70	1.67	10.52	1.50
22 to 28	3.64	0.52	0.70	0.10	2.70	0.39	7.03	1.00	5.59	0.80

No significant pattern of mercury release over time was observed for either the treated or control columns for both the fractions tested. Therefore, the results were grouped for the treatment and control for both fractions. Statistical analyses were performed to determine differences between the treatment and control for each fraction.

As with all previous leaching tests, the leachable mercury was predominately associated with the particulate fraction for both the humic/fulvic acid treated columns and the control. For the <25µm fraction, the average mass mercury was 105 µg for the humic/fulvic treated columns and 156 µg for the control columns. A Students t-test demonstrated no statistical difference between the mercury leached from the treatment versus the control for this fraction (Prob>t 0.2907). For the <0.1µm fraction, the average mass mercury was 5 µg for the humic/fulvic treated columns and 18 µg for the control columns. A t-test demonstrated a significant difference between the mercury leached in the treatment versus the control (Prob>t 0.0315). Therefore, for the SBMM mercury ore material tested under the conditions of the experiment, there was no increase in the particulate or dissolved mercury due to leaching with humic and fulvic acids. Furthermore, it appears that the humic/fulvic acids may have reduced the levels of dissolved mercury relative to the control. However, the overall levels of dissolved mercury leached from the mercury ore material were low as compared to the particulate-associated mercury. The higher levels of dissolved mercury in the control samples relative to the humic/fulvic acid treated samples may be attributable to differences in the pH of the effluent samples. The average pH of the control effluents was 6.31 as compared to a pH of 4.58 for the humic/fulvic acid treated material. As previously noted, an EPA study observed higher dissolved mercury with increasing pH.

The humic/fulvic acid tests also corroborated previous leaching experiments regarding the form of mercury leached from the mercury ore material. A plot of mercury vs. turbidity in Figure 4-17 reveals a linear relationship between turbidity (particulates) and mercury concentration. This relationship also extends to some of

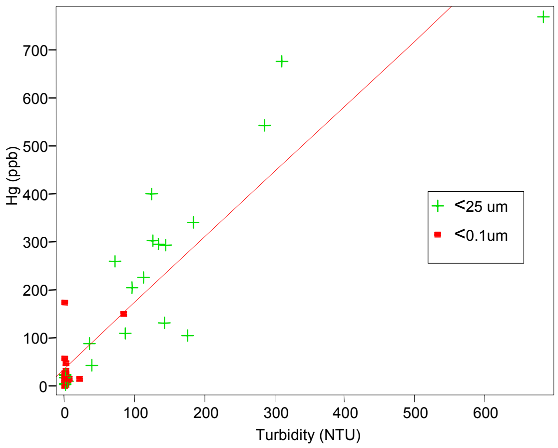


Figure 4-17. Turbidity vs. Hg from the <25µm and <0.1µm fractions from the humic/fulvic acid leaching tests.

the <0.1µm fraction samples. This is significant since several samples of the <0.1µm filtered leachates exhibited relatively high turbidities indicating the presence of sub-micron colloidal material. The correlation between mercury and turbidity further supports a release of mercury associated particulates as a leaching mechanism.

4.4.5 Geochemical and Mineralogical Analyses

Geochemical and mineralogical analyses were performed on untreated and treated mercury ore material by optical petrography and x-ray diffraction. The purpose of the analyses was to document any mineralogical or geochemical changes in the bulk properties of the mercury ore matrix attributable to the treatment technologies. Optical petrography and x-ray diffraction did not reveal any significant differences in the bulk mineralogy or geochemistry between the untreated and treated mercury ore materials examined. One noteworthy exception is higher phosphorus content in the phosphorous treated sample.

The examination did reveal some information relating to the mineralogical properties of the mercury ore material. Samples were sieved using a sequential stack of brass sieves in the order 500, 250, 150, 125, 63 microns. Petrographic examination reveals that the rock fragments are typical of an altered volcanic rock, comprising variably devitrified glass, secondary silica deposits, and siliceous aggregates with probable secondary sulfides.

The samples were further wet-filtered (10-44 micron fraction) with distilled water retaining more than 95% as sediment. The retained sediment was analyzed by x-ray diffraction to assess mineralogical characteristics. The x-ray diffraction revealed that only minor amounts of mineral are present in the bulk sample. Two phases of particular interest, quartz (peak at 26.64) and cinnabar (peak at 26.52) are not matched by the presence of a pronounced diffraction maxima. A minor broad peak may indicate the presence of one or both phases, but is not definitive. The presence of amorphous phases (glass, secondary silica, possible biogenic silica, and silica-bearing aggregates) is supported by the presence of a broad radial distribution.

4.5 Developers' Comments

The technology developers (E&C Williams and KEECO) were asked to comment on the performance of their processes based on the results from this treatability study. Their responses to this request are presented in this section. These responses do not reflect the views and assessments of either the Mine Waste Technology or SITE programs and are presented here as a courtesy to the technology developers.

4.5.1 E&C Williams' Comments

As we understand it, the KEECO system is one that microencapsulates the soil/rock particles, sequestering the leachable metals. Our calcium sulfide system is different because we effect a chemical change, forming metal sulfides which are insoluble and immobile. So, our chemistry is more dependent on the number and amount of metals in the soils. We had requested an assay or characterization of the soils in order to confirm our suspicions that the mercury ore soil contained more metals, and more of them, than the waste rock. We already knew from your work that the mercury content is greater in the mercury ore soils. Our chemistry reacts more on a "one-to-one" basis, making the dosage more critical than a gross encapsulation. Plus, all metals capable of forming sulfide compounds compete equally for the sulfide molecules. So, if a lot of iron is present, for example, that will "eat" the sulfides as readily as a regulated metal. This isn't unusual for remediation or treatment work where the chemistry is less dependent on encapsulation.

Our conclusion on the performance of the calcium sulfide system is that the dosage simply undershot the level of metals, and a larger dose is all that is necessary to achieve the desired results. We are comfortable with the application by injection, although we will recommend that the points of injection be slightly increased so as to slightly overlap the treated areas.

4.5.2 KEECO's Comments

Project Methods and Observations

In an effort to provide a comparison of in-situ treatment versus ex-situ treatment of the mining waste rock from the Sulfur Bank Mercury Mine Superfund site, KEECO performed two distinctly different process application techniques for the SITE project test program. The overall goals established by EPA were to demonstrate non-aggressive, realistic methods of chemical amendment into the mine waste while producing significantly decreased mercury mobility. Effectiveness would be verified throughout the series of tests outlined in the project Test Plan. Therefore, in truth, the challenge was not only one of demonstrating that the technology was able to achieve the goals of mercury stability under a variety of leaching conditions, but that it was able to do so using less-than-ideal techniques for chemical incorporation.

Project Approach

The SME product KB-SEA was utilized for these tests. For the ex-situ column samples, the dry chemical was evenly broadcast over the test material followed by gentle blending using a spoon to represent the type of mixing that may be expected through the use of an excavator to blend the material on site.

For the in-situ treatment, a slurry form of the product was prepared by mixing the dry chemical with deionized water. The untreated materials were loaded into the columns prior to chemical amendment. A pre-determined volume of chemical slurry was then applied to each column and allowed to infiltrate through the pore spaces. Although this technique is limited in its ability to make effective contact between the metal contaminants of concern and the reactive components of the SME chemical, the results proved better than anticipated, as outlined in Sections 2 and 3. Despite favorable results from these laboratory tests, KEECO believes that it is unlikely that the conditions present in the column would accurately represent the conditions encountered on-site using in-situ treatment techniques. Geochemical conditions and transport mechanisms in the waste piles are complex and not properly replicated in these laboratory test cells. As such, a pilot test on-site would be highly encouraged prior to full-scale treatment.

KEECO Objectives

In addition to the objectives of the study as outlined in the project Test Plan, KEECO established further objectives for the technology performance. They included:

- A comparison of in-situ versus ex-situ treatment for comparable trends, ability to control total metal contaminant release, stability under each of the project test methods and consistency of test results from column to column;
- Verification of previously established theories that materials treated with the SME Technology will exhibit greater stability over time.

While this project proved useful in assessing in-situ versus ex-situ chemical amendment and the ability of the process to withstand various leach test conditions, the tests will not however, demonstrate the optimum performance of the SME Technology when incorporated into materials using more aggressive mixing techniques. Therefore, the differences between optimum technology performance and performance as achieved with limited mixing cannot be assessed from this study.

Effectiveness of SME Technology Application - Mercury ore (Primary) Test Material

Despite the fact that the average whole rock mercury concentration of the KEECO sample materials were slightly higher (about 200 mg/kg) than the control, the sulfide and the phosphate samples, effectiveness of the SME application is evident as compared to results from all other tests.

When applied to the mercury ore samples, the SME chemical produced higher initial pH values than the established target end points identified by KEECO Lab for optimum performance. This suggests that the samples were slightly over-treated. This could be due to the mild mixing technique employed for the test, thus releasing unreacted chemical into the leachate rather than expending it in the reactive process typically accomplished through vigorous mixing. However, both the selected application techniques and the higher initial pH appear to have only minor impacts on sample stability.

Column Testing Observations

There are a number of observations that can be made from the column tests. Comparisons between in-situ versus ex-situ performance are discussed in Section 2.5. Overall, the SME treated columns achieved a significant reduction in leachable mercury as compared to the control columns. The objectives of the Test Plan were to achieve a 90% reduction in the cumulative mass of mercury in the test leachates relative to the control column leachates. For the in-situ columns, as observed in weeks 4, 8, 9 and 12, the total mass of mercury released was reduced by an average of 90.8% relative to the control, thus meeting the primary project objective. For the ex-situ columns, an average of 88.2% reduction of the mercury released into the leachate was observed relative to the control.[2] These figures were derived using the formula for %Hg reduction as outlined in the project Test Plan.

Another observation that can be made from the column testing is that the majority of the mercury released from the SME treated material was in a dissolved state. Therefore, while the unfiltered and 25µm fraction results are more favorable with SME, results collected solely from the 0.45µm fraction indicate that the SME columns leached a greater mass of dissolved mercury than both the control and sulfide treated columns. This is likely due to the method utilized to amend the samples, leaving some of the material untreated. Dissolved mercury will readily percolate under the influence of filtration due to precipitation from untreated material when the irrigation water is applied. Whereas, suspended particulates that may be liberated from the untreated material upon the outset of irrigation readily adsorb to neighboring silica-encapsulated materials before percolating completely through the column; thereby minimizing the release of mercury from the material that may not have received a thorough application of SME product. Typically, the goals of treatment for any project are to reduce the metal release to background levels. By week 12, after gradual improvement over time, the average mean concentration of dissolved mercury in the SME leachate was within 1.8 µg/L of the control columns.

As previously mentioned, one of the objectives that KEECO established for this study was to verify the theory that SME treated materials will exhibit increased stability over time. Results gathered from both the unfiltered and dissolved fraction data support this theory. In addition, the coefficient of variation improved over time, demonstrating the ability of the chemical to control the mercury release to consistent levels despite variations of total mercury present in the untreated material. This supports the prediction that material containing widely variable mercury concentrations or "hot spots" can be effectively treated with a single application of SME chemical to the entire material volume without having to separately treat the highly concentrated portions.

The drying phase that was undertaken between test weeks 8 and 9 did not show any significant impact on mercury stability in the SME-treated columns. A 1.5 µg/L increase in mean Hg concentration in the ex-situ columns was observed after the rest period, with a 4.6 µg/L increase evident from the in-situ columns. This suggests that the onset of irrigation after the drying period may have released a small amount of mercury into the leachate from the untreated material that may have been near the lower portion of the columns. As compared to the other test columns, the SME column increases were minimal, with a 19.1 µg/L increase from the control column, a 75.3 µg/L from the phosphate column and a 35.1 µg/L from the sulfide column. The minimal amount of total release evident from the SME treated columns suggests that a large contaminant plume is unlikely from SME stabilized materials after exposure to atmospheric oxygen.

SPLP Test Observations

The stability of mercury under static test conditions following treatment with SME was evident as compared to the control sample material. The control sample released a mean mercury concentration of 2143.6 µg/L, while the SME samples released 7.2 µg/L and 10.1 µg/L Hg, a 99.6% average decrease in leachable mercury relative to the untreated sample. The samples also exhibited greater than a 99% improvement in mercury stability relative to the sulfide and phosphate treated material.

Humidity Cell Test Observations

The released mercury in the humidity cell tests is primarily in a dissolved state. This is likely due to the limited mixing technique not allowing for effective contact and encapsulation of portions of the mercury-bearing material. Particulate or suspended mercury, if not encapsulated, will tend to adsorb to neighboring encapsulated material; therefore, the release of larger fraction particulate mercury is minimized. Even in this adsorbed state the mercury is quite resistant to leaching. This is evident when comparing the total mercury

---

[2] Week 1 results were not included due to the high variability of the results, suggesting that the reactive process was not yet complete. However, in week 1, the in-situ columns produced a 96.3% reduction in the mass of mercury release relative to the control; the ex-situ columns exhibited a 75.5% reduction.

released from the control, sulfide and phosphate cells to that released from the SME-treated cells. Although the dissolved mercury concentrations were slightly higher from the SME cells, the total mercury released in the 25 µm and 0.45 µm samples combined was much lower overall.

In-situ versus Ex-situ

Overall the SME Technology appears to be a viable option for stabilization of mercury in the mercury ore pile material, regardless of whether the technology is applied "in-situ" or "ex-situ." Both techniques exhibited comparable stability that remained consistent throughout the testing period. The greatest variations were observed within the data gathered during week 1 of the column tests. The in-situ columns appeared to release a much lower mean concentration of mercury immediately after treatment than the ex-situ columns (19.8 versus 125 µg/L respectively). However, from week 2 throughout the conclusion of the testing, the mean concentrations of mercury in the in-situ versus ex-situ samples were typically within 1 to 3 µg/L of each other. The robust nature of the technology reaction despite substantially different treatment methods is evident in these test results.

After the drying period between test weeks 8 and 9, the ex-situ columns produced slightly better results, with an increase in the mean mercury concentration of only 1.5 µg/L from week 8 to week 9. In-situ columns produced a mean mercury concentration increase of 4.6 µg/L over the same period. By the end of the 12-week testing period, when comparing mean concentrations of mercury evident in the leachate of the in-situ versus ex-situ columns, a difference of only 0.2 µg/L was evident.

With the exception of week 1 data, similar trends were also observed in regards to dissolved versus mobile, suspended mercury in the leachate. Of the total mercury released into the leachate, the majority of the mercury was present in the 0.45 µm fraction for both the in-situ and ex-situ columns.

Because contact between the metal contaminants of concern and the SME product is essential in order to achieve proper stability, effective mixing techniques are critical for the overall long-term stability of the treated substrate.

Effectiveness of SME Technology Application - Waste rock (Secondary) Test Material

Treatment of the waste rock pile test material with the SME chemical KB-SEA was conducted to replicate an ex-situ treatment method as well as an in-situ treatment method as outlined in Section 1. Initial results, based upon the pH of the leachate immediately after treatment, showed that the in-situ material successfully achieved the targeted pH end point of approximately 9.0. The ex-situ material appeared to be slightly overtreated with a pH of approximately 11.5 evident in week 1.

Since each test method involved treatment of only one column of waste rock pile material, statistical averaging and the ability to identify data spikes and anomalies cannot be accomplished.

Column Testing Observations

The SME treated waste rock pile samples all released a higher concentration of mercury into the leachate as compared to the control column results for all samples evaluated, with the exception of some of the week 1-leachate samples.

The liberated mercury evident in the SME column leachate appears to be predominantly in the 0.45 µm or dissolved fraction. This was also evident in the mercury ore pile testing.

Over the 8-week column test, a reduction in the concentration of the mercury in the leachate was achieved in the SME-treated columns, suggesting enhanced stability over time. However, the control sample leachate remained at or below the detection limit of 0.2 µg/L for the majority of the 8-week test period. While the SME treated materials never exceeded a mercury concentration of 6.1 µg/L in the leachate, the sulfide sample performed better with most of the samples at or below the detection limit. Unfortunately, since the control column also remained within detection limits for the majority of the sample testing, no technology could clearly be identified as successful for these tests.

The ex-situ and in-situ columns appeared to generate similar results after week 3, and by the conclusion of the 8-week test period, the concentrations of mercury were with 2-4 µg/L of each other.

SPLP Test Observations

The SME in-situ column material did not undergo SPLP testing. The ex-situ column test material performed better under SPLP test conditions than the control samples, the phosphate samples and the sulfide samples. However, the mercury leached from the control sample material (only 3 µg/L) was again quite low; therefore, no single technology could be identified as having achieved a significant reduction in the leachable mercury as compared to the untreated materials.

The results of the waste rock pile tests were fairly inconclusive, but suggest that further characterization of the waste rock pile material should be undertaken to determine whether chemical stabilization or any other treatment is warranted.

Section 5.0
Quality Assurance Summary

5.1 Introduction

Quality Assurance (QA) may be defined as a system of activities the purpose of which is to provide assurance that defined standards of quality are met with a stated level of confidence. A QA program is a means of integrating the quality planning, quality assessment, quality control (QC), and quality improvement efforts to meet user requirements. This includes all actions taken by project personnel, and the documentation of laboratory and field performance as specified in the QAPP. The objective of the quality assurance program is to reduce measurement errors to agreed upon limits and to produce results of acceptable and known quality. The QAPP specified the necessary guidelines to ensure that the measurement system was in control and provided detailed information on the analytical approach to ensure that data of high quality could be obtained to achieve project objectives. The results of the QA processes applied to the Suulfur Bank project are summarized below.

5.2 Conclusions and Data Quality Limitations

A review of the critical sample data and associated QC analyses was performed to determine whether the data collected were of adequate quality to provide proper evaluation of the project's technical objectives. The critical parameters included mercury in the leachates from the kinetic column studies. The results of the measurements designed to assess the data quality objectives are summarized below, along with a discussion of the impact of the data quality on achieving the project’s technical objectives.

Accuracy: Samples were collected and analyzed from each of the test columns over an initial 8-week period. Spiked duplicate samples were analyzed and recovery data were compared to the control limits established in the QAPP (80-120% recovery). All spikes (36 MS/MSD pairs) met QA objectives, as summarized below in Table 5-1. In addition, spiked blanks, or laboratory control samples (LCSs), also met recovery limits of 85-115%.

A select number of test columns were allowed to sit undisturbed for several weeks and the leaching process was then continued for an additional 4 weeks. These extended column leachate samples were also spiked, LCSs were analyzed and accuracy assessed. These data indicated as well that accuracy objectives were achieved, as noted in Table 5-2.

Table 5-1. Accuracy Data for Mercury for SBMM Column Leachates

Leachate Fraction	MS/MSD Average % Recovery	LCS Average % Recovery
Total	102	100
25µm filter	102	102
0.45µm filter	104	100

Table 5-2. Accuracy Data for Mercury for SBMM Extended Column Leachates

Leachate Fraction	MS/MSD Average % Recovery	LCS Average % Recovery
Total	107	106
25µm filter	100	102
0.45µm filter	100	104

Accuracy was further assessed through the analysis of second-source standards, or Initial Calibration Verification (ICV) standards. These standards were analyzed after each initial multi-point calibration curve and all ICV concentrations were within 10% of the “true” concentration, as required in the QAPP.

Precision of the mercury analyses was assessed by the Relative Percent Difference (RPD) between the spiked duplicate sample concentrations. Data quality objectives were established in the QAPP as RPD of less than 20%. All spiked duplicates, in both the original 8-week study and the extended study, had RPD values less than 10%, therefore data met the objectives for precision.

Sensitivity objectives in terms of detection limits and practical quantitiation limits were met for all samples.

Completeness objectives for the project were met. A few non-critical parameters were not analyzed for some leachates due to sample volume; this did not affect overall data collection efforts.

Comparability was addressed in the QAPP through the use of EPA approved methodology. Mercury was determined in accordance with SW846 Method 7470 for all critical column study leachates.

Representativeness refers to the degree with which a sample exhibits average properties of the site at the particular time being evaluated. This is assessed in part by the analysis of field duplicates, which also provide insight into the homogeneity, or heterogeneity, of the matrix. Field duplicate samples have inherent in the result combined field and analytical variability. Periodically throughout the 8-week column study, leachate samples were collected in duplicate. Mercury analysis of these samples indicated that reproducibility between the samples was within guidelines (RPD < 20%), with the exception of three duplicate leachate samples (see Table 2-3) filtered through 0.45 um filters that had RPD values >50%.