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Prepared for

Interim Pedricktown Site Group

FOCUSED FEASIBILITY STUDY
FOR
GROUNDWATER REMEDIATION

NL Industries Superfund Site
Pedricktown, New Jersey

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EXECUTIVE SUMMARY

The Focused Feasibility Study (FFS) Report describes current groundwater conditions at the NL Industries, Inc. Superfund Site (Site), located in Pedricktown, New Jersey, and potentially applicable techniques to address groundwater impacts. The FFS report provides a comparison of alternative groundwater treatment technologies that are anticipated to improve groundwater quality at the Site in relation to the pump and treat remedy previously selected in the 1994 Record of Decision for the Site.

The Site was formerly used by several companies for lead-acid battery recycling and secondary lead reclamation. The processes used in battery recycling and lead reclamation resulted in the release of acid from batteries and other materials. Some of the materials released contained lead and cadmium, which affected groundwater. The bulk of the lead and cadmium was adsorbed in soil. More than 150,000 tons of impacted soil was excavated, stabilized and disposed off-Site during the remedial action for soil that was completed in May 2003.

The remedial alternatives for groundwater evaluated in the FFS Report include the following:

- No Action;
- Monitored Natural Attenuation (MNA);
- Reagent Injection;
- Permeable Reaction Barriers; and
- Pump and Treat.

The remedial alternatives were evaluated using United States Environmental Protection Agency (EPA) criteria. The selection of technologies for evaluation was based primarily on the ability to implement the technologies, anticipated effectiveness, and projected cost.

1. INTRODUCTION

1.1 Purpose and Goal

The 1994 Record of Decision (ROD) [EPA, July 1994] documented the selection of a pump and treat remedy to address groundwater contamination; however, this portion of the 1994 ROD has yet to be implemented. The contaminated soil and sediment were addressed first. During the soil/sediment remediation, groundwater monitoring data continued to be collected. The data revealed significant reductions in lead and cadmium in groundwater, which are the primary contaminants of concern. Therefore, in 2006 the Interim Pedricktown Site Group (Group), which is a group of several PRPs, submitted a request to EPA to conduct a Focused Feasibility Study (FFS) to evaluate alternative remedies to the selected pump and treat remedy. The FFS for groundwater at the NL Industries, Inc. Superfund Site (Site) and the remedy evaluation process described in this document are consistent with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP).[1] As stated within the NCP, "[t]he purpose of the remedy selection process is to implement remedies that eliminate, reduce, or control risks to human health and the environment."[2] The goal of the process "is to select remedies that are protective of human health and the environment, that maintain protection over time, and that minimize untreated waste."[3] Thus, the FFS was performed to systematically evaluate potential alternative groundwater remedies for the Site, in relation to the pump and treat remedy previously selected for the Site in the 1994 ROD and ultimately to meet the objectives of the NCP.

1.2 Background Information

1.2.1 Site Description

The Site is located to the north of the Pennsgrove-Pedricktown Road, in Pedricktown, Oldmans Township, Salem County, New Jersey. The Site location is shown on Figure 1 and the Site overview is shown on Figure 2. The 44-acre (18-hectare) Site is bordered on the south by Pennsgrove-Pedricktown Road and is bisected by an active railroad (i.e., Conrail Right-of-Way). Approximately 16 acres (6 hectares) are located north of the railroad, including a closed, 5.6-acre (2.2-hectare) landfill operated and maintained by NL Industries, Inc. (NL Industries). The southern 28 acres (11 hectares) contain the former NL Industries process area and the NL Industries landfill access road. NL Industries maintains the closed landfill area and operates the leachate collection system.

The West and East Streams, which are reported in the ROD for the NL Industries Superfund Site to be intermittent tributaries to the Delaware River, border the Site to the west and east, respectively. These streams are also reported by the EPA to receive runoff

[1] 40 C.F.R. § 300 *et seq*.
[2] 40 C.F.R. § 300.430(a)(1)
[3] 40 C.F.R. § 300.430(a)(1)(i)

from the Site. Industrial properties are located east of the former NL Industries process area, as indicated in the Feasibility Study (FS) prepared by O'Brien & Gere Engineers, Inc. (O'Brien & Gere), of Edison, New Jersey [1993] for NL Industries. U.S. Route 130 is located north of the Site. Several residential properties are located adjacent to and west of the West Stream. Other properties in the general vicinity of the Site are used for commercial, residential, agricultural, and military purposes.

The Site is underlain by three hydrogeologic units: the unconfined (uppermost and water table) aquifer; the first confined aquifer; and the second confined aquifer. The unconfined aquifer is part of the Cape May Formation and averages approximately 20 feet in thickness. The unconfined and first confined aquifers are separated by a clay layer ranging in thickness from about 5 to 20 feet. The first confined aquifer exists approximately 50 to 70 feet below grade and is part of the Raritan Formation. The second confined aquifer is also part of the Raritan Formation. The first and second confined aquifers are separated by a clay layer of approximately 30 feet in thickness.

The unconfined aquifer has historically been subdivided into two zones; the shallow and deep zones. The terms shallow and deep relate to screened intervals of wells and not to geologic materials. Screen depths for monitoring wells in these zones range from approximately 5 feet below grade in the shallow zone to approximately 50 feet below grade in the deeper zone. Where two wells were installed as pairs, the shallower one was labeled shallow and the deeper of the pair was labeled deep. For purposes of evaluation herein, where a well is not installed as part of a pair it is grouped with either shallow or deep wells based on screen depth. A well is defined as a shallow well if the top of the screen interval is at or above mean sea level. A list of monitoring wells and their construction details (e.g., total depth, screened interval, etc.) is provided on Table 1.

1.2.2 Site History

The Site was used for lead-acid battery recycling and secondary lead reclamation between 1972 and 1984. NL Industries operated a secondary smelting, battery breaking, and lead recycling facility at the Site beginning in 1972. The process involved crushing of spent lead-acid batteries to separate the components of the batteries, draining the sulfuric acid from the batteries, and then processing the material for lead recovery at the smelting facility. According to the Remedial Investigation (RI) [O'Brien & Gere, 1990] and FS reports, wastes resulting from the battery-crushing operation and slag from the smelting process were disposed in the landfill located at the Site.

NL Industries ceased smelting operations in May 1982. In October 1982, NL Industries entered into an Administrative Consent Order (ACO) with the New Jersey Department of Environmental Protection (NJDEP) to remediate contaminated Site soils, paved areas, surface-water runoff, the on-Site landfill, and groundwater. In December 1982, the Site was placed on the National Priorities List (NPL) by the EPA. National Smelting of New Jersey (NSNJ) bought the facility and performed smelting operations at the Site between February 1983 and January 1984. NSNJ ceased operations in January 1984 and filed for bankruptcy in March 1984. In April 1986, NL Industries entered into an ACO with the EPA, in which NL Industries assumed responsibility for conducting, with EPA oversight, an RI and FS for the Site.

The EPA performed a multi-phased Removal Action at the Site beginning in March 1989. A total of five phases of work were performed including:

- Phase I - fence installation and encapsulation of slag piles;
- Phase II - additional encapsulation of slag and removal of 20 tons of material;
- Phase III - stormwater control improvements;
- Phase IV - slag bin retaining walls repair; and
- Phase V - removal of contaminated sediments from the West Stream.

Phase V of the EPA Removal Action was initiated in the fall of 1993 and was scheduled for completion in the summer of 1994.

Recognizing the size and complexity of the Site, the remaining remedial efforts were phased into two operable units (OUs), OU1 and OU2. While RI/FS activities were being performed, EPA completed a FFS for a portion of OU2, and issued a ROD (September 1991) and Explanation of Significant Differences for OU2. In response to a Unilateral Administrative Order (UAO) issued by EPA in March 1992, a group of PRPs commenced response activities for OU2. The response action for OU2, completed in September 1995, included off-Site reclamation of certain lead-containing materials, solidification/stabilization and off-Site disposal of slag and other materials, decontamination of building floors and surfaces, off-Site treatment and disposal of contaminated standing water, building demolition, and environmental monitoring. Activities related to OU1 are described below.

To evaluate the extent of contamination and remediation alternatives for the Site, O'Brien & Gere performed an RI [1990] followed by an FS [1993] on behalf of NL Industries. Based on these investigations, EPA issued a ROD in July 1994 that specified selected remedies for remediation of soil, sediment, and groundwater at the Site. In June 1996, the EPA issued an ACO for Remedial Design (RD), which directed the Group to design the remedy for OU1 which included soil, stream sediment, and groundwater, as specified in the ROD. The ACO included a Statement of Work that provided requirements for the pre-design investigation and RD activities.

The Group retained GeoSyntec Consultants (GeoSyntec) of Columbia, Maryland to perform a pre-design field investigation and develop the RD for the Site. The RD for soil and sediment was submitted to and approved by the EPA in January 2000. In February 2000, the Group retained ENTACT, Inc. to perform remedial activities for soil and sediment in accordance with the RD. ENTACT began performing the RA in June 2000. The RA was completed in May 2003. CSI performed quality assurance oversight of the RA activities along with a representative of the United States Army Corps of Engineers (ACOE), who represented the EPA's interests. The focus of the RA was to achieve the Remedial Action Objective (RAO) for the soil and sediment portion of OU1 which was to leave no greater than 500 parts per million (ppm) of lead remaining in Site soil and stream sediments. Actions taken to meet the RAO included the following:

- Excavation of soil with lead concentrations greater than 500 ppm;
- Removal of contaminated sediment containing lead concentrations greater than 500 ppm from the East Stream, West Stream and channel north of U.S. Route 130;
- Stabilization of the excavated soil and sediment; and
- Disposal of the stabilized soil and sediment in an approved off-Site disposal facility.

A total of 150,928 tons of treated soil and sediment were disposed of at the Gloucester County landfill, Cumberland County landfill and the Atlantic County landfill. The soil and sediment were treated on Site using either dolomitic lime or EnviroBlend. The landfills utilized the treated soil and sediment as daily cover. In addition, the concrete foundation from the former smelting facility was demolished and the concrete removed from the Site. Approximately 10,887 tons of concrete was shipped off-Site. Another approximately 182 tons of scrap metal, 35 tons of miscellaneous debris and 24 tons of decontaminated railroad ties were also removed from the Site during the RA. ENTACT documented the RA efforts in an Interim Remedial Action Report [ENTACT, July 2003].

Subsequent to the soil and sediment RA completion, CSI conducted groundwater monitoring events in January 2004 and April 2007. The sampling events were documented in two reports entitled *Groundwater Monitoring Report* produced by CSI in April 2004 and September 2007 (revised May 2008).

In addition to monitoring groundwater quality on the Site, CSI collected potable water samples from private wells at five residences and one commercial property located along Route 130 on four separate occasions (January 2004, April 2006, April 2007 and December 2010). After evaluating the December 2010 groundwater elevation data (shown on Figure 3), CSI confirmed that shallow groundwater in the vicinity tends to flow toward local surface water bodies as previously reported. These surface water bodies include the West Stream, East Stream and a series of wet areas located between the NL Industries landfill and properties along Route 130 (see Figure 3). CSI also noted evidence of a groundwater flow divide, which is a hydrogeologic barrier to shallow groundwater flow between the Site and the businesses and residences along Route 130. Therefore, constituents in groundwater at the Site are not likely to flow to the private wells along Route 130. Recent (2010) monitoring data further supports the presence of the groundwater flow divide.

Monitoring wells 13, 14, 15, 16, and 17 are located at the Site (Figure 3) in the area between the former operations areas and the residential and commercial properties located along Route 130. Groundwater samples obtained from the monitoring wells during the December 2010 groundwater sampling event were also analyzed for lead and cadmium as part of the on-going groundwater evaluation of the Site. Data obtained from the analysis of groundwater collected from monitoring wells 13, 14, 15, 16, and 17 during the December 2010 groundwater sampling event are provided on Table 2. As reported on Table 2, neither lead nor cadmium was detected at concentrations exceeding a New Jersey Groundwater Quality Standard (NJGWQS) in the groundwater samples from these wells.

1.2.3 Nature and Extent of Contamination

Soil and Sediment

As summarized in the ROD, the results of the RI revealed that lead was formerly detected in soil at concentrations up to 12,700 parts per million (ppm) within the NSNJ property limit and 1,770 ppm in soil located outside of the property limit. Although several other metals were detected in soil, lead was the most prevalent and was defined in the ROD as the primary contaminant of concern (COC) [EPA, 1994]. Lead concentrations in the East and West Stream sediments ranged from 5 to 59,700 ppm, [O'Brien & Gere, 1990]. The highest concentrations were detected in the West Stream sediment adjacent to the former facility.

Contaminated soil and sediment were excavated by ENTACT during remedial activities that were performed from 2000 to 2003. After remedial activities were completed, CSI conducted sediment sampling in the West Stream in November 2005 and supplementary sediment sampling in June 2006, April 2008, June 2010, and December 2010. The results of the sampling events were presented in separate reports submitted to EPA in January 2006, August 2006, July 2008, July 2010, and February 2010. Based upon these data, additional sediment containing lead concentrations greater than 500 ppm of lead will be removed from the West Stream to meet the RAO established in the 1994 ROD. However, based on the data, the concentrations of lead that currently remain in the shallow surface sediment of the West Stream at the Site have not impacted the groundwater. Sediment remediation is being addressed separately; therefore it is not included in this FFS Report.

Surface Water

During the RI, several inorganic constituents were detected in the surface water in the East and West Streams and in the channel north of U. S. Route 130 at varying, but generally low, concentrations. Lead, however, was detected in the surface water samples obtained from the East and West Streams, at concentrations ranging from 10 micrograms per liter (µg/L) to 2,200 µg/L in 1989 and at concentrations ranging from 4 µg/L to 206 µg/L in 1990. These concentrations exceeded EPA's Ambient Surface Water Quality Criterion of 3.2 µg/L for lead, which is the concentration that is estimated to be protective of aquatic life based on chronic toxicity. As noted in the ROD, the EPA anticipated that remediation of contaminated soil and sediment would also satisfactorily address lead in the surface water. Surface water and sediment are being further addressed through the separate sediment action referenced above.

Groundwater

The information presented in the RI indicates that the Site is underlain by three hydrogeologic units that were identified as the unconfined (i.e., water table) aquifer, the first confined aquifer, and the second confined aquifer [O'Brien & Gere, 1990]. In addition to on-Site groundwater monitoring, groundwater evaluations performed as part of the RI included sampling potable water from wells at residences along Route 130 to

the north of the Site in 1988 and 1989 by representatives of NL Industries, Inc. and the EPA. The results of the potable well sampling events indicated that the groundwater at the residences had not been adversely impacted.

The groundwater monitoring activities included in the RI were conducted in 1988 and 1989. At that time, fifty-two wells (on-Site and off-Site) were sampled, with the majority being sampled during both events. The groundwater samples were analyzed for antimony, arsenic, cadmium, chromium, copper, lead, selenium, chloride, sulfate, total organic carbon, and total organic halogens. A subset of forty-four monitoring wells was also analyzed for radiological parameters. Based upon the 1988 results, additional radiological and volatile organic compound analyses were conducted during the 1989 sampling in specific areas to further evaluate the 1988 data.

Site-related contaminants were detected in the groundwater of the unconfined aquifer at the Site during the RI and the data indicated that the contamination in groundwater was limited to the unconfined aquifer. The contaminants detected in the unconfined aquifer were comprised primarily of lead and cadmium; however, volatile organic compounds (VOCs) and radiological parameters were also detected in localized areas of the Site. Specifically, hydrocarbon-related compounds were detected in monitoring well SD and chlorinated compounds were detected primarily in monitoring well 11. The hydrocarbon and chlorinated compounds were anticipated to naturally attenuate in a relatively short time frame. The radiological parameter analysis did not indicate a radionuclide source at the Site as there was no clear pattern of radionuclide occurrence in the subsurface (O'Brien and Gere, 1990). Therefore, it was suggested that the radionuclide source may have been naturally occurring because of the detection of elevated gross alpha and beta activity adjacent to clay layers at the Site. Further study was recommended and performed and based on the results, radionuclides were eliminated as a possible contaminant of concern. The findings of the groundwater evaluations are described below.

During the RI, arsenic was detected at elevated concentrations in monitoring well 2R2. However, monitoring well 2R2 was located in the vicinity of leachate collection devices and leachate seeps related to the NL Industries landfill. The arsenic detected was believed to be related to landfill leachate, which contained high concentrations of arsenic. Subsequent improvements were made by NL Industries to the landfill, eliminating the seeps. Other metals detected in groundwater at lower concentrations included beryllium, chromium, copper, nickel, and zinc.

As part of the RD, the Group performed two phases of groundwater evaluations and reported the results to the EPA in *Phase I Groundwater Evaluation Technical Memorandum* (Phase I Technical Memorandum) [GeoSyntec, 1998] and *Phase II Groundwater Evaluation Technical Memorandum* (Phase II Technical Memorandum) [GeoSyntec, 2000]. The results presented in both documents support the findings that the area of impacted groundwater is stationary at the Site and that the mass of contaminants in groundwater is declining. The Phase I and II Technical Memoranda are incorporated herein by reference.

The Phase I evaluations were conducted in September and October 1997 and included the collection of twenty groundwater samples that were analyzed for sulfates, VOCs, semi-volatile organic compounds (SVOCs), total and dissolved metals, cyanide, and radiological parameters. All samples also were monitored for the water quality parameters pH, specific conductivity, oxidation-reduction potential, dissolved oxygen, and turbidity. The Phase I Technical Memorandum identified the relationship between pH and the presence of lead and cadmium in groundwater. It was noted that the lower pH groundwater historically contained more elevated concentrations of lead and cadmium.

The analytical results described in the Phase I Technical Memorandum indicated, in general, that the concentrations of COCs in groundwater at the Site decreased since the late 1980s when the RI was conducted. Specifically, lead concentrations in the central portion of the Site dropped significantly. In samples obtained from monitoring well KS, lead concentrations decreased from 3,130 µg/L to 328 µg/L and in the samples obtained from monitoring well SD, lead concentrations declined from 2,960 µg/L to 51 µg/L. Similar reductions in the concentrations of lead and cadmium were noted across the Site. Furthermore, it was noted that previously measured high concentrations of lead had not migrated to downgradient locations but instead remained in the central portion of the Site. A general decline in concentrations and limited migration were shown to be true for cadmium as well [GeoSyntec, 1998].

Through the Phase I and II evaluations, cadmium and lead were again found to be the only inorganic constituents that were detected at significantly elevated concentrations. Several other inorganic constituents were detected at isolated locations; however, they were not primary contaminants of concern. Based upon the Phase I data, it was recommended that the only inorganic constituents to be evaluated during the Phase II evaluations should be total and dissolved lead and cadmium.

The VOC and SVOC concentrations in groundwater reported in the Phase I Technical Memorandum were lower than the concentrations reported during the RI with the exception of a detection of vinyl chloride in the sample from well 12. The decreased concentrations for all other VOCs and SVOCs support the conclusion presented in the RI that these compounds would naturally attenuate. Because of the lack of detection of SVOC constituents, the Phase I Technical Memorandum included a recommendation that there was no need to analyze the groundwater for SVOCs during the Phase II evaluations.

The radiological parameter results presented in the evaluations performed and reported as part of the Phase I Technical Memorandum were equivocal as they contained a high degree of uncertainty (i.e. large margin errors). In general, the measured occurrence of radiological isotopes decreased from those measured in 1988 and 1989. However, because the data were equivocal, it was recommended in the Phase I Technical Memorandum that further evaluation of radiological parameters be included in the Phase II evaluations, which were later performed and the findings from which are described below.

The evaluations that culminated in the Phase II Technical Memorandum were designed to close data gaps identified in the Phase I Technical Memorandum and to

further assess potential remedial alternatives for groundwater. Specifically, the evaluations included (i) the installation of additional monitoring wells as recommended by the EPA; (ii) sampling of on-Site and off-Site monitoring wells, including potable groundwater from residential wells along Route 130; (iii) assessment of the former septic beds as a potential source of contamination; (iv) aquifer testing; (v) evaluation of the likely capture zone of groundwater extraction wells, if they were installed; (vi) geochemical evaluation of Site subsurface soils; and (vii) groundwater flow and transport modeling [GeoSyntec, 2000]. The results of these Phase II evaluations are discussed below and in Section 1.2.4.

To investigate areas of the Site that had not been previously studied, twelve new monitoring wells were installed in 1998. The wells were installed in locations and at depths recommended by the EPA. During the Phase II evaluations, the twelve new monitoring wells were sampled along with twelve existing wells using low-flow sampling techniques. The samples were analyzed for VOCs and total and dissolved lead and cadmium. The new monitoring wells and Exxon Well No. 2 were also analyzed for radiological and general chemistry parameters. In addition, during purging and sampling activities, the water quality parameters pH, temperature, specific conductivity, oxidation-reduction potential, dissolved oxygen, and turbidity were monitored.

Significant findings of the Phase II evaluations were related to pH and decreasing lead and cadmium concentrations. An analysis of historical groundwater pH indicates that pH has generally trended toward ambient conditions. Detailed review of the data show that pH increased by more than 0.20 units between 2004 and 2010 (or 2007 and 2010, if no 2004 data were available) in seventeen monitoring wells, decreased by more than 0.20 units in five monitoring wells, and has been fairly stable (e.g., within +/- 0.20 units) in six monitoring wells. Historical data and pH isopleth maps are provided in Appendix D. The area with the lowest pH in the unconfined aquifer at the Site, as measured in 2010, is centered around wells KDR and KSR, north of the former battery breaking area. Groundwater monitoring wells where pH was found to be decreasing between 2004 and 2010 showed a range of pH reduction between 1.19 units (well KSR) and 0.24 units (well 33). Where groundwater pH was increasing, the range was 2.69 units (well 13) and 0.23 units (well 32) with an average increase of 0.96 units. Notably, as pH increased, the presence of lead and cadmium in groundwater decreased. Provided current trends continue and the pH of groundwater continues to trend upward at the majority of the monitoring locations to ambient conditions, the area of impacted groundwater containing lead and cadmium and the concentrations of lead and cadmium in groundwater are anticipated to continue to decrease as well. A further discussion of the mechanisms by which pH impacts the concentrations of lead and cadmium is provided in Section 1.2.4.

The analytical results for VOCs presented in the Phase II Technical Memorandum confirmed the findings of the Phase I Memorandum and the RI. Concentrations of VOCs continued to decline relative to previous sampling events, with the exception of vinyl chloride in monitoring wells 12 and 24. . Monitoring wells 12 and 24 are screened in the first confined aquifer on the upgradient side of the Site. Site related constituents were not detected in any aquifer below the unconfined aquifer.

Additionally, an investigation of the former septic beds, located in the southwestern corner of the Site along the Pennsgrove-Pedricktown Road, was conducted in July 1998 to determine if the septic system beds were a potential source of VOCs downgradient of this location. Soil samples were obtained from borings drilled into the former septic beds. Monitoring wells 31 and 32 were installed adjacent to and downgradient from the septic beds. The results of the septic bed investigation revealed no significant VOC detections in soil or groundwater samples. Ultimately, VOCs initially identified as COCs in the 1994 ROD, will continue to be monitored in the groundwater to ensure that the cleanup standards or RAOs referenced in the 1994 ROD are achieved.

The inorganic analyses presented in the Phase II Technical Memorandum also confirmed the results provided in the Phase I Technical Memorandum and the RI. The Phase II data showed concentrations of lead in groundwater above the cleanup standards at five monitoring wells including OS, SD, 27, 28 and 30. Concentrations of cadmium in groundwater above the cleanup standards were detected at 12 of the 24 monitoring wells sampled. The concentrations of lead and cadmium detected during the Phase II evaluation were generally lower than their respective concentrations found during the prior investigations.

To further evaluate the trend, zones of impact were depicted for historical data similar to those shown on Figures 4 and 5. The zones of impact and the concentrations of lead and cadmium within the zones of impact were used to calculate the approximate masses of lead and cadmium remaining in groundwater at the Site. The mass of lead in groundwater at the Site was estimated to have declined from approximately 220 lbs in 1983 to 8.8 lbs in 1998. The mass of cadmium in groundwater at the Site was estimated to have declined from approximately 70.5 lbs in 1988 (earliest available cadmium data) to 14.1 lbs in 1998 [GeoSyntec, 2000].

The results of the Phase II potable well sampling conducted in July 1998 and January and May 1999 at the residences along Route 130 varied slightly from the results of the Phase I Memorandum and RI studies. The residential sampling event resulted in the detection of total lead at concentrations above the cleanup standards at three residences. However, the cleanup standard was not exceeded for dissolved lead or total or dissolved cadmium at any of the residences. The disparity between the dissolved and total detection of lead in the residential wells indicated that the wells had not been adversely affected by impacted groundwater at the Site.

Potable well sampling was most recently conducted in November and December 2010 and was reported to the EPA on February 10, 2011 in CSI's *Residential Water Sampling Report*. Total and dissolved cadmium were not present in any of the residential water samples at concentrations above the drinking water standard for cadmium, which is 4 parts per billion. Total and dissolved lead were not present in any of the residential water samples at concentrations above the drinking water standard for lead, which is 5 parts per billion, except for samples collected at one residential property. The one residential sample that slightly exceeded the drinking water standard for lead had been compromised due to blank contamination. In addition, because the reported total lead concentration in the water sample was higher than the reported dissolved lead

concentration, the data indicate that a component of the total lead concentration was attributable to solids suspended in the water sample. This suggests that the lead concentration is influenced by the components of the plumbing system at the property and is not related to the Site. Furthermore, the general flow direction of the groundwater in the upper aquifer is toward the west and not in the direction of the residential properties located north of the Site.

Radiological parameters were only detected in samples obtained from deep-zone wells during the Phase II evaluations, which led to the conclusion that the radiological parameters are naturally occurring and not related to former Site uses. With supporting data presented by O'Brien and Gere during the RI in 1990, it was concluded that there was no need to continue to address radiological parameters and they were eliminated from further evaluation.

Groundwater data reported in the Phase I and Phase II Technical Memoranda suggested that lead and cadmium are the primary COCs. Accordingly, it was determined that subsequent evaluations of lead and cadmium would be required for groundwater at the Site. While additional investigations focused on lead and cadmium, COCs listed in the 1994 ROD, including VOCs, continued to be monitored.

Following the completion of remedial activities for soil at the Site, the Group conducted groundwater sampling activities in January 2004, April 2007, and November/December 2010 in accordance with EPA-approved work plans. The results of the groundwater sampling were presented in three reports entitled *Groundwater Monitoring Report* prepared by CSI in April 2004, September 2007 (revised May 2008) and February 2011. Figures 4 and 5 depict the current and historical limits of groundwater impacted by concentrations of cadmium and lead exceeding applicable NJGWQSs, respectively. A summary of historical lead, cadmium, and VOC data for the monitoring wells at the Site is provided on Table 3. Figures 6 and 7 depict the lead concentrations in groundwater from wells in the shallow and deep zone, respectively, of the upper aquifer sampled during the 2010 groundwater monitoring event, which is the most recent groundwater data obtained from the Site. Figures 8 and 9 depict the cadmium concentrations in groundwater from wells in the shallow and deep zone, respectively, of the upper aquifer sampled during the 2010 groundwater monitoring event, which is the most recent groundwater data obtained from the Site.

Using the 2010 groundwater quality data, the estimates of masses of lead and cadmium were updated and determined to have continued to decline. CSI determined that the approximate mass of lead remaining in groundwater is 2.7 pounds, and the approximate mass of cadmium remaining is 5.9 pounds. The current volume of groundwater calculated to be impacted by lead at the Site is approximately 1.5 million gallons. The volume of water calculated to be impacted by cadmium is approximately 11.8 million gallons. Although variations in interpretation of the area affected as well as variations in the concentrations of lead and cadmium detected affect the volume and mass estimates a clear trend in mass and affected area reductions are evident. The mass and area estimates are summarized in the figures and tables in Appendix H.

VOC analyses were also performed on the groundwater samples obtained by CSI in 2004, 2007, and 2010. As indicated above, the historical lead, cadmium, and total VOC data for the Site are presented on Table 3. VOCs were historically detected primarily in the unconfined aquifer in wells BR, 11 and SD. As of December 2010, the total VOC concentration at monitoring well 11 was 10.9 µg/L (decreased from 5,124 µg/L in 1989) and at well BR there have been no detections of VOCs since 1997 (79 µg/L). None of the VOCs detected in the groundwater sample from well 11 in 2010 exceeded the NJGWQSs. Trace concentrations of hydrocarbon-related compounds (ethylbenzene, toluene and xylenes) and chloroform have historically been detected at well SD. However, the 2010 data indicated a total VOC concentration of 4.24 µg/L which demonstrates a decline in VOC concentrations in the groundwater sample obtained from well SD. Vinyl chloride was detected at concentrations of 7.7 µg/L and 6.9 µg/L in the groundwater samples obtained during the 2010 sampling event from wells 12 and 24, respectively. Monitoring wells 12 and 24 are screened in the first confined aquifer and are located hydraulically upgradient from impacted areas at the Site. CSI believes that vinyl chloride detected in these wells may be from an off-Site source(s) based on the groundwater flow direction, presence of potential nearby sources, and lack of a detection of related compounds in shallow monitoring wells in areas on the Site that could affect the first confined aquifer in the vicinity of 12 and 24; however, vinyl chloride will continue to be monitored to ensure that the cleanup standard for vinyl chloride is met over time.

The primary COCs for groundwater as defined by EPA on Table A of the 1994 ROD for the Site are: arsenic, beryllium, lead, 1,2-dichloroethane, 1,1-dichloroethylene, PCE, and vinyl chloride. The human health risk assessment, as presented in the 1994 ROD, determined that the above listed COCs posed an unacceptable human health risk in groundwater. Therefore, while lead is the primary contaminant of concern, a remedial action is warranted to restore the unconfined aquifer to drinking water standards for all contaminants. All contaminants will be monitored until the applicable standards are met, with the exception of arsenic and beryllium. Arsenic and beryllium were eliminated from groundwater sampling at the Site, with the approval of the EPA, subsequent to the Phase I Technical Memorandum based on a lack of detection. Note that sample parameters may be subject to change over time, at EPA's discretion.

Cadmium, although not listed as a COC on Table A of the 1994 ROD for groundwater, is included herein for evaluation purposes as it was listed as a COC for soil and has been determined to be prevalent in the groundwater in concentrations that greatly exceed the applicable drinking water standards.

Although all of the COCs will be included in the RA, the remainder of this FFS Report focuses on lead and cadmium, the primary COCs, in groundwater. As required by the ROD, the RAO for groundwater at the Site is to restore the impacted, unconfined aquifer to drinking water standards. Drinking water standards are defined as the most stringent of the most recent New Jersey Maximum Contaminant Levels (NJMCLs), NJGWQSs, Practical Quantitation Limits (PQLs), or the Federal Maximum Contaminant Levels (MCLs). The drinking water standards are listed on Table F of the 1994 ROD (Appendix A). Some of the standards listed on Table F have been modified since the

1994 ROD. The most recent and stringent standards will be used to demonstrate achievement of the cleanup standards for the Site. Completion of remedial activities for groundwater at the Site will need to include a demonstration that the cleanup standards have been met for all constituents listed on Table F of the 1994 ROD (Appendix A).

1.2.4 Contaminant Fate and Transport

Inorganics

The fate of lead and cadmium in groundwater is related to the pH, solubility, oxidation reduction potential (Eh) of groundwater, and adsorption onto soil surfaces and into coatings on soil surfaces. The pH is a measure of the availability of protons (H+) and the Eh is a measure of the availability of electrons in water. Lower pH values favor dissolution of lead and cadmium. Eh is less important than pH for the dissolution of lead and cadmium, however cadmium is more soluble where dissolved oxygen is low and Eh tends toward reducing conditions (e.g. lack of air and thus lack of carbonate alkalinity). As the pH levels in the central portion of the Site (particularly near wells OS, SS/SD and KS/KD) naturally increase to ambient levels between a pH of 5 and 6, it is anticipated that lead and cadmium will be less soluble and undergo natural geochemical reactions and adsorption onto soil and into soil coatings in the aquifer. The net result of increasing pH is a reduction in lead and to a lesser extent cadmium concentrations. The concentrations of lead and to a lesser extent cadmium will decrease as pH tends toward ambient and as Eh tends toward oxidizing conditions [EPA, 2007]. Current pH and Eh data are provided on Table 2. Current and historic pH levels in groundwater are shown in a series of figures in Appendix D along with a table that compares the water quality data obtained from the 2004, 2007 and 2010 sampling events.

In research conducted by Yong and Phadungchewit (1993b), it was shown that both lead and cadmium retained in several different soil types was appreciably lower at pH values between 4.5 and 5.0 for lead and 5.5 to 6.5 for cadmium. Other research activities focusing on heavy metal mobility has documented that acidic pH increases the solubility of metal cations. For example, Dzombak and Morel (1987) also reported that "[m]etal cations are most mobile under acidic conditions" and Chuan, Shu, and Liu (1995) reported that "[m]etals were sparingly soluble under alkaline conditions (pH = 8.0)", but were "higher when under slightly acidic conditions (pH = 5.0), and increased drastically when pH was kept at 3.3."

The dissolution and retention mechanisms for lead and cadmium in soils are strongly influenced by the pH of the groundwater and soil system [Yong and Phadungchewit, 1993]. At high pH values (generally, above 5.0), precipitation mechanisms (e.g., hydroxides) play a key role in the dissolution of metals and their immobilization. The pH of groundwater at the Site tends to be low in the center of the Site. The Eh of the groundwater tends to be low in the deeper portions of the unconfined aquifer, where dissolved oxygen is absent or nearly so.

Chuan, Shu, and Liu also found strong relationships between heavy metal solubility and the Eh of the solution (1995). In their study, under constant pH conditions,

they found that "metal solubilities increased as redox potential decreased." In increasingly reducing environments the solution has a tendency to lose electrons. Since lead and cadmium are cations, their precipitates require the introduction of electrons (e.g., such as the reaction between lead and the hydroxide ion). Therefore, while pH is a more dominant driver of heavy metal solubility, Eh plays a secondary role.

Carbonate alkalinity (e.g. from CO2 in air) may be present in shallow groundwater where groundwater may be better aerated from contact with air in the vadose zone. Lead carbonate tends to be relatively soluble when compared to other lead compounds, which are insoluble. Cadmium carbonate, on the other hand, is insoluble. The dissolved oxygen concentration and Eh of the deeper groundwater tends to be lower than in the shallow groundwater. These characteristics help explain the occurrence of lead predominantly in the shallow unconfined aquifer and cadmium predominantly in the deeper unconfined aquifer.

An analysis of the trends in historical groundwater pH at the Site indicates that pH has generally increased. The pH of groundwater has increased or remained fairly stable in 23 of the monitoring wells. In five of the wells sampled, pH apparently decreased a small amount (Appendix D). The area with the lowest pH in the unconfined aquifer at the Site, as measured in 2010, is near the center of the Site (i.e. wells KDR and KSR), near the former battery breaking area, which is generally where it has been located throughout the monitoring period.

An analysis of the trends in historical groundwater Eh indicate that Eh has increased or remained fairly stable in 11 monitoring wells. In 2010, Eh was lower than the level measured in 2004 in 17 monitoring wells. The area with the lowest Eh in the unconfined aquifer at the Site, as measured in 2010, is around the former process area (in the area of wells SS, JS, and 22). The largest decrease in Eh since 2004 was measured in the vicinity of well 22 (screened in the deeper zone of the unconfined aquifer). Lower Eh values tend to be associated with lower concentrations of dissolved oxygen. The lower dissolved oxygen concentrations were detected in the deeper zone of the unconfined aquifer.

Provided current trends continue and the pH of groundwater continues to trend upward at the majority of the monitoring locations to more neutral conditions, the area of impacted groundwater containing lead and cadmium is anticipated to continue to decrease as well. However, the dissolution of cadmium may be somewhat muted where Eh tends toward more reducing conditions. The figures in Appendix D help to demonstrate the gradual increases in pH levels, the dominant driver of dissolution reactions, in groundwater at the Site at most monitoring locations.

The presence of iron and manganese oxide/hydroxide coatings on soil particles in the subsurface at the Site were identified through detailed thin section petrography and bulk and clay X-ray diffraction performed by Core Laboratories and presented in the Phase II Technical Memorandum. The Core Laboratory report, included as Appendix B and described in the Phase II Technical Memorandum, provides supporting information related to the tendency of inorganic constituents like lead and cadmium to adsorb onto

soil and thus have limited mobility in the subsurface. It should be noted that some degree of mobility of lead and cadmium in groundwater is possible under some conditions (such as a lack of adsorption capacity or coatings on soil coupled with instances of high concentrations of dissolved organic matter, for example). Such conditions are rarely encountered in the field.

Soil samples were obtained in July 1998 as part of the Phase II evaluation during the installation of monitoring wells 26, 28, and 29 from the water column near the top of the water table were used for the Core Laboratory analysis. The evaluation was conducted as recommended by the EPA's National Risk Management Research Laboratory following the review of the Phase I Technical Memorandum in 1998. The iron and manganese oxide/hydroxide coatings in the soil provide adsorption capacity for lead and cadmium that is anticipated to precipitate out of groundwater or otherwise adsorb onto soil or into soil coating at the Site.

The adsorption capacity of the aquifer materials at the Site was further identified through calculation of the cation exchange capacity (CEC) of the same soil samples analyzed by Core Laboratories, as described above. The CEC analysis was performed by Toxscan, Inc./Soil Control Lab and the data are included in Appendix C. The capacity of aquifer material to adsorb lead,[4] for example, was determined to significantly exceed the amount required for the Site. The same is true of other inorganic constituents including cadmium. The transfer of lead and cadmium from groundwater to aquifer materials at the Site is desirable because it does not create any concerns regarding soil quality. For example, as stated in the Phase II Technical Memorandum, "if all of the lead detected in groundwater at the Site were sorbed onto aquifer material, then the resultant change in inorganic concentration in soil would be on the order of one to two ppm. A similar relationship is true for cadmium." With the decreased groundwater concentrations of lead and cadmium detected in 2007, the increase in lead and cadmium concentrations in soil resulting from adsorption would be in the parts per billion to parts per million range. As discussed in Sections 3.2.2, 3.3.2, and 3.4.3, if favorable geochemical conditions are achieved and maintained, lead and cadmium are expected to be removed from groundwater via adsorption to aquifer materials.

Evidence of the permanence of the adsorption of lead and cadmium to soil is included in the Toxscan Laboratory report provided in Appendix C. Included therein are the results of a sequential extraction analysis performed on soil samples from the Site. This analysis used sequentially more acidic solutions to attempt to extract cadmium and lead from the soil samples. The study indicated that a solution with a pH of less than 2 was needed to extract cadmium and lead from the soil samples at detectable concentrations, thereby suggesting that after adsorption of lead and cadmium onto soil, it would be unlikely that the metals would resolubilize.

[4]Aquifer adsorption capacity was estimated using the relationship identified in *Behavior of Lead in Soil* (Zimdahl and Skogerboe, 1977). For example, the aquifer material at the Site has the capacity to adsorb lead up to a concentration of 5,000 mg/kg, which exceeds by an extraordinarily large margin the amount required to achieve RAOs for groundwater.

All of the mechanisms described above (adsorption, dissolution and precipitation) aid in the natural attenuation of lead and cadmium in groundwater. The interaction of the mechanisms varies as water chemistry varies and the effects of the individual mechanisms vary as concentrations decline and as geochemical conditions change. Therefore, the interactions among and dominance of the various attenuation mechanisms are in flux in response to declining constituent concentrations and changes in geochemical conditions.

In addition to addressing the mechanisms which determine the fate of lead and cadmium, as described above in Section 1.2.3, several studies were conducted during the Phase II evaluation that also addressed the lack of significant mobility of lead and cadmium in groundwater. The initial step in assessing the mobility and thus the lack of transport of inorganic constituents by groundwater was to perform an aquifer test. A pumping well and an observation well were installed for testing purposes. The aquifer test included ambient water-level monitoring; a variable-rate pumping test (step test) and a 72-hour constant-rate pumping test (CRT) [GeoSyntec, 2000]. Throughout the course of the CRT, the pH and turbidity of the groundwater were monitored, and samples were collected for analysis of lead, cadmium, and general chemical parameters.

Based on hydraulic data provided in the Phase II Technical Memorandum, the hydraulic conductivity was estimated to be approximately 26 feet per day on the Site. Using this value and the groundwater data collected in 2004, 2007, and 2010, the average groundwater flow rate is approximately 27.5 feet per year. The flow direction, as inferred based on groundwater elevation data, is primarily west across the Site and south from the residential properties located along U.S. Route 130 toward the Site in the shallow zone. Localized variations in groundwater flow patterns are controlled by surface topography.

The analytical results from the aquifer test indicated that the concentrations of lead and cadmium in groundwater declined during the course of the CRT to levels that are too low to effectively remove mass from the subsurface. Lead concentrations were below detectable levels at the conclusion of the CRT and cadmium concentrations steadily declined. It was estimated that the cadmium concentrations would have declined below detectable levels within 12 to 15 days of pumping, but not as a result of removing it from the subsurface, but only as a consequence of the inability to capture cadmium through groundwater extraction. Based upon these data, it was calculated that it would take between 50 and 60 years of aggressive pumping to remove a reasonable amount of the mass of the lead and cadmium from the Site by extracting groundwater. The analytical results from the aquifer test are provided in Appendix G. Additional discussion of the aquifer test is provided below and in Section 3.5.2 as part of the evaluation of the pump and treat remedial alternative.

The hydraulic parameters obtained during the performance of the aquifer test were subsequently used to prepare and refine a capture zone model for the Site. The capture zone model was developed as requested by the EPA for inclusion in the remedial design for groundwater at the Site. The capture zone model was created using MODFLOW [McDonald & Harbaugh, 1983]. The model was calibrated using data obtained through the aquifer test and data previously reported (e.g., Geraghty and Miller,

1983, O'Brien and Gere, 1990). The uppermost portion of the unconfined aquifer was modeled as it is the principally impacted zone. Several simulations were run after the model was calibrated. The most representative simulation indicated that pumping through well PW would capture the majority of the groundwater within the impacted area in less than one year. However, the ability to capture groundwater is entirely different from the ability to remove lead or cadmium, because they do not migrate appreciably with groundwater.

Subsequent to the capture zone modeling, the results were used to perform fate and transport modeling using MT3DMS. Using this model, two separate simulations were performed for both lead and cadmium. The lead simulations reflected the 1983 to 1989 and 1989 to 1998 timeframes. The cadmium simulations reflected the beginning of 1989 to the end of 1989 and also 1989 to 1998. These timeframes correlate to the availability of sample data from the Site. Lead data were available from 1983, but cadmium data were not available until 1989. Thus an additional model run was performed for the 1983 to 1989 timeframe, while an initial cadmium model was run for 1989 only. These initial runs were utilized to synchronize the more extensive model run for both lead and cadmium for the 1989 to 1998 timeframe. These simulations included pH values obtained during the 1983 and 1997 sampling events. Starting concentrations for lead were based upon the 1983 sampling results. Starting concentrations for cadmium were based upon the 1989 sampling results. The model predicted that lead and cadmium would not be significantly transported and that the adsorption of lead and cadmium to soil due to varying geochemical conditions as water from other areas was drawn into the impacted area rendered the inorganic constituents immobile. Simulated groundwater pumping from well PW resulted in no observable effect on the concentration or distribution of lead and cadmium. Subsequent groundwater data from 2004 through 2010 have verified that lead and cadmium zones of impact have generally decreased and have had minimal migration.

Volatile Organic Compounds

As previously indicated, VOCs have historically been detected in wells 11, 12, BR, SD and 24 at the Site. During the 2010 groundwater sampling event, VOCs were not detected in well BR and were close to non-detect and significantly below the NJGWQSs and Federal MCLs in well 11 and SD. Vinyl chloride was detected at a concentrations above its NJGWQS in the samples from wells 12 and 24 (i.e. at concentrations of 7.7 µg/L and 6.9 µg/L, respectively). These concentrations are lower than or generally consistent with those reported previously. The concentrations of vinyl chloride have decreased slowly since 1998 at these wells. A concentration of vinyl chloride of 13 µg/L was reported in well 12 in 1998 and was detected in 2010 at a concentration of 7.7 µg/L. Vinyl chloride is the end degradation product of PCE and remains fairly persistent in groundwater. Therefore, the trend of slowly declining concentrations of vinyl chloride at wells 12 and 24 is expected to continue. There is no evidence to suggest that the vinyl chloride is migrating beyond the area monitored by the wells in which they were detected. The only other detection which exceeded its NJGWQS was tetrachloroethylene in well 11. VOCs will continue to be monitored until the applicable standards have been achieved.

1.2.5 Baseline Risk Assessment

A baseline risk assessment was conducted as part of the RI (O'Brien and Gere, 1990) and was based on COC concentrations from groundwater samples collected in 1989. The baseline risk assessment addressed the potential risks to human health by identifying potential exposure pathways by which the public may be exposed to contaminated groundwater (via ingestion). Groundwater exposures were assessed for both potential present and future land-use scenarios. Current land use was considered to be an industrial facility and future land use was characterized as either an industrial facility or residential area in the risk assessment. Current receptors included off-Site residents (child and adult) and off-Site workers. Future receptors included on-Site residents (child and adult), off-Site residents (child and adult), on-Site workers and off-Site workers. Results of the quantitative risk assessment concluded that there was an unacceptable risk for the potential future receptors due to exposure to contaminated groundwater via ingestion, with the exception of the on-Site worker. The potential exposure pathways, land-use scenarios and receptors identified in the 1990 risk assessment remain applicable for the Site; therefore, the original risk assessment is still valid.

The unconfined aquifer at the Site is classified as a Class II aquifer in the state of New Jersey. The designated use of Class II ground waters is to provide potable water and this is considered to be the most beneficial use for the aquifer. Accordingly, while the groundwater at the Site is not currently being used for drinking water, the goal is to restore the aquifer to its most beneficial use.

A review of the most recent groundwater data reveals that the concentrations of COCs, primarily cadmium and lead, continue to exceed their respective New Jersey Department of Environmental Protection Groundwater Quality Criteria and Federal Maximum Contaminant Levels. These standards were promulgated to ensure that public water systems used as potable water sources remain protective of human health by limiting levels of contaminants in the drinking water. The RAO for the Site is to restore the unconfined aquifer to drinking water standards for all contaminants and this RAO has not yet been met for all of the constituents; therefore, unacceptable human health risk remains and will be addressed through the development of the alternatives presented in this feasibility study. A remedial action will be implemented to more rapidly improve the groundwater quality and achieve the RAOs.

2. IDENTIFICATION AND SCREENING OF TECHNOLOGIES

2.1 Overview

Groundwater sampling has been performed at the Site since 1983. Based on groundwater data collected during the RI, RD, and subsequent monitoring events performed in 2004 and 2007 after the soil remediation was completed (the data are summarized in Section 1.2.3 above), CSI and the Group in consultation with EPA representatives identified the five most viable groundwater alternatives for the Site. The remedial alternatives chosen for evaluation in this FFS include the following:

- No Action;
- Monitored Natural Attenuation (MNA);
- Reagent Injection;
- Permeable Reaction Barriers; and
- Pump and Treat.

These alternatives were presented to the EPA in a draft outline for this FFS in March 2007.

2.2 Remedial Action Objectives (RAOs)

RAOs are goals for reducing human health and environmental risks and/or meeting established regulatory requirements at the Site. Applicable or Relevant and Appropriate Requirements (ARARs) were used to define RAOs.

Based on current data and evaluations of potential risk, lead and cadmium in groundwater were identified as being the primary COCs. However, Table A of the 1994 ROD (EPA, 1994) for the Site lists arsenic, beryllium, lead, 1,1-dichloroethane (1,1-DCA), 1,1-dichloroethylene (1,1-DCE), PCE, and vinyl chloride (VC) as the COCs in groundwater. The Group considers cadmium to be a COC because of its presence in groundwater at concentrations that exceed applicable New Jersey drinking water standards. The primary risk to human health at the Site is through potential ingestion of affected groundwater as described in Section 1.2.5.

An updated list of RAOs for groundwater, including the 1994 ROD RAO for groundwater, is provided below:

- Restore the contaminated unconfined aquifer to drinking water standards for all contaminants;

- Minimize the potential for migration of the contaminants of concern in groundwater; and

- Prevent or minimize potential current and future human exposures; including ingestion of groundwater, that presents a significant risk to public health and the environment.

For the purpose of evaluating a groundwater remedy at this time for the Site, the primary COCs of lead and cadmium will drive the remedy selection process. Although all RAOs must be met subsequent to the remedial action, this FFS focuses on lead and cadmium and the remedial alternatives that are best suited to remediate those constituents in groundwater. Achievement of the cleanup standards for lead and cadmium will likely result in the achievement of cleanup standards for other COCs, as all of the COCs are subject to declining concentrations in groundwater by both natural attenuation and response to remedial activities.

While lead and cadmium are the primary COCs, the groundwater remedy will not be considered complete until all Site-related constituents have concentrations that meet the applicable standards. However, it is expected that all other Site-related constituents will meet the applicable standards within the timeframe required to remediate lead and cadmium. The criteria used to evaluate achievement of the RAOs for lead and cadmium are based on the most stringent of the current state and federal standards. For lead and cadmium, the most stringent standards are the NJGWQSs (NJAC 7:9C) which are 5 µg/L for lead and 4 µg/L, for cadmium. The practical quantitation limit (PQL) is the lowest concentration that can be reliably detected by a laboratory during routine laboratory operating conditions as established by NJDEP as part of the NJGWQSs. The PQL for lead is 5 µg/L and for cadmium it is 0.5 µg/L. Therefore, the cleanup standards for lead and cadmium of 5 µg/L and 4µg/L, respectively, are demonstrably attainable using standard laboratory methods. Note that the PQL for lead has decreased from 10 µg/L at the time of the ROD to 5 µg/L, as referenced above. All other cleanup standards for groundwater will be evaluated concurrent with the remedy implementation. A list of the current NJGWQSs are provided in Appendix I.

2.2.1 Applicable or Relevant and Appropriate Requirements (ARARs)

ARARs can be divided into three general types. Chemical-specific ARARS set limits on concentrations of specific hazardous substances, pollutants and contaminants in the environment. Examples of these types of ARARs are drinking water standards and ambient water quality criteria. Location-specific ARARs set restrictions on certain activities based on their location (i.e. wetlands, floodplains, historic sites, etc). These ARARs generally apply to most alternatives as they are based on the location of the Site. Finally, action-specific ARARs place restrictions on the technologies used for remedial action. The Resource Conservation and Recovery Act (RCRA) regulations for waste treatment, storage, and disposal are an example of such action-specific ARARs.

<u>Potential Chemical-Specific ARARs:</u>

<u>Federal</u>

- Clean Water Act, Water Quality Criteria
- RCRA Ground Water Protection Standards (40 CFR Part 264.94)
- Federal Water Quality Criteria (51 *Federal Register* 436665)
- Federal MCLs

New Jersey

- New Jersey Ground Water Quality Standards (NJGWQS) (NJAC 7:9-6)
- New Jersey MCLs

Potential Action-Specific ARARs

Federal

- RCRA Groundwater Monitoring and Protection Standards (40 CFR 264, Subpart F)
- Clean Water Act – NPDES Permitting Requirements for Discharge of Treatment System Effluent (40 CFR 122-125)
- EPA Action Level for Lead in Drinking Water

New Jersey

- New Jersey Pollutant Discharge Elimination System Regulations (NJPDES) and Effluent Limitations (NJAC 7:14A et seq)

Potential Location-Specific ARARs

Federal

- Fish and Wildlife Coordination Act (16 USC 661 et seq.)
- National Environmental Policy Act (42 USC 4341 et seq.)
- Natural Historic Preservation Act
- Endangered Species Act
- Coastal Zone Management Act
- Farmland Protection Policy Act

New Jersey

- New Jersey Rules on Coastal Resources and Development (7:7E-1.1 et seq.)
- New Jersey Freshwater Wetlands Regulation

2.2.2 Development of Remedial Goals

The RAOs for groundwater are to restore the groundwater in the unconfined aquifer to the most recent drinking water standards for all chemicals of concern as listed on Table F of the ROD [EPA, 1994], included in Appendix A; minimize the potential for migration of the contaminants of concern in groundwater; and prevent or minimize potential current and future human exposures, including ingestion of groundwater, that presents a significant risk to public health and the environment. The FFS is focused on lead and cadmium in groundwater, because they are the only constituents that currently exceed an applicable standard that may reasonably be expected to continue to exceed

standards for an extended period without remediation. However, all COCs listed in the ROD will continue to be monitored to ensure that the cleanup standards for groundwater are met. For lead and cadmium, the remedial goal for this FFS is to achieve the most stringent of the recent NJMCLs, NJJGWQS, or Federal MCLs standards for concentrations of lead and cadmium in groundwater across the Site which are currently 5 µg/L for lead and 4 µg/L, for cadmium.

2.2.3 Assessment of Areas to be Remediated

There are approximately 11.8 million gallons of groundwater at the Site impacted by cadmium and 1.5 million gallons of groundwater impacted by lead at concentrations exceeding the NJGWQS. The impacted water is located on the Site as depicted on Figures 4 (cadmium) and 5 (lead). The volume of impacted groundwater was calculated using the most recent December 2010 groundwater data. The depth of impacted groundwater was estimated by averaging well depths of the impacted wells and the areas impacted are shown in Figures 4 and 5, respectively. A porosity of 30% was used in the volume calculation. Using the December 2010 data, CSI determined the current mass of lead remaining in groundwater at the Site to be approximately 2.7 pounds, and the approximate mass of cadmium remaining in groundwater at the Site is 5.9 pounds. The basis for these estimates is summarized in the figures and tables in Appendix H.

2.3 General Response Actions

General response actions are the broad categories of actions that may be taken to satisfy RAOs at a particular site. The following are the general response actions considered for this Site.

2.3.1 No Action

The No Action alternative is required to be considered by the National Contingency Plan (NCP-40 CFR Part 300.430 [e][6]) to provide a baseline against which all other remedial actions can be compared. This remedial alternative would not change the status of the Site, and no actions would be taken to limit the potential for exposure to impacted groundwater at the Site.

2.3.2 Monitored Natural Attenuation

MNA is a response action that involves the use of natural biochemical reactions to remediate groundwater. The constituents are immobilized through various natural conditions such as dilution, volatilization, adsorption, biodegradation, and chemical reactions with subsurface materials. These natural attenuation mechanisms can be modeled and predicted using various techniques. MNA includes groundwater monitoring to verify the rate of attenuation that is occurring.

2.3.3 In-situ Treatment

In-situ treatment is a response action that immobilizes or reduces the toxicity and/or volume of the constituents in groundwater without extraction. The action relies upon physical/chemical or biological means to alter the constituents in groundwater thus reducing their toxicity, mobility, or volume. This response action includes extensive groundwater monitoring to determine the effectiveness of the in-situ treatment method prescribed. The in-situ treatment methods considered in this FFS include reagent injection and permeable reaction barriers.

2.3.4 Collection/Extraction

Collection or extraction of groundwater typically involves pumping groundwater from collection trenches or wells. Through pumping of the groundwater, the mobility of the impacted water is reduced by changing the localized hydraulic gradient and contaminant mass is removed. An appropriate groundwater collection/extraction technology is dependent upon the type of constituents impacting groundwater, aquifer characteristics, depth of impacts, ability to extract the COCs from the aquifer using pumping techniques, and the remedial objectives. The collection/extraction technology is typically combined with treatment and discharge technologies.

2.3.5 Ex-situ Treatment

Ex-situ treatment response actions seek to reduce the mobility, toxicity, or volume of groundwater impacts through chemical, biological, or physical processes. Ex-situ treatment technologies are dependent on the ability to extract the COCs from the aquifer using pumping techniques. Treatment to reduce the toxicity or mobility of the COCs is then employed prior to discharge of the groundwater. Automated systems are typically employed to monitor the rate of extraction, apply the treatment technology, and monitor the effluent to ensure that impacted waters are not discharged inappropriately. Discharge technologies are employed to safely return the treated water to the environment.

2.3.6 Disposal/Discharge

Disposal/discharge technologies facilitate the safe return of treated water back to the environment. The disposal/discharge options typically include injection wells, discharge to publicly owned treatment works, discharge to surface water, discharge to recharge basins/infiltration galleries and discharge to public water systems. These methods are regulated through various effluent permits and require monitoring to ensure that treated waters meet applicable requirements.

The general response actions were used by the Group and CSI in developing potential remedial alternatives for the Site.

2.4 Identification and Screening of Remedial Technologies and Process Options

The remedial action technologies discussed in this FFS were selected based on their ability to reduce the risk to human health and the environment from exposure to lead and cadmium in groundwater in a reasonable amount of time and in a cost-effective manner.

2.4.1 Identification of Remedial Technologies and Process Options

The technologies identified for further consideration in this FFS have been identified through multiple studies as outlined in Section 1.2.3 above and with input from EPA representatives. The NCP and CERCLA require the evaluation of a No Action alternative as a basis for comparison with other remedial alternatives. Since the groundwater pump and treat system was the remedy selected in the 1994 ROD it must also be retained for consideration in this FFS. Monitored natural attenuation (MNA) and reagent injection were recommended in the Phase II Technical Memorandum [GeoSyntec, 2000]. At the request of EPA representatives, permeable reaction barriers (PRBs) will also be considered in this FFS.

2.4.2 Screening of Remedial Technologies and Process Options

In accordance with 40 CFR § 300.430(e) (7), the development of the remedial alternatives was guided by initial screening criteria including effectiveness, implementability and cost. The screening criteria are further described below:

- Effectiveness – This criterion evaluates the effectiveness of each alternative in protecting human health and the environment through reductions in toxicity, mobility or volume of contaminants.

- Implementability – This criterion, as a measure of both the technical and administrative feasibility of constructing, operating, and maintaining a remedial alternative, is used to evaluate the combinations of process options with respect to conditions at a specific site.

- Cost – This criterion considers both capital and O&M costs, where appropriate, during the screening of alternatives.

The short- and long-term aspects of these factors were considered during the remedial alternative selection process. The screening criteria were applied to the technologies and process options described in Section 2.4.1. All remedial technologies/process options were retained for further evaluation with the exception of the PRBs. A description of PRBs and an evaluation of the screening criteria are provided below.

PRB Description:

A PRB, as defined on EPA's CLU-IN website, is an in situ method for remediating contaminated ground water that combines a passive chemical or biological treatment zone with subsurface fluid flow management. Treatment media may include zero-valent iron, chelators, sorbents, and microbes to address a wide variety of ground-water contaminants, such as chlorinated solvents, other organics, metals, inorganics, and radionuclides. The contaminants are concentrated and either degraded or retained in the barrier material, which may need to be replaced periodically. A depiction of a PRB is provided as Figure 12.

PRBs can be installed as permanent or semi-permanent units. The most commonly used PRB configuration is that of a continuous trench in which the treatment material is backfilled. The trench is perpendicular to and intersects a mobile ground-water plume. Another frequently used configuration is the funnel and gate, in which low-permeability walls (the funnel) direct the ground-water plume toward a permeable treatment zone (the gate). Some gates are in situ reactors that are readily accessible to facilitate the removal and replacement of reactive media. These PRBs use collection trenches, funnels, or complete containment to capture the plume and pass the ground water, by gravity or hydraulic head, through a vessel containing either a single treatment medium or sequential media. In circumstances where in situ treatment is found to be impracticable, reactive vessels have been located above ground.

PRB Screening Criteria:

Effectiveness: The limited mobility of lead and cadmium in groundwater at the Site will prevent significant volumes of impacted groundwater from entering the PRB. The flow direction of groundwater, as inferred based on 2010 groundwater elevation data, is primarily to the west in the unconfined aquifer. The flow rate is estimated to be approximately 27 feet per year. However, constituent transport is not at the same rate as groundwater flow rate therefore there is no "groundwater plume" to flow through the barrier. At the Site, where the primary constituents of concern are lead and cadmium, lead and cadmium have not migrated appreciably. Therefore, lead and cadmium are not likely to flow through the PRB and concentrations of lead and cadmium in groundwater will remain untreated. At this Site, the PRB will provide no additional protection of human health and the environment than that provided by no-action.

Implementability: A PRB could be constructed at the Site using a variety of trenching and excavation techniques. However, the configuration of the Site presents several construction challenges (i.e. railroad tracks, wetlands, and streams). Figure 13 depicts a possible location for a PRB funnel and gate at the Site. Because the locations of the highest concentrations of lead and cadmium in the groundwater at the Site are found near the Conrail railroad tracks at locations OS and KDR, the PRB would need to be placed between these well locations and the railroad tracks. In addition, two 800-foot long containment walls (e.g. slurry

walls) will be needed to attempt to funnel groundwater into the PRB. The unconfined aquifer described as the Cape May Formation where elevated concentrations of lead and cadmium are present ranges in depth from 20 to 40 feet bgs [GeoSyntec, 2000]. Therefore, the slurry/containment walls would need to be approximately 20 to 40 feet deep. Furthermore, the threshold requirement to successfully implement this remedial alternative is a mobile plume of contaminants. A review of the Site-related data reveals that the threshold requirement is not met at the Site. Figures 4 and 5 depict the extent of lead and cadmium concentrations above NJGWQSs from 1983 to 2010. As shown, the area of impact has remained relatively stationary, but decreased in size.

Cost: Based upon the assumptions and construction criteria presented above, the estimated cost to construct the PRB is $4,904,149 (Table 11). This estimate is provided in 2011 dollars. The cost estimate shown does not include operation and maintenance (O&M) costs or groundwater monitoring costs. The O&M costs for this remedy are estimated to be approximately $2 million every 3-5 years to replace and dispose of media that has become fouled with bacterial growth, precipitates or sediment. The groundwater monitoring costs would be approximately $1.2 million for thirty years of monitoring.

Based on the evaluation of a PRB, it was determined that the PRB technology is not effective for this Site and is not evaluated further in this FFS.

3. EVALUATION OF ALTERNATIVES

3.1 Overview

Subsequent to the application of screening criteria, the retained remedial technologies and process options were organized into four remedial alternatives: Alternative 1 - No Action; Alternative 2 - Monitored Natural Attenuation Plus Institutional Controls; Alternative 3 - Reagent Injection Plus Institutional Controls; and Alternative 4 - Pump and Treat Plus Institutional Controls. Each of these four alternatives was further evaluated in this FFS using the following nine criteria, in accordance with the NCP and CERCLA:

Threshold Criteria
1. Overall Protection of Human Health and the Environment
2. Compliance with ARARs

Primary Balancing Criteria
3. Long-Term Effectiveness and Permanence
4. Reduction of Toxicity, Mobility, or Volume
5. Short-Term Effectiveness
6. Implementability
7. Cost

Modifying Criteria
8. State/EPA Acceptance
9. Community Acceptance

A description of each of the nine criteria is provided below.

3.1.1 Threshold Criteria

Overall Protection of Human Health and the Environment

Alternatives were further evaluated based on their ability to protect human health and the environment in both the short- and long-term by eliminating, reducing, or controlling possible exposures to lead and cadmium in groundwater at concentrations exceeding RAOs.

Compliance with ARARs

The ability of alternatives to meet all applicable and relevant federal, state, and local environmental requirements (ARARs) was assessed for each alternative. The use of a waiver under 40 CFR § 300.430(f)(1)(ii)(C) was considered, where applicable.

3.1.2 Primary Balancing Criteria

Long-Term Effectiveness and Permanence

The long-term effectiveness of the alternatives was assessed along with the degree of certainty that the alternatives will prove successful. This was evaluated by considering the magnitude of constituents remaining in groundwater upon conclusion of remedial activities and the adequacy and reliability of any control measures necessary to address constituents remaining in groundwater.

Reduction of Toxicity, Mobility, or Volume

The degree to which the alternative reduces toxicity, mobility, and/or volume was assessed. The factors considered include: the processes employed; the amount of constituents to be addressed; the degree of expected reduction of toxicity, mobility, and/or volume; the degree to which the treatment is irreversible or permanent; the type and quantities of any residual wastes, if any; and the degree to which remedy implementation reduces risks to human health or the environment.

Short-Term Effectiveness

The short-term impacts were evaluated based on the risks posed by the implementation of the alternative, including the potential impacts on workers, the community, and the environment during remedial activities, and the time until protection is achieved.

Implementability

The ease or difficulty of implementing the alternative was considered. The factors impacting this consideration include: technical feasibility, including difficulties and unknowns; administrative feasibility, including coordination with all parties and the time involved in obtaining approvals and permits; and the availability of services and materials necessary to implement the alternative.

Cost

Costs were evaluated for each alternative. The costs included in the evaluation include capital costs, annual O&M costs and the net present value of capital and O&M costs.

3.1.3 Modifying Criteria

State/EPA Acceptance

State and/or EPA acceptance will be assessed upon receipt of comments to the FFS Report.

Community Acceptance

Anticipated community concerns were considered as part of the remedial alternative selection process, such as the timeframe required to meet RAOs, potential future uses of the Site, and the likelihood that implementation of the remedy would impact the community (e.g. any discharges to the environment). The EPA will address community comments during the public review process.

3.2 Alternative 1 – No Action

3.2.1 Description of No Action Alternative

The No Action alternative provides a baseline upon which the other alternatives can be evaluated and is required to be evaluated under the NCP. Under the No Action alternative, no remedial actions would be taken to specifically address lead and cadmium in groundwater. Institutional and engineering controls would not be implemented to restrict the use or access to the contaminated groundwater on-Site. Furthermore, there would be no monitoring associated with this alternative to evaluate progress toward achieving the RAOs.

3.2.2 Evaluation of No Action Alternative

Threshold Criteria

Overall Protection of Human Health and the Environment

Groundwater concentrations above the cleanup standards still remain on-Site. In the absence of institutional controls to restrict the use of contaminated groundwater, this alternative would not provide protection of human health and the environment.

Compliance with ARARs

The following chemical-specific ARARs were identified for the no action alternative:

Potential Chemical Specific ARARs:

Federal

- Clean Water Act, Water Quality Criteria
- RCRA Ground Water Protection Standards (40 CFR Part 264.94)
- Federal Water Quality Criteria (51 *Federal Register* 436665)
- Federal MCLs

New Jersey

- New Jersey Ground Water Quality Standards (NJGWQS) (NJAC 7:9-6)
- New Jersey MCLs

Action and location-specific ARARs do not apply to the No Action alternative because it will not involve any discharge or impact to wetlands or Site features. The same is true for location-specific ARARs, because no action is taken for this alternative. The status of the location is not affected.

For lead and cadmium, the NJGWQSs are the most stringent of the groundwater ARARs referenced above. Review of historical data reveals that lead and cadmium concentrations are generally declining in groundwater in the majority of the monitoring wells without active intervention. While the limited number of data points limits the ability to perform an extensive statistical trend analysis, general trends can be evaluated. A best-fit trend analysis (Appendix J) was performed on historical lead and cadmium data in an attempt to discern general trends in the concentration of lead and cadmium in groundwater at Site monitoring wells.

Typically one expects the rate at which metals such as lead and cadmium precipitate out of solution to decline asymptotically. Inorganic removal from solution occurs more rapidly initially, when concentrations are greater, and slows as concentrations decline. Considering all of the data, the time required to achieve the applicable groundwater standards is expected to exceed 50 years as the concentrations asymptotically decline. The graphs provided in Appendix J indicate that the decline in lead and cadmium concentrations tend to show this asymptotic rate of removal from solution in most instances, however a number of wells (27, 31, KDR and OS) are atypical.

A simple, but reasonable approximation method for determining the rate of attenuation is to take the average rate of change over an extended period and wide range of concentrations. Using the difference between the first available data point and the 2010 data, a period of more than 20 years and order of magnitude change in concentrations provides a useful average rate of change. The average rate of decrease in the lead and cadmium concentrations from groundwater was derived by subtracting the current concentration from the first available historical value and dividing by the number of years between the samples. The average rate of attenuation for lead was calculated to be -8.2 ug/L per year, with a range of values between -106.9 ug/L per year (SD) and +52.0 ug/L per year (OS – atypical). The average rate of attenuation for cadmium was calculated to be 2.6 ug/L per year, with a range of values between -22.8 ug/L per year

(28) and +3.5 ug/L per year (26 - atypical). Using these average attenuation values and the current concentrations measured in 2010, an approximate length of time until the RAOs can be met can be calculated. A summary of these calculations is provided in Appendix J.

It is important to note that the 1994 ROD had established a cleanup standard of 5 µg/L for lead in groundwater; however, the PQL at the time was 10 µg/L. Therefore, at the time of the ROD, achievement of the lead cleanup standard would have been determined by compliance with the PQL. Currently, the PQL for lead is 5 µg/L which means the cleanup standard for lead (5 µg/L) is now demonstrably attainable using standard laboratory methods. . The reduction of the PQL for lead has increased the estimated length of time required to achieve the standard without active remediation.

Of the eighteen wells with current and/or historical detections of lead and/or cadmium, twelve have declining trends in lead concentration and nine of those twelve locations do not currently (as of 2010) have lead above the cleanup standard of 5 ug/L. The cadmium concentration trend evaluation shows fourteen locations with declining cadmium concentrations and six of those fourteen do not currently (as of 2010) have cadmium above the cleanup standard of 4 ug/L.

The average attenuation rate for total lead across all monitoring locations is -8.2 ug/L per year. Using this rate, it can be estimated that it will take a maximum of 133.5 years before lead concentrations decline to levels below the standard in all monitoring wells. Monitoring well OS was calculated to require this length of time, the next longest attenuation to the standard duration calculated was for monitoring well 31 and was 17.7 years.

The average attenuation rate for total cadmium across all monitoring locations is -2.6 ug/L per year. Using this rate, it can be estimated that it will take a maximum of 67.7 years before cadmium concentrations fall below the standard in all monitoring wells. Monitoring well SD was calculated to require this length of time, the next longest attenuation to the cleanup standard duration calculated was for monitoring well 28 and was 40.8 years.

Alternative 1 – No Action would not comply with ARARs as there is no monitoring requirement to determine if cleanup standards have been achieved. Levels of contaminants are predicted to decrease via natural processes; however, the progress of this would not be measured.

Primary Balancing Criteria

Long-Term Effectiveness and Permanence

Based on the historical data, the reduction in concentrations of lead and cadmium under the no action scenario is expected to be permanent provided that geochemical conditions outlined in Section 1.2.4 are maintained. However, without the monitoring element, there is no mechanism for determining whether the concentrations required by the RAOs have been achieved.

Reduction of Toxicity, Mobility, or Volume

Based on the historical data showing decreasing concentrations of lead and cadmium in groundwater at most monitoring points, reduction of toxicity and volume of contaminants could potentially be achieved through the no action alternative through natural processes. Based on trending and average attenuation calculations the achievement of standards for lead and cadmium could exceed 50 years via natural processes, such as adsorption to aquifer materials. Natural processes will likely effectively reduce the toxicity and volume of contaminated groundwater.

The volume of impacted groundwater is expected to decrease in the future; however, the No Action alternative would not include monitoring so the decreased volume of contaminated groundwater would not be measured.

Short-Term Effectiveness

Alternative 1 has no impact on short-term effectiveness since this alternative does not involve remedial construction. .

Implementability

The No Action alternative is technically and administratively feasible to implement since it does not require any actions. However, the No Action alternative lacks a mechanism for determining whether or not remedial goals have been achieved.

Cost

There is no cost associated with the No Action alternative.

Modifying Criteria

State/EPA Acceptance

The No Action alternative is not likely to gain State/EPA acceptance due to the lack of monitoring and associated inability to determine whether or not RAOs have been achieved. This criterion can be further evaluated after input from the State.

Community Acceptance

This criterion will be gauged after the Focused Feasibility Study and Proposed Plan are released for public comment.

3.3 Alternative 2 - Monitored Natural Attenuation (MNA) Plus Institutional Controls

3.3.1 Description of MNA

The evaluations performed since the RI show that, generally speaking, the lead and cadmium concentrations are decreasing in the groundwater at the Site without migrating to downgradient locations. The decline in the areas of impacted groundwater and concentrations of lead and cadmium are the result of source removal, conducted between 1989 and 2003, and subsequent natural attenuation via geochemical and possibly biochemical reactions in the subsurface. Monitored natural attenuation is a viable remedy for groundwater at many sites and may be appropriate for this Site. EPA[5] defines MNA as:

> The reliance on natural attenuation processes to achieve Site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods.

A host of reactions such as biochemical reactions, dispersion, dilution, and sorption processes occur naturally in the subsurface and serve to reduce lead and cadmium concentrations in groundwater at the Site. MNA implementation at the Site would be in conformance with applicable guidance including the MNA guidance document for inorganic constituents (EPA, 2007). This document provides technical guidance for determining whether MNA is an effective approach for remediating groundwater impacted with inorganic constituents at a particular site.

The MNA guidance document (EPA, 2007) identifies a tiered analysis approach for reducing uncertainty in the remedy selection process while distributing costs to address four primary issues including:

[5] EPA's Office of Solid Waste and Emergency Response (OSWER) Directive titled "Use of MNA at Superfund, RCRA Corrective Action and Underground Storage Tank Sites" (Directive No. 9200.4-17p).

1. Demonstration of active contaminant removal from groundwater and dissolved plume stability;
2. Determination of the mechanism and rate of attenuation;
3. Determination of the long-term capacity for attenuation and stability of immobilized contaminants; and
4. Design of a performance monitoring plan, including defining triggers for assessing MNA failure and establishing a contingency plan. [EPA, 2007]

Most of the technical evaluations which satisfy the tiered analysis approach outlined above were presented in the Phase II Technical Memorandum [GeoSyntec, 2000]. The technical evaluations performed in the Phase II Technical Memorandum were requested by members of the USEPA Office of Research and Development, National Risk Management Laboratory (USEPA Risk Management Lab) subsequent to review of the Phase I Technical Memorandum [GeoSyntec, 1998]. The recommendations made by the USEPA Risk Management Lab were designed to assess the on-going natural attenuation of constituents in groundwater at the Site.

The MNA alternative would also entail the implementation of institutional controls, such as a Classification Exception Area (CEA), to limit access and potential use of impacted groundwater at the Site. This would protect human health and the environment until cleanup standards are achieved. The MNA alternative is evaluated in further detail in Section 3.3.2.

3.3.2 Evaluation of MNA

The following MNA evaluation was performed using the tiered analysis approach presented in the MNA guidance document [EPA, 2007] outlined above.

3.3.2.1 Demonstration of Active Contaminant Removal from Groundwater and Dissolved Constituent Stability

In February 2000, remedial activities were performed to remove the source of lead and cadmium at the Site. The remedial action was completed in May 2003. A total of 150,928 tons of treated soil and sediment were disposed of at the Gloucester County landfill, Cumberland County landfill and the Atlantic County landfill. The soil and sediment were treated on Site using either dolomitic lime or EnviroBlend. The landfills utilized the treated soil and sediment as daily cover. In addition, the concrete foundation from the former smelting facility was demolished and the concrete removed from the Site. Approximately 10,887 tons of concrete was shipped off-Site. Another approximately 182 tons of scrap metal, 35 tons of miscellaneous debris and 24 tons of decontaminated railroad ties were also removed from the Site during the source removal.

As shown on Figure 4 (cadmium) and Figure 5 (lead), the approximate areas of impacted groundwater at the Site have decreased with time. While zones of lead and cadmium in groundwater have changed and migrated to some extent over time, the general trends indicate a decrease in concentrations, as presented on Table 3.

The historical groundwater data provided on Table 3, in addition to the trend graphs (Appendix J) based on that data show that the concentrations in groundwater have generally declined when compared to data obtained prior to 2004. The following exceptions to the declining concentration trends were noted, but they are not believed to be material evidence of contrary trends and instead are considered aberrant detections commensurate with the large area of the Site, long period through which it has been monitored, and limited data points needed for averaging and statistical evaluation.

- Lead data from wells 31, SS, ND, and OS appear to be inconsistent with the general trends. However, variance in the data and lower or non-detected dissolved lead data reported in 2010 in groundwater obtained from these locations suggest that the total lead concentrations reported for these wells may in part be related to sampling or analysis (e.g. sediment entrainment in the sample or other interference). Water quality data from 2004, 2007 and 2010 are tabulated in Appendix D.

- A review of the cadmium data provided also shows decreasing concentrations in samples obtained from all but five monitoring wells (26, 31, KDR, NS, and OS).

- An analysis of the trends in historical groundwater pH indicate that pH has increased generally across the Site. The figures showing the change in pH over time as well as tabulated water quality data for 2004, 2007 and 2010 are included in Appendix D.

In general, it appears that lead and cadmium are effectively being removed from groundwater by natural attenuation processes and that collectively the data demonstrate an overall improvement in groundwater quality. Therefore, MNA is an effective remedy.

3.3.2.2 Determination of the Mechanism and Rate of Attenuation

Studies have been conducted at various sites to evaluate the mechanisms and the rate of attenuation of metals in groundwater. For example, Yong et al [1993] determined that:

"At high soil solution pH values, retention of heavy metals by precipitation mechanisms prevails, whereas at low soil solution pH, retention by cation exchange mechanisms becomes dominant."

A study of the cation exchange capacity (CEC) of the soil at the Site revealed that the soil has the capacity to adsorb the lead and cadmium present in groundwater at the Site. As discussed in Section 1.2.4, the adsorption capacity of the aquifer materials at the Site was evaluated as part of the Phase II evaluation, and the results of the CEC analysis are included in Appendix C. As also stated in Section 1.2.4, the capacity of aquifer material to adsorb lead and cadmium is more than sufficient at the Site for groundwater remediation purposes.

Much of the natural attenuation of lead and cadmium occurs through cation exchange. In areas where the groundwater and soil pH equilibrates to a higher pH over time, precipitation is also effective. The presence of iron and manganese oxide/hydroxide coatings on soil particles in the subsurface at the Site were identified as described in Section 1.2.4 and Appendix B. The iron and manganese oxide/hydroxide coatings provide adsorption sites in the soil for lead and cadmium.

Previous studies have shown that the soil at the Site has the CEC and sufficient iron/manganese soil coatings to adsorb the constituents present in groundwater at the Site. However, based upon the most recent groundwater quality data collected by CSI in 2010, the pH and Eh in the central portion of the Site are not ideal for cadmium adsorption to aquifer material. Nonetheless, data showing the general reduction (e.g., declining concentrations) of lead and cadmium concentrations in groundwater is evidence of the attenuative capacity of the subsurface of the Site. The rate of attenuation of these constituents is estimated as the approximate rate of reduction of lead and cadmium concentrations in groundwater.

The rate of attenuation is measurable through trend analysis of historical analytical data for groundwater at the Site. However, based on the limited number of data points and variations within the data, the accuracy of best-fit trend line evaluation is minimal. Performing calculations of concentration increase and decrease can also be used to estimate average attenuation at the Site. Based on the data obtained to date and the trend analysis/attenuation calculations presented in Appendix J and discussed in detail in Section 3.2.2, the decrease of lead and cadmium concentrations is expected to require on the order of 50 or perhaps more years to achieve[6] the cleanup standards based on natural attenuation.

3.3.2.3 Determination of the Long-Term Capacity for Attenuation and Stability of Immobilized Contaminants

The results of the Phase II evaluation documented that the soil has more than enough capacity to adsorb the remaining lead and cadmium present in groundwater at the Site. The stability of the immobilized constituents is directly related to the pH and Eh of groundwater at the Site and the geochemical reactions that occur. Included in the ToxScan Laboratory report provided in Appendix C is a sequential extraction analysis. This analysis used sequentially more acidic solutions to extract cadmium and lead from the soil samples provided. The study concluded that a solution with a pH of less than 2 was needed to extract cadmium and lead from the soil samples at detectable concentrations. The study verifies that after adsorption of lead and cadmium onto soil, it would be reasonably permanent because conditions causing an ambient groundwater pH of 2 or less are very unlikely to occur at the Site. Institutional controls, such as a CEA, would need to be put in place to prevent persons from drinking groundwater until RAOs are achieved.

[6] See footnote 5.

3.3.2.4 Performance Monitoring Plan

MNA for the Site would initially entail quarterly groundwater monitoring for total and dissolved lead and cadmium, VOCs and required MNA water quality parameters (i.e. chloride, nitrate, sulfate, ferrous iron and total alkalinity), at the wells identified on Table 4. The existing monitoring well network would be enhanced by the addition of two monitoring wells to provide additional data along the western perimeter of the Site, as shown on Figure 10. Figure 10 also depicts the locations of the proposed existing and new monitoring wells to be sampled. With the addition of the two new monitoring locations, the monitoring well network will meet the MNA criterion for a monitoring well network outlined in the *Use of MNA at Superfund, RCRA Corrective Action and Underground Storage Tank Sites* guidance document produced by the EPA in 1999. The criterion outlined in this EPA guidance [EPA, 1999] includes:

- The ability to verify that the impacted zones of groundwater are not expanding (either downgradient, vertically or laterally);
- The ability to verify no unacceptable impact to downgradient receptors;
- Demonstrate that natural attenuation is occurring according to expectations;
- Identify any toxic and/or mobile transformation products;
- Detect changes in environmental conditions (i.e. hydrogeologic, geochemical, microbiological or other changes) that may reduce the efficacy of natural attenuation process;
- Detect new releases of chemicals to the environment that could impact the effectiveness of the natural attenuation remedy;
- Demonstrate the efficacy of institutional controls that were put in place to protect potential receptors; and
- Verify attainment of remediation objectives.

Sampling would be conducted as defined in CSI's *Groundwater Monitoring Plan for the NL Industries Superfund Site* [CSI, 2006] to provide the data needed to evaluate MNA. The plan outlines sampling methods and quality assurance procedures to be performed. The plan would be modified to include additional analyses required to satisfy the MNA criterion (i.e. by adding sulfate, nitrate and chloride). A letter report documenting the results of each quarterly sampling event would be provided to the EPA following each event. At the end of one calendar year of sampling, recommendations would be made to modify the sampling program based upon the data obtained. The monitoring program may be modified over time, as appropriate.

3.3.2.5 Proposed Triggers for Determining MNA Failure or Success

The anticipated triggers for determining failure of the MNA remedy at the Site would be the confirmed detection of lead and/or cadmium at a location where no detections were previously reported and/or an order of magnitude increase in concentration of any COC at any well. The MNA remedy would be considered a success provided the concentrations of the COCs trend downward over time such that even with some perturbations and variations in COC concentrations and trends, the weight of

evidence indicates improving groundwater quality. MNA would be considered complete when all sampled wells contained no COCs above the cleanup standards identified for the Site as outlined on Table F of the ROD [EPA, 1994] included in Appendix A.

Threshold Criteria

Overall Protection of Human Health and the Environment

The MNA alternative, coupled with institutional controls restricting exposure to groundwater in the unconfined aquifer in the affected area of the Site, would be protective of overall human health and the environment. By restricting access and by restricting use of the impacted groundwater, human health will be protected. The limited mobility of lead and cadmium in groundwater at the Site will ensure that impacted groundwater does not migrate from the Site. Long-term groundwater monitoring would be performed as part of efforts to ensure the effectiveness of the remedy.

Compliance with ARARs

The ARARs identified for this alternative include the following chemical-specific ARARs; location and action-specific ARARs do not apply to this alternative:

<u>Potential Chemical Specific ARARs:</u>

<u>Federal</u>

- Clean Water Act, Water Quality Criteria
- RCRA Ground Water Protection Standards (40 CFR Part 264.94)
- Federal Water Quality Criteria (51 *Federal Register* 436665)
- Federal MCLs

<u>New Jersey</u>

- New Jersey Ground Water Quality Standards (NJGWQS) (NJAC 7:9-6)
- New Jersey MCLs

The most stringent of the federal and state standards will be used to determine whether the RAO for restoring the confined aquifer to drinking water standards has been met. It is estimated to require more than 50 years to achieve the groundwater cleanup standards under the MNA scenario. The groundwater monitoring program will provide ample opportunities to document effectiveness and any changes that may occur in groundwater.

Primary Balancing Criteria

Long-Term Effectiveness and Permanence

A high degree of long-term effectiveness and permanence can be achieved by MNA. As demonstrated by the historical data provided on Table 3 and illustrated in Figures 4 and 5, lead and cadmium are relatively immobile in groundwater at the Site. Lead tends to be detected more prevalently in the shallow zone of the unconfined aquifer where groundwater is better aerated, but where pH is low. Cadmium tends to be detected more prevalently in the deeper zone of the unconfined aquifer where groundwater lacks dissolved oxygen (probably due to less contact with air in the vadose zone and biochemical reactions) and Eh is more generally reducing. As conditions return to a neutral pH over time and conditions become less reducing (i.e. increasing Eh), groundwater quality will improve more rapidly.

The low pH on the Site is a result of the former secondary lead smelting and lead-acid battery reclamation operations; however, other activities such as anaerobic bacterial reactions may also contribute to low pH to a much smaller degree. Anaerobic bacteria tend to thrive under reducing conditions. These reducing conditions are exacerbated by the dissolved metals: lead and cadmium. Most anaerobic bacteria produce acidic compounds which depress pH. As groundwater with dissolved oxygen replenishes the target zones, anaerobic bacterial activity will decline, along with the production of pH depressing acidic by-products. Thus, as discussed above, with the removal of source material and decreased bacterial activity, the groundwater pH should slowly recover to a more neutral pH. The average ambient pH for the Site is between a pH of 5 and 6.

As the pH levels in the central portion of the Site (particularly near wells OS and KS/KD) increase over time, lead and cadmium are expected to continue to adsorb onto soil particles. Iron and manganese oxide/hydroxide coatings on soil particles at the Site provide adsorption sites for lead and cadmium. The aquifer materials contain more than sufficient capacity to adsorb the amount of lead and cadmium present in groundwater at the Site, without adverse impact in soil. The transfer of lead and cadmium from groundwater to aquifer materials at the Site is desirable and permanent, provided that geochemical conditions, as described in Section 1.2.4 are achieved and maintained.

Reduction of Toxicity, Mobility, or Volume

As indicated, it is anticipated that cleanup goals will be achieved in more than 50 years using unenhanced natural attenuation. Toxicity, mobility, and the volume of lead- and cadmium-impacted groundwater will steadily decline to insignificant levels during this period.

The limited mobility of lead and cadmium in groundwater has been documented through historical groundwater monitoring (the data are provided on Table 3 and are shown in Figures 4 and 5). These data demonstrate that, although mobility of lead and cadmium is possible depending on geochemical conditions, the area of impacted groundwater containing elevated concentrations of lead and cadmium has remained generally in the same location since 1983.

The volume of impacted groundwater has declined considerably since the 1980s. The current volume of groundwater calculated to be impacted by lead at concentrations above the NJGWQS at the Site is approximately 1.5 million gallons. The volume of water calculated to be impacted by cadmium concentrations above the NJGWQS is approximately 11.8 million gallons. The current mass of lead remaining in groundwater at the Site (2.7 lbs) was calculated to be 0.7% of the mass in 1983. The current mass of cadmium in groundwater at the Site (5.9 lbs) was calculated to be 9.1% of the 1988 mass. Therefore, the volume of contaminated groundwater at the Site has reduced dramatically in little more than 20 years through source removal and natural attenuation processes.

Short-Term Effectiveness

The MNA alternative is estimated to require a period of more than 50 years to achieve the RAOs. Impacts associated with the construction and implementation phase of Alternative 2 are expected to be minimal; however, interim measures, including monitoring and implementation of institutional controls, will be required to provide continued protection of human health and the environment.

Implementability

Alternative 2 – MNA Plus Institutional Controls is technically and administratively feasible to implement. The procedures for performing the required groundwater monitoring are already in place with approved groundwater monitoring and quality assurance plans [CSI, 2006]. Installation of additional monitoring wells to satisfy EPA's MNA monitoring well network criterion can be accomplished through the use of a New Jersey licensed well driller. The implementation of institutional controls is also feasible. There are no foreseeable technical obstacles to prevent implementation of the MNA alternative.

Cost

A cost estimate to perform MNA at the Site is presented on Tables 5 and 6. Table 5 presents the cost for performing one round of groundwater monitoring at the wells identified on Table 4. Samples will be analyzed for total and dissolved lead and cadmium, other metals, and VOCs as well as the required

MNA water quality parameters (i.e. chloride, nitrate, sulfate, ferrous iron, and total alkalinity). Table 6 includes the present worth cost of a thirty-year monitoring program.

For purposes of the cost estimate, the monitoring program is assumed to require two years of quarterly sampling, three years of semi-annual sampling and twenty-five years of annual sampling. The monitoring frequency would be adjusted based on the data obtained; however these assumptions were used to develop the cost estimate provided on Table 6. A present worth of $1,213,204 is estimated for a thirty-year monitoring period using the above assumptions. As discussed above in Section 3.3.1, it is anticipated that two additional wells would need to be installed at the Site for adequate monitoring of the western perimeter. This would entail a one-time cost of approximately $20,000 that is included in the cost estimate provided on Table 6.

Modifying Criteria

State/EPA Acceptance

This criterion can be further evaluated after input from the State.

Community Acceptance

This criterion will be gauged after the Focused Feasibility Study and Proposed Plan are released for public comment.

3.4 Alternative 3 - Reagent Injection Plus Institutional Controls

3.4.1 Description of Reagent Injection

Reagent injection involves the introduction of a reagent into the water table aquifer using injection wells or well points to be installed at a later date. The reagent applied will be selected based upon the results of the bench scale treatability study (BSTS), as presented in Appendix E and a field pilot study, which would be conducted as part of the RD. Preliminarily, the results of a BSTS reveal that phosphate reagents will be highly effective for both lead and cadmium in groundwater. The use of phosphates for treating lead impacted soils and waters has been widely used to immobilize inorganic constituents including lead. A field scale study, to be conducted at a later date, should be used to confirm effectiveness at this Site and assist in calculating parameters required for successful remediation (i.e. number of well points, spacing, application method, etc).

The reagent injection technique is based on the fact that metals dissolved or entrained in groundwater may react to form insoluble compounds and precipitate, or otherwise be immobilized by adsorption onto a substrate (i.e. the native soil) and/or by incorporating the metal into a molecular structure (interculation) which may then adsorb or become incorporated into soil as a complex or precipitate [Water Remediation Technologies (WRT), 2007]. A more alkaline environment (i.e., pH of approximately 8.0

to 9.0) will be created through addition of a basic compound to promote reactions between the native metals and the soil. Prior to the injection of reagents a basic solution, such as sodium hydroxide, can be used to increase the pH of the groundwater in localized areas to promote subsequent removal of lead and cadmium from groundwater when the reagent is injected. The increased pH value is not required to be maintained following reagent injection and will return to ambient levels (i.e., pH of approximately 5.0 to 6.0) over time.

Generally speaking, precipitation reactions, such as those induced through certain injection reagents including phosphates, tend to react with elements and compounds following a kinetic order of reaction. The order of reaction varies from compound to compound and with the geochemical conditions in which the reagent is applied (e.g., pH and reagent concentration). For example, when phosphate is injected into groundwater it tends to react with dissolved lead before dissolved cadmium (based upon their individual solubility products). Concentration can have an effect on the order of reaction, but not at the relatively low concentrations of lead and cadmium detected at the Site.

Solubility products (Ksp) are often useful for predicting reaction sequences among compounds. Smaller solubility products indicate a less soluble compound and one likely to form before a more soluble compound under given conditions. The following Ksp values[7] illustrate that lead phosphate is more likely to form first among the compounds listed because it has the lower solubility product.

Aluminum phosphate	Ksp = 6.3×10^{-19}
Calcium phosphate	Ksp = 1.0×10^{-29}
Cadmium phosphate	Ksp = 1.0×10^{-31}
Lead phosphate	Ksp = 1.0×10^{-42}

These Ksp values indicate that lead phosphate is significantly less soluble than cadmium phosphate, calcium phosphate, or aluminum phosphate. Cadmium is included due its presence at elevated concentrations at the Site. Aluminum and calcium are included because they are typically found in groundwaters and will have a tendency to consume some of the reagent injected into the subsurface. It is expected that lead and cadmium will react with the phosphates first followed by calcium and aluminum.

The low Ksp values also indicate that phosphate would be a good candidate for immobilizing lead and cadmium with minimal consumption from non-target compounds like calcium and aluminum. To determine the appropriate amount of phosphate needed to overcome its consumption by non-target compounds, a reagent demand test is usually incorporated into the pilot test. This test is used to assess the impact of phosphate consumption from non-target compounds and help determine an appropriate concentration of the reagent.

[7] Bard, Allen J. (1966). *The Handbook of Chemical Equilibrium,* Department of Chemistry, University of Texas, Published by Harper and Row, Appendix C.2

Many of the available reagents are commonly used in water treatment applications. For example, trisodium polyphosphate (TSPP) is used in drinking water systems and has been found to have no deleterious environmental impacts. However, one of the goals of pilot testing will be to determine the amount of reagent required to minimize unreacted phosphate.

Several studies[8] have been conducted to assess potential plugging of the aquifer pores from reagent precipitation. Generally, those studies have shown that the volume of precipitate that forms is inconsequential relative to the surrounding pore space. It is possible for phosphate to react with calcium to form insoluble calcium phosphate. However, very large quantities of phosphate, which greatly exceed those contemplated for this project would be required to "plug" a formation. Therefore, if any pore spaces are filled with precipitates, it will be a small amount that will not adversely affect water flow or the effectiveness of the remedy.

The locations at which the pH adjustment and reagent injection will occur will be determined based upon the results of a pilot study and subsequent groundwater monitoring. However, for the purpose of this FFS, CSI assumed that four injections over the course of one year, through 12 injection points, may be sufficient to achieve the cleanup standards for all COCs, primarily targeting lead and cadmium, in groundwater at the Site. This estimate can be refined after field scale studies are conducted. It will also be necessary to adjust the pH of the impacted groundwater to be higher than 3 and preferably to between 8 and 9. The volume of sodium hydroxide (NaOH) required to adjust twenty-five million gallons of water from a pH of 3 to 4 to between 8 and 9 is approximately 5,000 pounds. This pH adjustment is a one-time event, prior to each injection, which will not require substantial maintenance. It is done prior to reagent injection to promote precipitation and adsorption reactions. Some proposed locations for reagent injection will most likely include separate injection points in the areas surrounding monitoring wells OS, KDR, KDS, SS, and SD. Installation of a well point grid in these areas for performing the reagent injections is anticipated. A conceptual representation of the reagent injection process is presented on Figure 11.

The most effective methodology for implementing reagent injection would be determined during a pilot study. The pilot study would involve the installation of injection points in the vicinity of two or three highly impacted wells. Different methods for NaOH and reagent distribution would then be tested at the separate locations to determine the most effective means of delivering the NaOH and reagent to the impacted groundwater. Groundwater quality data, particularly pH, and groundwater samples would be obtained periodically from nearby wells to assess the success of distribution. As this is a commonly practiced remedial technique where successful distribution methods have been developed, the Group would rely upon the existing literature to develop distribution methods with a high probability for success. The pilot study would require a period of 3-4 months to perform and achieve the goals of determining the most effective injection

[8] Long Term Performance of Permeable Reactive Barriers Using Zero Valent Iron: Geochemical and Microbiological Effects" by R.T. Wilkin, R.W. Puls, and G.W. Sewell. GROUNDWATER 41, no. 4, pp 493-503.

methodology as well as determining the amount of reagent and NaOH necessary to reduce lead and cadmium concentrations in groundwater.

The effectiveness of the reagent injection alternative would be assessed by periodic groundwater sampling and analysis. For cost estimating purposes, it is assumed that quarterly sampling will be performed initially, followed by semi-annual and annual sampling. The monitoring frequency will be modified based upon the data obtained during the pilot study and initial post-reagent injection monitoring events. The groundwater monitoring program would be similar to the program outlined above for the MNA remedy. Institutional controls would also be implemented as part of Alternative 3 to prevent exposure to contaminated groundwater until RAOs are achieved.

3.4.2 Evaluation of Reagent Injection

Groundwater samples were obtained from wells JDR, JS, KDR, KSR, NS, OS, SD, SS, 11, 23, 31, and 34 and analyzed for dissolved iron, total iron, alkalinity, hardness, BOD, COD, chlorides, and sulfate in April 2007. The analytical data from these samples, summarized on Table 7, along with the results from a bench scale treatability study (BSTS) were used to evaluate the reagent injection alternative.

3.4.3 Bench Scale Treatability Study

CSI retained WRT in 2007 to perform a BSTS on samples of groundwater obtained from the Site. The purpose of the BSTS was to preliminarily identify reagents that effectively cause a decrease in lead and cadmium concentrations in the water samples and to tentatively estimate dosing requirements for field application. Based upon WRT's experience and expertise with treating inorganics in groundwater, the reagents tested were limited to phosphates and sulfates. These reagents are the most technically viable for the treatment of lead and cadmium in groundwater.

CSI obtained 5-gallon samples of groundwater from four representative wells (OS, SS, SD, and KDR). The well locations were chosen based on the results of the April 2007 groundwater monitoring event. Monitoring wells containing the highest concentrations of lead and cadmium from the Site were chosen. The aliquots of groundwater were sent to WRT to perform a BSTS. WRT performed the BSTS using the following procedures:

- Separated aliquots of groundwater into multiple beakers;
- Added a known amount of a single reagent into each beaker and stirred using gang stirrer or similar device at low revolutions per minute (<50);
- Monitored the formation of any precipitates;
- Filtered the supernatant and analyzed the supernatant for lead and cadmium using EPA Method 200.8;
- Evaluated results and varied reagent addition, as necessary.

WRT's report containing the BSTS results and a March 2009 memorandum providing additional information on the formation of metal phosphates are provided in Appendix E. The following is a summary of the main findings of the BSTS:

- The three reagents tested were organosulfur (Test A), organosulfur with pH adjustment (Test B) and sodium polyphosphate (Test C);
- The range of post-adjustment pH values associated with Test B and C were between 8.48 and 9.39. No pH adjustment was performed for Test A.
- All three reagents were effective in reducing lead and cadmium concentrations in the samples provided;
- Organosulfur with pH adjustment (Test B) and sodium polyphosphate (Test C) both reduced lead and cadmium concentrations to below detectable limits for all four sample aliquots;
- The cost for treatment of 1000 gallons of water using sodium polyphosphate is dramatically less than using organosulfur with pH adjustment.

In summary, the BSTS was successful in demonstrating that reagent injection using sodium polyphosphate is effective at precipitating lead and cadmium and is a cost effective and viable remedial alternative for this Site. Further studies are needed during the Remedial Design process to confirm the precipitation mechanism, ultimate stability of the precipitated metals and to make a final determination on the most effective reagent.

Threshold Criteria

Overall Protection of Human Health and the Environment

The reagent injection alternative and the implementation of institutional controls will effectively achieve overall protection of human health and the environment by reducing lead and cadmium concentrations in groundwater to concentrations below the NJQWQSs and restricting groundwater usage until RAOs have been achieved.

Compliance with ARARs

The following ARARs have been determined to be potentially applicable to this alternative:

<u>Potential Chemical Specific ARARs:</u>

<u>Federal</u>

- Clean Water Act, Water Quality Criteria
- RCRA Ground Water Protection Standards (40 CFR Part 264.94)
- Federal Water Quality Criteria (51 *Federal Register* 436665)
- Federal MCLs

New Jersey

- New Jersey Ground Water Quality Standards (NJGWQS) (NJAC 7:9-6)
- New Jersey MCLs

Potential Action Specific ARARs

Federal

- RCRA Groundwater Monitoring and Protection Standards (40 CFR 264, Subpart F)
- EPA Action Level for Lead in Drinking Water

Potential Location Specific ARARs

Federal

- Fish and Wildlife Coordination Act (16 USC 661 et seq.)
- National Environmental Policy Act (42 USC 4341 et seq.)
- Endangered Species Act
- Coastal Zone Management Act
- Farmland Protection Policy Act

New Jersey

- New Jersey Rules on Coastal Resources and Development (7:7E-1.1 et seq.)
- New Jersey Freshwater Wetlands Regulation

The reagent injection alternative is compliant with all ARARs. Based on the BSTS results, NJGWQSs are expected to be met for groundwater at the Site in less than approximately ten years using this remedial alternative, therefore achieving all ARARs considered for this Site. This estimate is based upon the documented decreases in the lead and cadmium concentrations which have been observed in the groundwater data collected at the Site to date. Specifically, current trends in groundwater concentrations have generally decreased in most monitoring wells through natural attenuation mechanisms. Pilot testing will be required to more accurately determine the anticipated timeframe for meeting the cleanup standards and achieving the RAOs.

The specific grades of inorganic phosphates proposed for use are approved for direct contact with drinking water by the National Sanitation Foundation (NSF), Section 61. The inorganic phosphorous should be consumed in beneficial reactions while stabilizing and immobilizing the target compounds. If there is any excess phosphorous, migration should be minimal, given its

tendency to react with numerous metals typically found in soil. Unreacted phosphorous should be non-toxic, assuming NSF approved product is utilized. Thus, the use of the reagents in groundwater are not anticipated to affect any other applicable chemical or location specific ARARs; however, groundwater monitoring would be performed to ensure that no other criteria are exceeded.

Primary Balancing Criteria

Long-Term Effectiveness and Permanence

The preferred reagent injection technology is to permanently remove cadmium and lead from solution by precipitating them as metal phosphates. This removes the contaminants from solution and provides groundwater that meets or exceeds the cleanup standards.

The metals are incorporated into a crystalline lattice using the phosphate precipitation process. The crystalline lattice consists of calcium phosphate and either lead or cadmium phosphate. Metal phosphates are highly insoluble [Nriagu, 1984] and, it has been suggested, their low solubility renders metals in metal phosphates non-bioavailable [e.g. Ma *et al*., 1993; Cotter-Howells and Caporn, 1996]. Over the long-term, it is anticipated that the pH levels in groundwater at the Site will equilibrate to ambient levels, typically between pH 5 and 6. The ambient pH will not cause any significant resolubilization of lead or cadmium after the metals have reacted to form metal phosphate compounds and/or they have adsorbed to soil.

Included in the Toxscan Laboratory report provided in Appendix C are the results of a sequential extraction analysis performed on soils from the Site. This analysis used sequentially more acidic solutions to extract cadmium and lead from the soil samples that were tested. The study concluded that a solution with a pH of less than 2 was needed to extract cadmium and lead from the soil samples at detectable concentrations. The results of the study suggested that after adsorption of lead and cadmium onto soil, it would be unlikely that the metals would resolubilize. The phosphate precipitates also formed through reagent injection would be of comparable solubility and thus the interculation of cadmium and lead in these precipitates may be regarded as permanent. Additional information regarding the solubility of metal phosphates is provided in Appendix E. Therefore, the reagent injection alternative provides a high degree of long-term effectiveness and permanence.

Reduction of Toxicity, Mobility, or Volume

The formation of metal phosphates is known to remove cadmium and lead from solution and is used to treat groundwater to meet the RAOs. The metals are adsorbed onto soil or incorporated into metal phosphate compounds using the reagent injection process. Precipitation and adsorption is done in-situ, so there are no wastes produced through this treatment process. The precipitation

and adsorption processes will effectively reduce contaminant mobility and volume which in turn reduces toxicity.

The volume of impacted groundwater is expected to continue decreasing naturally as is evident through analysis of historical data provided on Table 3 and Figures 4 and 5. The volume of impacted groundwater at the Site is approximately 1.5 million gallons (lead) and 11.8 million gallons (cadmium). Reagent injection is anticipated to increase the rate of reduction in volume of impacted water. It is anticipated with reagent injection that the total volume of contaminated groundwater can be treated in less than 10 years. Pilot testing is required for a more precise estimate.

The low concentrations of VOCs currently present at the Site will continue to degrade naturally after implementation of the reagent injection alternative. The reagent injection alternative is not anticipated to adversely affect VOC concentrations.

Short-Term Effectiveness

Institutional controls will assure short-term protectiveness by preventing or minimizing potential current and future human exposures until the groundwater cleanup standards are achieved.

Implementability

The technology is simple and relatively easy to implement. The reagents are safe and can be applied with standard personal protective equipment. The reagents can be injected relatively easily into the shallow, sandy Site subsurface using a Geoprobe™ to install well points. Pilot testing would be conducted to determine the most effective means of introducing the reagents into the shallow aquifer at the Site. These reagent introduction methods may include methods such as the installation of large tanks with manifold systems to drip the reagents into the various well points to simply pouring the reagents from small containers directly into the well points. Likewise, should additional evaluations regarding the permanence of the remedy be needed, they will be defined and performed as part of pilot studies. Reagents are relatively inexpensive and readily available.

Cost

Costs for the sodium polyphosphate reagents as estimated in the BSTS [WRT, 2007] are between $1 and $9 per 1000 gallons treated (a median cost of $5 was used for this cost estimate). The actual cost is contingent upon the number of injections required to treat the maximum of 11.8 million gallons of impacted groundwater at the Site. CSI assumed that four injections over the course of one year, through 12 injection points, will be sufficient to achieve the cleanup standards for groundwater at the Site. The pH adjustment was

also factored into the cost of this alternative. This pH adjustment is a one-time event, prior to each injection, which will not require substantial maintenance. It is done prior to reagent injection to promote precipitation and adsorption reactions. Table 8 provides an estimate for performing the four reagent injections and pH adjustment. Table 9 provides a present worth cost calculation for performing this work. The present worth cost for performing the reagent injection alternative as described above is approximately $890,489.

The costs for performing associated groundwater monitoring activities are included on page 1 of Table 9 which depicts "present worth values." The scope of groundwater monitoring activities incorporates the MNA remedial alternative described above and uses a monitoring period of up to ten years (estimated to be two years of quarterly monitoring, three years of semi-annual monitoring, and five years of annual monitoring with well installation in the first year), the cost for performing groundwater monitoring is approximately $684,766. Monitoring frequencies will be adjusted based upon the pilot study and post-reagent injection sampling results. With groundwater monitoring the total cost for this alternative is estimated to be $1,575,255.

3.5 Alternative 4 – Pump and Treat Plus Institutional Controls

3.5.1 Description of Pump and Treat

The groundwater remedial alternative that was selected in the ROD [EPA, 1994] was the "extraction and treatment of contaminated groundwater with direct discharge of the treated groundwater to the Delaware River." This alternative, as initially described by O'Brien & Gere in the 1993 FS, involved the use of a well point system at the Site that no longer exists. O'Brien & Gere initially specified 49 well points to contain water within the Site. Water would be pumped from these well points and manifolded into four sub-systems which would pump the water to the treatment facility. The treatment method prescribed in the FS [O'Brien & Gere, 1993] was precipitation/flocculation followed by an ion exchange polishing step. Following treatment, the water would then need to be pumped to the Delaware River. An effluent outfall would have to be constructed at the discharge location. The distance from the railroad tracks on the Site to the Delaware River is approximately 1 ½ miles. For the purposes of this FFS, institutional controls would also be included to prevent exposure to contaminated groundwater until all RAOs are achieved.

3.5.2 Evaluation of Pump and Treat

The pump and treat remedial alternative was extensively evaluated in a pilot study performed at the Site in 1999 and described in the Phase II Technical Memorandum [GeoSyntec, 2000]. An aquifer test was performed to (i) confirm the hydraulic parameters determined by Geraghty and Miller in 1983; (ii) predict the performance of a groundwater extraction system that might be designed to remove lead and cadmium from the aquifer; and (iii) establish input parameters for capture zone modeling as requested by

the EPA [GeoSyntec, 2000]. The applicable text, tables, and figures from the Phase II Technical Memorandum [GeoSyntec, 2000] regarding the aquifer test results are attached in Appendix G. The salient point obtained from the aquifer test is that although groundwater was extracted, very little lead and cadmium were removed from the subsurface in the groundwater that was extracted.

In order to calculate the length of time it would take to extract the mass of lead and cadmium calculated to be present in groundwater at the Site (see Table 9-6 in Appendix G), constant extraction concentrations of 1 µg/L and 2 µg/L for lead and cadmium, respectively, were used. These extraction concentrations were used because they are greater than the extraction concentrations for lead and cadmium observed during the aquifer test; therefore, they provide a conservative and valid demonstration of the remedy's ability to extract these contaminants using pump and treat techniques. Based upon these assumptions, GeoSyntec calculated that it would require approximately 61 years of constant pumping to remove the estimated 9 lbs of lead calculated to remain in groundwater at that time. The 14 lbs of cadmium calculated to be present in groundwater at that time would require approximately 48 years [GeoSyntec, 2000] of constant pumping.

The Phase II Technical Memorandum [GeoSyntec, 2000] results are supported by the literature regarding inorganic contaminants in groundwater. In *Remediation of Metals-Contaminated Soils and Groundwater* [Evanko and Dzombak, 1997], the author stated that "[t]ypically metals are relatively immobile in subsurface systems as a result of precipitation or adsorption reactions." Specifically, many studies regarding lead indicate that "most lead that is released to the environment is retained in soil" [Evans, 1989]. Furthermore, the processes of adsorption, ion exchange, precipitation, and complexation with sorbed organic material limit the amount of lead that can be transported into surface water or groundwater [Evanko and Dzombak, 1997].

Cadmium is more soluble under the conditions encountered at the Site than lead. Under acidic groundwater conditions, such as those found in the central portion of the Site, cadmium reacts with hydroxide, carbonate, chloride and sulfate to the extent they are present.

When pumping is conducted in an area where the groundwater pH is low, the pumping process may initially allow for the removal of constituents at that location. However, as pumping continues, water is drawn into that well from more distant areas which affects the geochemical characteristics of the area pumped. This can be counterproductive as the changes in geochemical parameters cause the mobility of the COCs to decrease temporarily, thus reducing the ability to extract them. The inefficiencies of the pump and treat technique was demonstrated by the aquifer test performed for the Phase II Technical Memorandum [GeoSyntec, 2000], the results of which are provided in Appendix G. The results indicated that lower concentrations of the metals were removed as pumping progressed. It may be possible to address inefficiencies associated with the pump and treat technology for this Site through engineering and optimization techniques to increase contaminant mass removal, but the issue is not

certain. A significant effort would be required to identify and evaluate ways to compensate for the inefficiencies inherent in the pump and treat technology.

Threshold Criteria

Overall Protection of Human Health and the Environment

Overall protection of human health and the environment can be achieved with this alternative when combined with institutional controls; however, based upon the results of the aquifer test reported in the Phase II Technical Memorandum (Appendix G), this alternative is unlikely to appreciably reduce concentrations of lead and cadmium in groundwater in a reasonable time period.

Compliance with ARARs

The following ARARs have been determined to be potentially applicable to this alternative:

Potential Chemical Specific ARARs:

Federal

- Clean Water Act, Water Quality Criteria
- RCRA Ground Water Protection Standards (40 CFR Part 264.94)
- Federal Water Quality Criteria (51 *Federal Register* 436665)
- Federal MCLs

New Jersey

- New Jersey Ground Water Quality Standards (NJGWQS) (NJAC 7:9-6)
- New Jersey MCLs

Potential Action Specific ARARs

Federal

- RCRA Groundwater Monitoring and Protection Standards (40 CFR 264, Subpart F)
- Clean Water Act – NPDES Permitting Requirements for Discharge of Treatment System Effluent (40 CFR 122-125)
- EPA Action Level for Lead in Drinking Water

New Jersey

- New Jersey Pollutant Discharge Elimination System Regulations (NJPDES) and Effluent Limitations (NJAC 7:14A et seq)

Potential Location Specific ARARs

Federal

- Fish and Wildlife Coordination Act (16 USC 661 et seq.)
- National Environmental Policy Act (42 USC 4341 et seq.)
- Endangered Species Act
- Coastal Zone Management Act
- Farmland Protection Policy Act

New Jersey

- New Jersey Rules on Coastal Resources and Development (7:7E-1.1 et seq.)
- New Jersey Freshwater Wetlands Regulation
- New Jersey Pollutant Discharge Elimination System Regulation

ARARs can be achieved through the implementation of the pump and treat technology; however, given the inefficiencies inherent with this technology and the treatment of inorganics, the process is anticipated to take more than 50 years. Additional action-specific ARARs would need to be considered for this remedy such as the Clean Water Act NPDES permitting requirements and NJPDES effluent limitations for the discharge of extracted groundwater.

Primary Balancing Criteria

Long-Term Effectiveness and Permanence

Reductions in concentrations of lead and cadmium in groundwater can be achieved by active pumping and treating of impacted groundwater; however, the anticipated length of time to achieve RAOs using Alternative 4 would remain in the 68-134 year timeframe. Once concentrations have been reduced to levels below the RAOs, it is anticipated that this would be a permanent condition, provided that favorable geochemical conditions are maintained.

Reduction of Toxicity, Mobility, or Volume

As discussed above under long-term effectiveness and permanence, it is anticipated that toxicity, mobility, and the volume of lead and cadmium-impacted groundwater would steadily decline and groundwater cleanup standards would be achieved in more than 50 years under the pump and treat alternative.

More than 150,000 tons of impacted soil was excavated, stabilized and disposed off-Site during the remedial action for soil that was completed in May 2003. This source removal has contributed to the current limited mobility of the contaminants in groundwater. Contaminant concentrations in groundwater have been documented through historical groundwater monitoring data provided on Table 3 and shown in Figures 4 and 5. The data demonstrates that, in general, the impacted groundwater containing elevated concentrations of lead and cadmium persists generally in the area beneath the former facility where the highest concentrations of contaminants were initially found, but has continued to decrease in volume since 1983.

As discussed above under the No Action alternative, the volume of impacted groundwater has declined considerably since the 1980s thru natural processes. The current mass of lead remaining in groundwater at the Site was calculated to be 0.7% of the mass in 1983. The current mass of cadmium in groundwater at the Site was calculated to be 9.1% of the 1988 value. Therefore, significant contaminant reductions have already been achieved in the past 20 years in the absence of an active remedy. Implementation of a groundwater pump and treat system is anticipated to foster further reductions of contaminants and ultimately achieve groundwater RAOs in more than 50 years.

Short-Term Effectiveness

The pump and treat alternative is expected to achieve RAOs in a more than 50 year timeframe. Greater initial reductions in lead and cadmium are expected in the short-term. However, the Phase II [GeoSyntec, 2000] aquifer test results (Appendix G) indicate that after the initial lead and cadmium is removed in the vicinity of the well point by pumping, the rate of lead and cadmium removal quickly approaches zero. Impacts associated with construction and implementation phase of Alternative 4 are expected to be minimal; however, construction of the treatment plant may impact surrounding wetland areas depending on the location of the plant and access to the construction Site. Interim measures, including monitoring and implementation of institutional controls, will be required to provide continued protection of human health and the environment in the short- and long-term.

Implementability

The construction of a groundwater extraction system requires reasonably routine construction techniques. The discharge of treated water, which as specified in the ROD will require discharge to the Delaware River, will necessitate effective wastewater treatment techniques that operate continually. Discharge to the Delaware River will require the construction of approximately 1.5 miles of discharge piping and appurtenances. The piping will require protection for heavy equipment and the elements and will have to include access for repair and maintenance. The construction period for such a system would be greater than a year and would be a significant undertaking.

Access to properties owned by others will need to be negotiated and secured for an extended period and a discharge permit would be required. Should this alternative be selected, then additional discharge options should be considered.

Cost

A cost estimate for the pump and treat alternative of $10.1 million was calculated in 1993 [O'Brien & Gere, 1993]. The actual cost of the alternative, including long term operation and maintenance and thirty years of groundwater monitoring, may be somewhat lower due to a smaller area of impact at the Site today than was present in 1993 and is estimated to be approximately $5.7 million. Table 10 depicts the breakdown of the current cost estimate in 2011 dollars.

Modifying Criteria

State/EPA Acceptance

This criterion can be further evaluated after input from the State.

Community Acceptance

This criterion will be gauged after the Focused Feasibility Study and Proposed Plan are released for public comment.

4. COMPARATIVE ANALYSIS OF REMEDIAL ALTERNATIVES

4.1 Overview

A comparative analysis of the retained remedial alternatives for each of the nine criteria is provided below, with the exception of State/EPA and Community Acceptance which will be evaluated after this document has been reviewed by the public.

Threshold Criteria

Overall Protection of Human Health and the Environment

The evaluation focuses a specific alternative's ability to provide adequate protection of human health and the environment, and how Site risks associated with each pathway are eliminated, reduced or controlled through treatment, engineering or institutional controls.

Alternative 1, No Action, will not be protective of human health and the environment because this alternative does not include implementation of institutional controls to restrict the use of contaminated groundwater and does not include monitoring to determine when the applicable standards have been met and the RAOs have been achieved. Alternative 2 – MNA Plus Institutional Controls, Alternative 3 – Reagent Injection Plus Institutional Controls and Alternative 4 – Pump and Treat Plus Institutional Controls are all protective of human health and the environment as they all include institutional controls, will result in the decrease of Site-related contaminants and include a monitoring plan to determine when the RAOs have been achieved. However, Alternatives 2, 3 and 4 are estimated to achieve the cleanup standards in varying lengths of time.

Compliance with ARARs

The three broad categories of ARARs include chemical-specific, location-specific and action-specific ARARs. ARARs have been established for groundwater as part of the OU1 remedial action objective to restore the unconfined aquifer to drinking water standards. A listing of these ARARs for the Site is provided in Section 2.2.1. Alternative 1, No Action, would not comply with ARARs since a determination as to whether or not the applicable standards have been met would not be able to be made due to the lack of monitoring. Alternatives 2, 3 and 4 are expected to comply with the applicable ARARs.

Primary Balancing Criteria

Long-Term Effectiveness and Permanence

Long-term effectiveness and permanence refer to the ability of a remedy to reliably maintain protection of human health and the environment over time, once

remedial activities have been completed. Factors which are considered include the magnitude of residual risks remaining following remedial action, and adequacy and reliability of the engineering and institutional controls, if used to manage untreated wastes or treatment residuals.

The highest degree of permanence and long-term effectiveness is achieved for those alternatives that result in the greatest removal of contaminants from the Site. Alternative 1, No action, does not provide a mechanism to monitor contaminant migration or attenuation; therefore long-term effectiveness and permanence cannot be determined. Alternative 2 – MNA Plus Institutional Controls, Alternative 3-Reagent Injection Plus Institutional Controls and Alternative 4-Pump and Treat Plus Institutional Controls are all expected to mitigate long-term risks from Site contaminants; however, Alternative 3 – Reagent Injection Plus Institutional Controls has a higher degree of permanence due to the chemical reaction with the reagent in which the primary contaminants of concern, lead and cadmium, are bound in less soluble metal complexes.

The Alternative 3 reagent injection technology permanently removes cadmium and lead from solution by precipitating them as metal phosphates. The metals are incorporated into a crystalline lattice using the phosphate precipitation process. Metal phosphates are highly insoluble [Nriagu, 1984] and, it has been suggested, their low solubility renders metals in metal phosphates non-bioavailable [e.g. Ma *et al*., 1993; Cotter-Howells and Caporn, 1996]. Over the long-term, it is anticipated that the pH levels in groundwater at the Site will equilibrate to ambient levels, typically between pH 5 and 6. The ambient pH will not cause any significant resolubilization of lead or cadmium after the metals have reacted to form metal phosphate compounds and/or these phosphate compounds have adsorbed to the aquifer materials. Resolubilization is a potential concern with Alternative 2. If there were to be a scenario where there was a significant shift in pH toward acidic conditions, the pH shift could potentially cause desorption of lead and cadmium from aquifer surfaces. Such a scenario is unlikely to occur and as has been demonstrated through monitoring, even if it did occur contaminant migration will likely remain minimal. Alternative 4 – Pump and Treat requires a significantly longer period of time to meet the applicable standards and is therefore not as efficient in removing contaminants as Alternative 3 – Reagent Injection.

Reduction of Toxicity, Mobility, or Volume

This evaluation criterion addresses the statutory preference for selecting remedial actions that use treatment technologies to permanently and significantly reduce the toxicity, mobility, or volume of the hazardous substances as their principal element.

Groundwater concentrations of Site-related contaminants have generally decreased over time, as evidenced through the groundwater monitoring events. Furthermore, there has been minimal migration of the impacted groundwater. All

alternatives, with the exception of Alternative 1 – No Action, are expected to reduce the toxicity, mobility or volume of contaminants to meet the applicable standards; however, the Alternatives are estimated to achieve these reductions at different rates.

Alternative 2 – MNA Plus Institutional Controls and Alternative 4 – Pump and Treat Plus Institutional Controls are expected to take over 50 years to reduce the contaminant levels to concentrations meeting the applicable standards. Alternative 3 – Reagent Injection Plus Institutional Controls is expected to reduce contaminant levels to concentrations meeting the applicable standards in less than 10 years. This increased rate of reduction is due to the mechanisms in which the primary contaminants of concern, lead and cadmium, will be removed from solution. Reagent injection utilizes both natural processes, including biochemical reactions, dispersion, dilution and sorption which are also utilized by MNA, in addition to the enhanced formation of metal phosphates which eliminates the bioavailability of lead and cadmium in the aquifer.

Short-Term Effectiveness

This criterion addresses the effects of the alternatives on human health and the environment during construction and implementation of the remedial action until remedial response objectives are met. Factors that are considered include protection of remediation workers and the community during remedial actions, environmental impacts from construction and implementation, and the time until remedial action is completed.

With the exception of Alternative 1 – No Action, which has no impact on short-term effectiveness, all of the Alternatives (2, 3 and 4) are expected to have minimal impacts on remediation workers and nearby residents during remedy implementation. Alternative 2 – MNA and Alternative 3 – Reagent Injection mainly involve the installation of monitoring wells/injection points while Alternative 4 – Pump and Treat involves the construction of a groundwater treatment plant which is anticipated to take longer to construct.

The potential risks to Site workers and area residents during remedy implementation will be addressed by adherence to protective worker practices, safety standards, and equipment. A Site-specific health and safety plan will be prepared and trained personnel will perform remedial activities. Appropriate personnel monitoring and emission controls and monitoring will be provided, as needed, during remedy implementation.

Implementability

This criterion addresses the technical and administrative feasibility of implementing the alternative, and the availability of services and materials required for its implementation. Factors that are considered include reliability of the technology, ability to construct and operate the technology, ease of

undertaking additional remedial actions (if necessary), ability to monitor effectiveness of the remedy, coordination with other agencies, availability of the treatment, storage, and disposal services necessary to implement the alternative; the availability of the technologies; and the availability of additional equipment or specialists.

All of the alternatives are technically and administratively feasible, have been implemented at other similar sites, and make use of standard engineering practices. Alternative 1 - No Action requires the least effort to implement; however, without having the monitoring component to determine effectiveness of the remedy, it would not demonstrate when RAOs have been met.

Alternative 2 – MNA would be the most readily implementable alternative as it only involves installation of monitoring wells. Alternative 3 – Reagent Injection would require a pilot study to optimize its effectiveness as well as the installation of monitoring/injection wells. Alternative 4 – Pump and Treat would be the most difficult to implement as it would require the greatest degree of construction. The availability of service and materials required for the implementation of all alternatives is adequate. All alternatives, other than Alternative 1, require services and materials that are currently readily available from technology vendors, and are therefore, not expected to present a challenge to remedy implementation.

Cost

Alternative 1 - No Action is the lowest cost alternative, but because of the lack of a monitoring mechanism, achievement of remedial success could not be measured. Alternative 2 - MNA would be the least costly alternative, aside from Alternative 1 – No Action, to implement with a cost of approximately $1.2 million which includes a 30-year groundwater monitoring program and well installation. Alternative 3 – Reagent Injection is estimated to cost $1.57 million assuming a 10-year groundwater monitoring program. This is comparable to the cost of Alternative 2 - MNA. Alternative 4 – Pump and Treat is the most expensive alternative with an estimated cost of $5.7 million which includes a 30-year groundwater monitoring program.

5. REFERENCES

Adams, Bill (EPA Region 10) et al, *PRB Containing Fish Bones Sequesters Metals from Ground Water,* published at http://cluin.org/products/newsltrs/tnandt/view.cfm?issue=0306.cfm, 2005.

Bard, Allen J. (1966). *The Handbook of Chemical Equilibrium,* Department of Chemistry, University of Texas, Published by Harper and Row, Appendix C.2

Chuan, M.C., Shu, G.Y., & Liu, J.C. (1995). Solubility of heavy metals in a contaminated soil: effects of redox potential and pH. *Water, Air, and Soil Pollution, 90*, 543-556.

Cotter-Howells JD, Caporn S (1996). *Applied Geochemistry*, **11**, 335-342.

CSI Environmental, LLC, *Groundwater Monitoring Plan for the NL Industries Superfund Site*, December 2006.

CSI Environmental LLC, *Groundwater Monitoring Report,* April 2004.

CSI Environmental LLC, *Groundwater Monitoring Report,* September 2007, Revised May 2008.

ENTACT, *Interim Remedial Action Report, NL Industries Site, Pedricktown, NJ,* July 2003.

Evanko and Dzombak, *Remediation of Metals-Contaminated Soils and Groundwater,* Carnegie Mellon University Department of Civil and Environmental Engineering, October 1997.

Evans, L.J., *Chemistry of Metal Retention by Soils*, Environ.Sci. Tech., 23: pp-1046-1056, 1989.

GeoSyntec Consultants, *Phase I Groundwater Evaluation Technical Memorandum, NL Industries Superfund Site, Pedricktown, New Jersey,* December 1997.

GeoSyntec Consultants, *Phase II Groundwater Evaluation Technical Memorandum, NL Industries Superfund Site, Pedricktown, New Jersey,* January 2000.

GeoSyntec Consultants, *Remedial Design Work Plan, NL Industries Superfund Site, Pedricktown, New Jersey,* December 1997.

Ma QY, Traina SJ, Logan TJ (1993) *Environ. Science and Technology*, 27, 1803-1810.

McDonald, Michael, G., and Arlen Harbaugh. 1983. "*A Modular Three-Dimensional Finite Difference Groundwater Flow Model*", Techniques of Water Resources Investigations of the United States Geological Survey, Open-File Report 83-875.

MSE Technology Applications, Inc., *Final Report – Permeable Treatment Wall Effectiveness Monitoring, Nevada Stewart Mine Site,* EPA/600/R-06/153, February 2007.

New Jersey Department of Environmental Protection, *Known Contaminated Sites in New Jersey for Salem County, seventh edition*, Spring 2006.
Nriagu JO (1984) 318-329 *Phosphate minerals* (Ed. JO Nriagu and PB Moore) Springer-Verlag, Berlin

O'Brien & Gere Engineers Inc., *Final Remedial Investigation NL Industries, Inc. Site,* 1990.

Puls and Barcelona, Low-Flow (Minimal Draw Down) Ground-Water Sampling Procedures, 1998.

Ruth Associates, Inc., *Groundwater Remedial Assessment for the Brown's Battery Breaking Site,* 30 November 1998.

United States Environmental Protection Agency (EPA) Region III, *Record of Decision, NL Industries Inc., Pedricktown, Salem County, New Jersey,* July 1994.

EPA, Office of Solid Waste and Emergency Response, *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action and Underground Storage Tank Sites,* Directive No. 9200.4-17P, April 1999.

EPA, Wilhelm, Ronald, *Framework Document for Monitored Natural Attenuation of Inorganic Contaminants in Ground Water,* 2003.

EPA, Ford, Robert G. et al, *Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Volumes I and II,* prepared by the United States Environmental Protection Agency Office of Research and Development, National Risk Management Laboratory, October 2007.

United States Geological Society, David B. Smith et al., *Major and Trace Element Concentrations in Soils from Two Continental-Scale Transects of the United States and Canada*, Open File Report 2005-1253, Prepared for the U.S. Geological Survey, 2005.

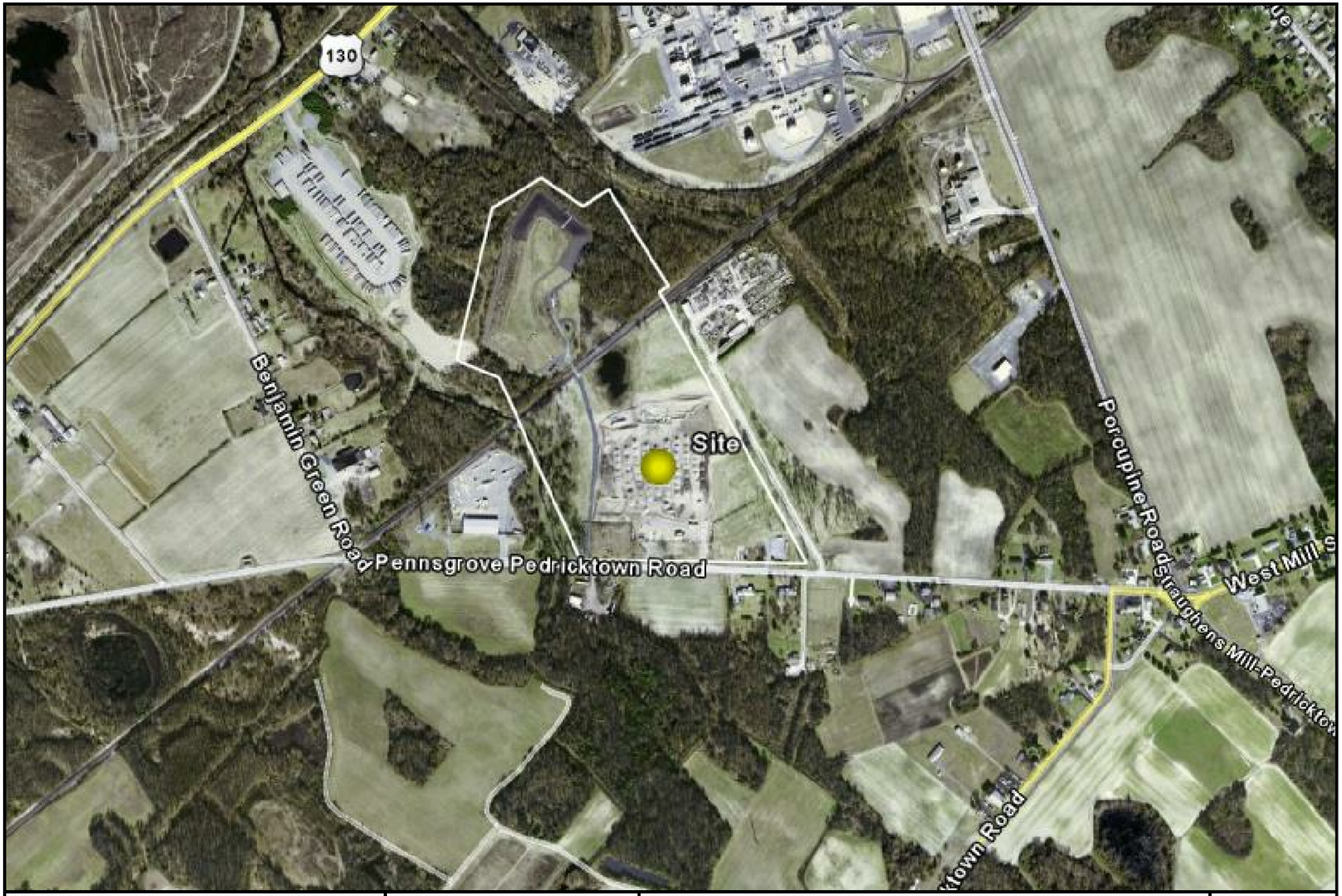
Wright, Judith (PIMS NW Inc.) and Conca, James (Los Alomos National Laboratory), *Remediation of Groundwater Contaminated with Zn, Pb and Cd using a Permeable Reactive Barrier with Apatite II*, November 2002.
www.rtdf.org/public/permbar/minutes/110702/conca.pdf

Yong, R.N and Phadungchewit, Y. (1993). Selective sequential extraction analysis of heavy-metal retention in soil. *Canadian Geotechnical Journal, 30*(5), 834-847.

Yong, R.N and Phadungchewit, Y. (1993b). pH influences on selectivity and retention of heavy metals in some clay soils. *Canadian Geotechnical Journal, 30*(5), 821-833.

Zimdahl, R. L. and Skorgrboe, R. K., Dec. 1977, "*Behavior of Lead in Soil*", ES&T, Vol. 11, No. 13, 1202-1207 pp.

FIGURES



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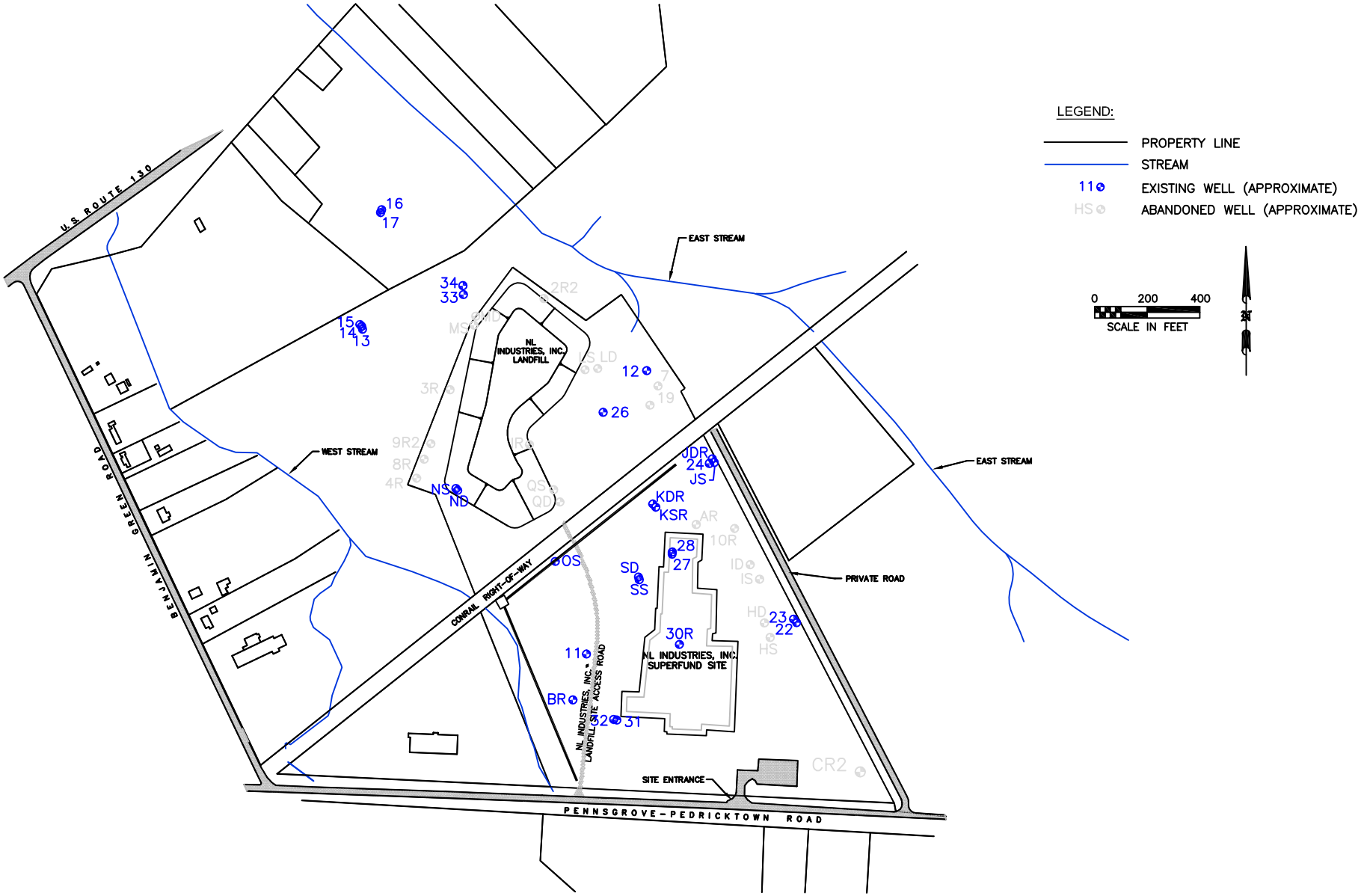
Approved By: J.D. Ferris

Prepared: 2/2/2011

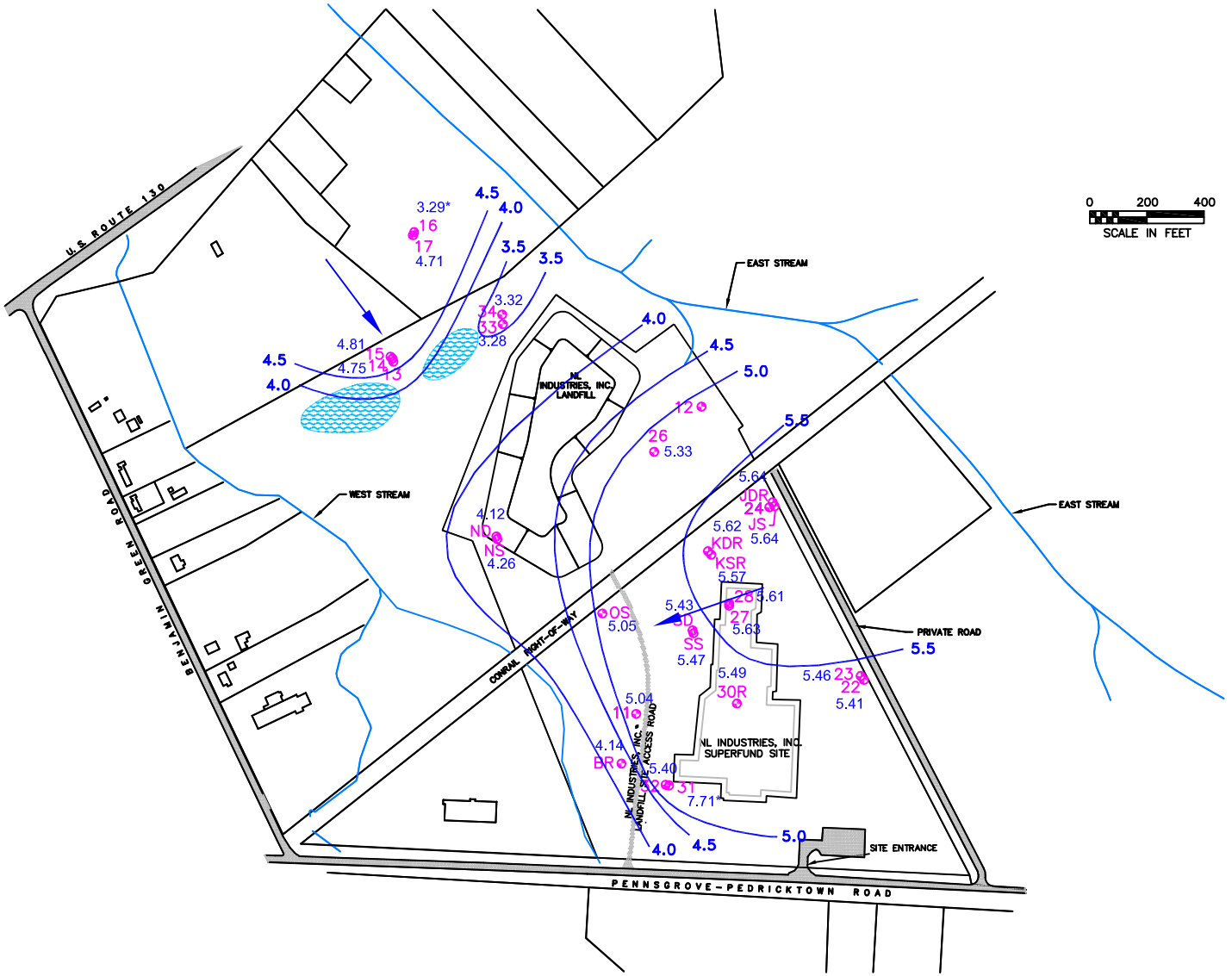
SITE LOCATION

NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

FIGURE
1
500074



CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Ballantine Approved By: J.D. Ferris Prepared: 2/1/2011	SITE OVERVIEW NL Industries, Inc. Superfund Site Pedricktown, New Jersey	FIGURE 2 500075



0 200 400
SCALE IN FEET

N

LEGEND:

- PROPERTY LINE
- STREAM
- 11 EXISTING WELL (APPROXIMATE)
- 6.0 POTENTIOMETRIC SURFACE CONTOUR
- GENERALIZED GROUNDWATER FLOW DIRECTION
- 7.40 GROUNDWATER ELEVATION
- 7.40 * GROUNDWATER ELEVATION ANOMOLY (NOT MAPPED)
- SURFACE WATER

NOTE:

1. GROUNDWATER ELEVATION DATA COLLECTED IN NOVEMBER 2010.
2. WATER LEVELS FROM THE UNCONFINED AQUIFER ARE USED FOR THIS FIGURE.

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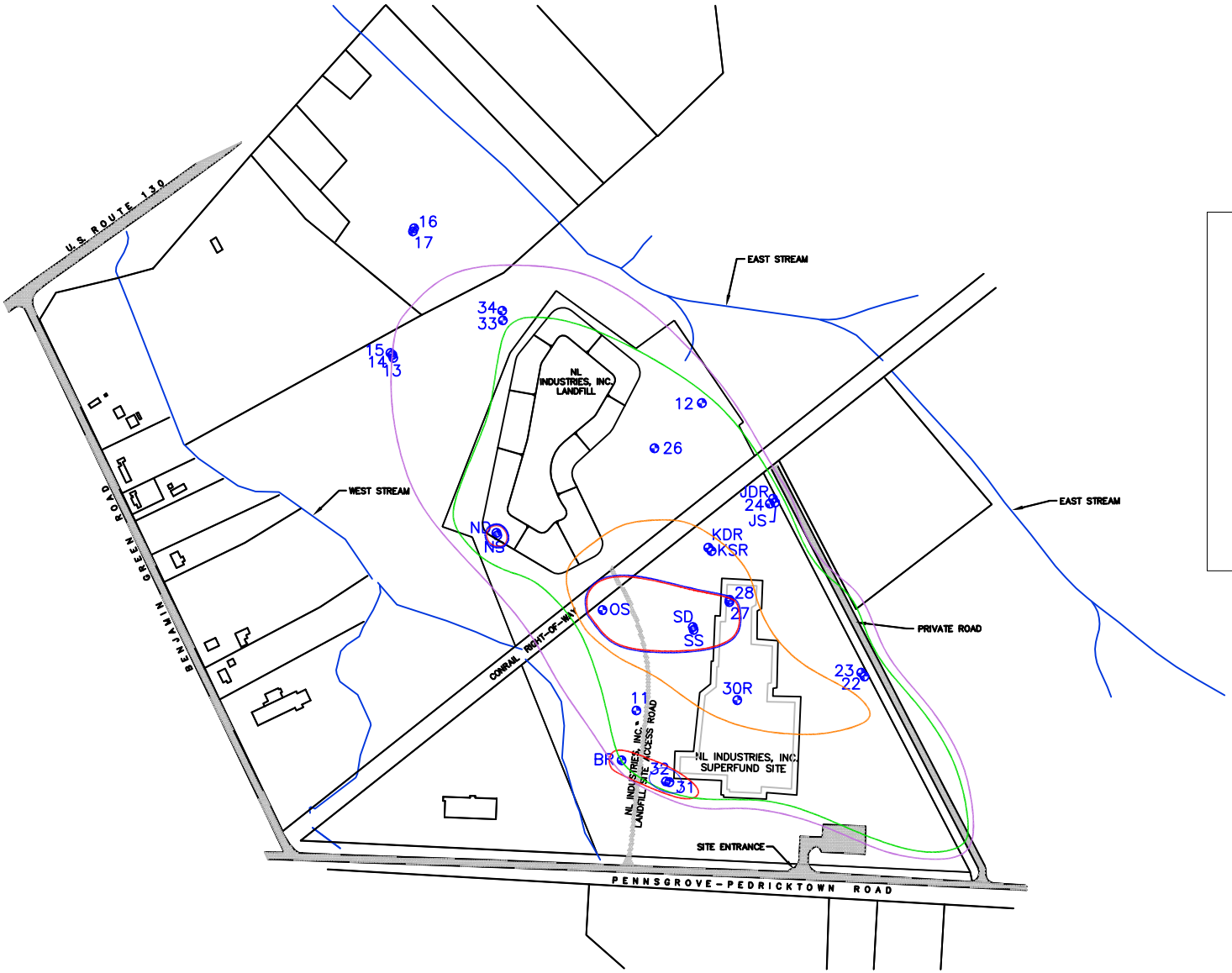
Upper Aquifer Groundwater Elevations
November 2010

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE
3
500076



N

0 200 400

SCALE IN FEET

Legend

- Property Line
- Stream
- 11 Existing Well

Areas with Pb concetrations greater than the NJGWQC

- 1983 (Area = 2,274,279.10 sq ft)
- 1988 (Area = 1,714,643.96 sq ft)
- 1998 (Area = 421,922.14 sq ft)
- 2007 (Area = 127,852.84 sq ft)
- 2010 (Area = 138,938.63 sq ft)

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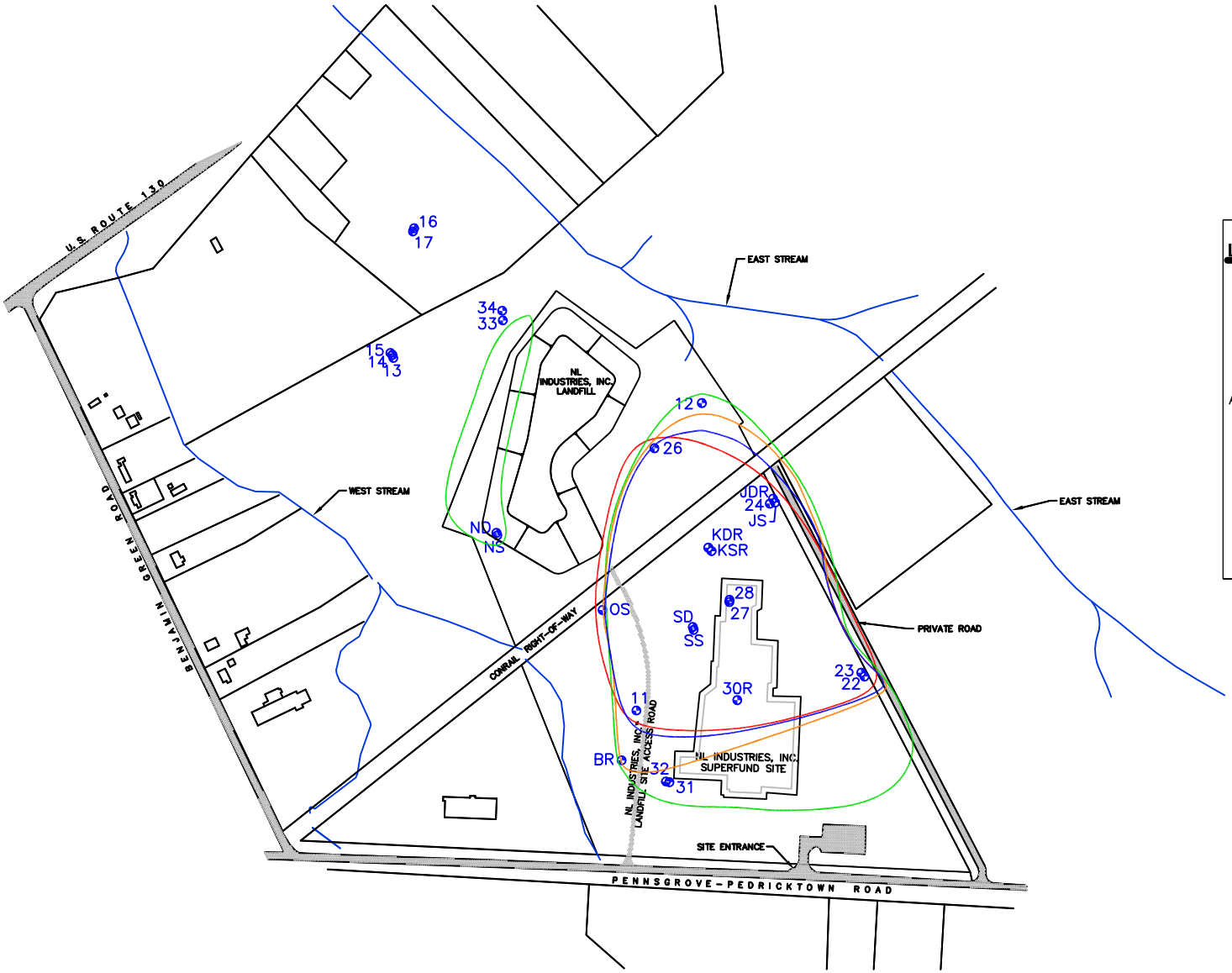
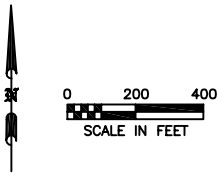
HISTORICAL EXTENT OF LEAD CONCENTRATIONS ABOVE THE GROUNDWATER QUALITY STANDARD

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE 4

500077





Legend

- Property Line
- Stream
- 11 Existing Well

Areas with Cd concetrations greater than the NJGWQC

- 1988 (Area = 1,231,268.12 sq ft)
- 1998 (Area = 833,701.64 sq ft)
- 2007 (Area = 731,651.89 sq ft)
- 2010 (Area = 742,912.73 sq ft)

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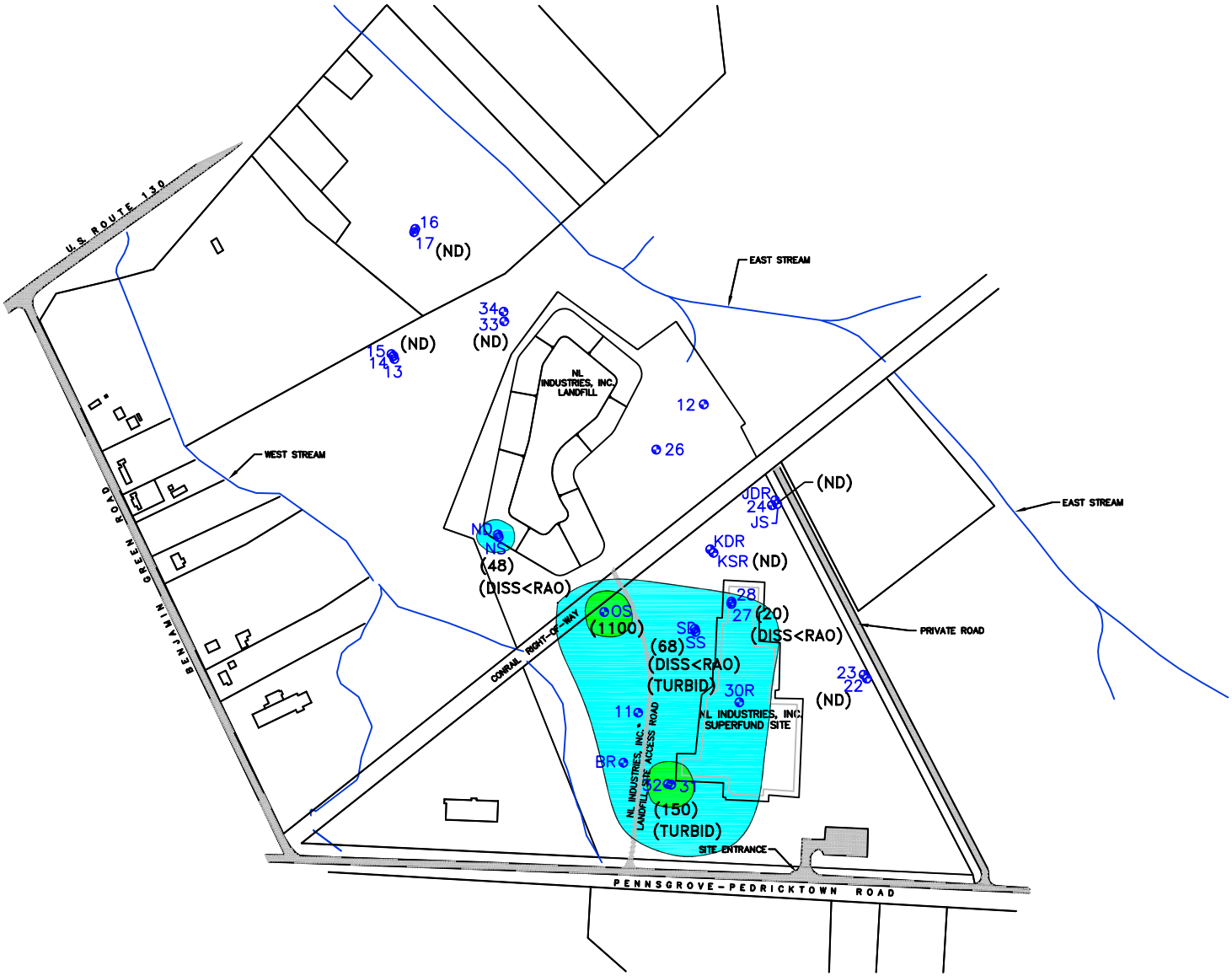
HISTORICAL EXTENT OF CADMIUM CONCENTRATIONS ABOVE THE GROUNDWATER QUALITY STANDARD

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE
5
500078



LEGEND:

———	PROPERTY LINE
———	STREAM
11 ⊙	EXISTING WELL (APPROXIMATE)
(J)	RESULT IS GREATER THAN LABORATORY DETECTION LIMIT, BUT BELOW LABORATORY QUANTITATION LIMIT
(ND)	NOT DETECTED
(4.9)	LEAD CONCENTRATION IN ppb
(DISS<RAO)	DISSOLVED LEAD CONCENTRATION IS BELOW RAO
(TURBID)	SAMPLES HAD HIGH TURBIDITY MEASURED IN FIELD
(NS)	NOT SAMPLED
	LEAD CONCENTRATION, ≥100 ppb
	LEAD CONCENTRATION, 5 ppb≤ AND <100 ppb

0 200 400
SCALE IN FEET

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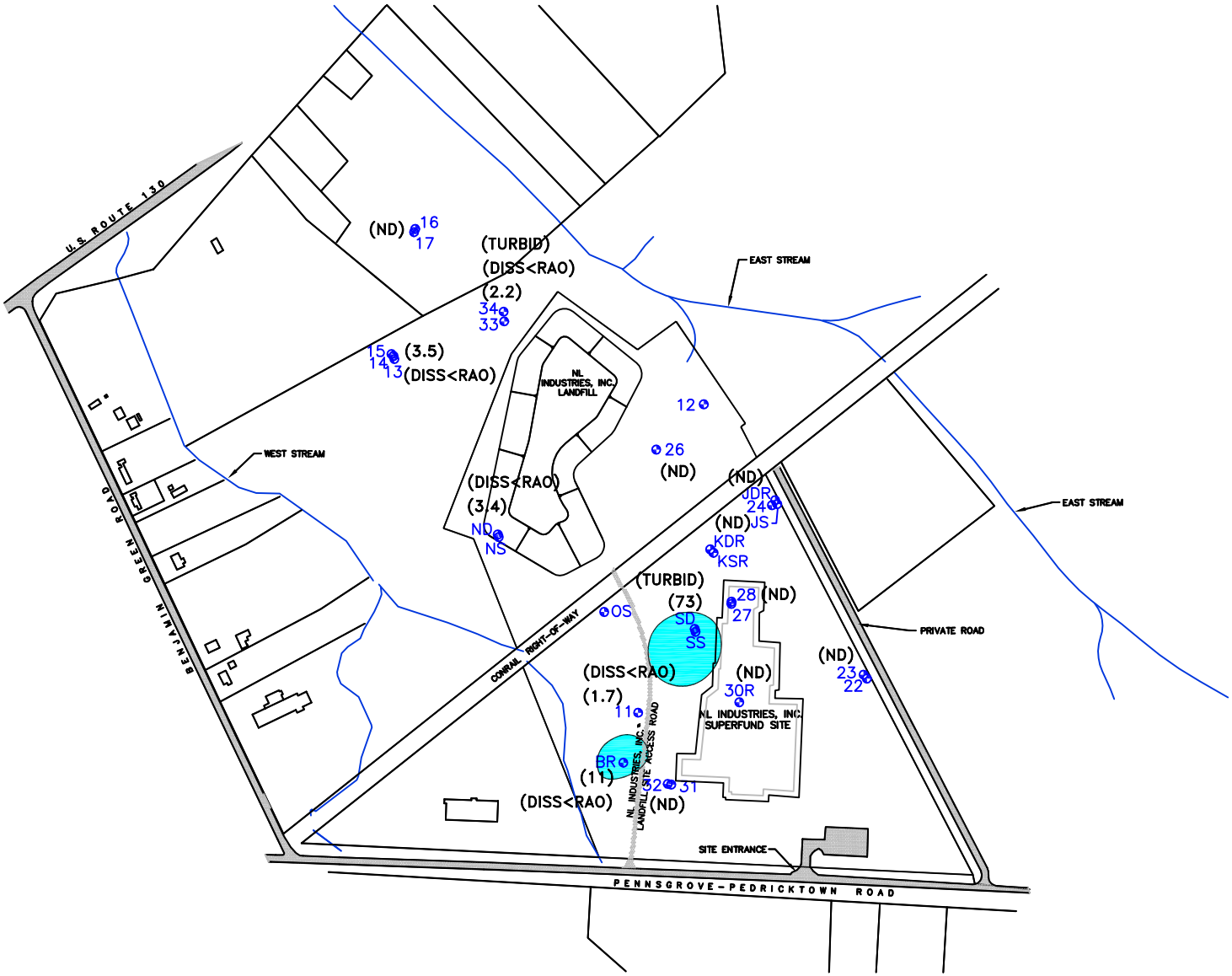
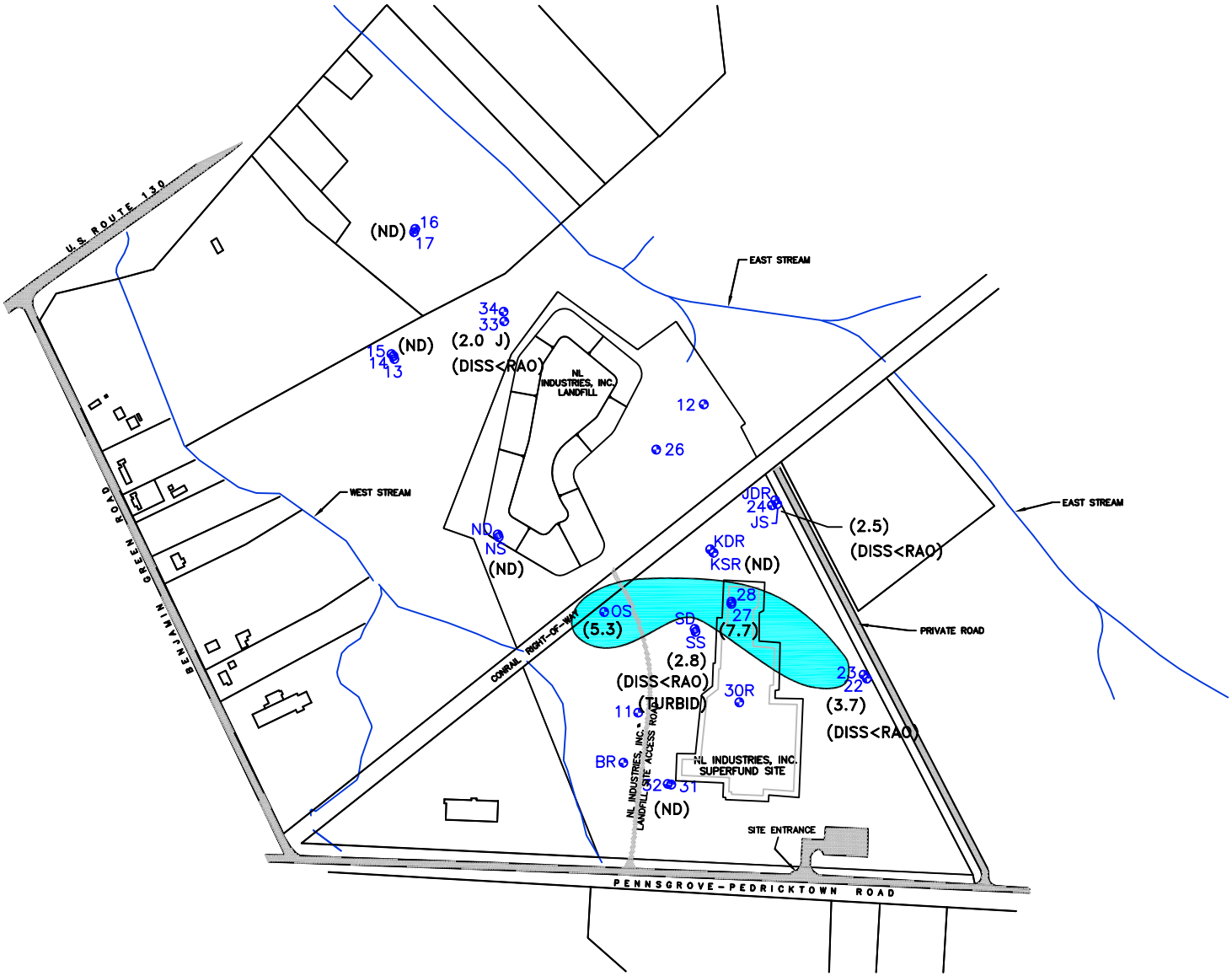
Total Pb Distribution - Shallow Zone
November 2010

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE
6
500079



CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Hickey Approved By: J.D. Ferris Prepared: 2/2/2011	Total Pb Distribution - Deep Zone November 2010 NL Industries, Inc. Superfund Site Pedricktown, NJ	FIGURE 7 500080

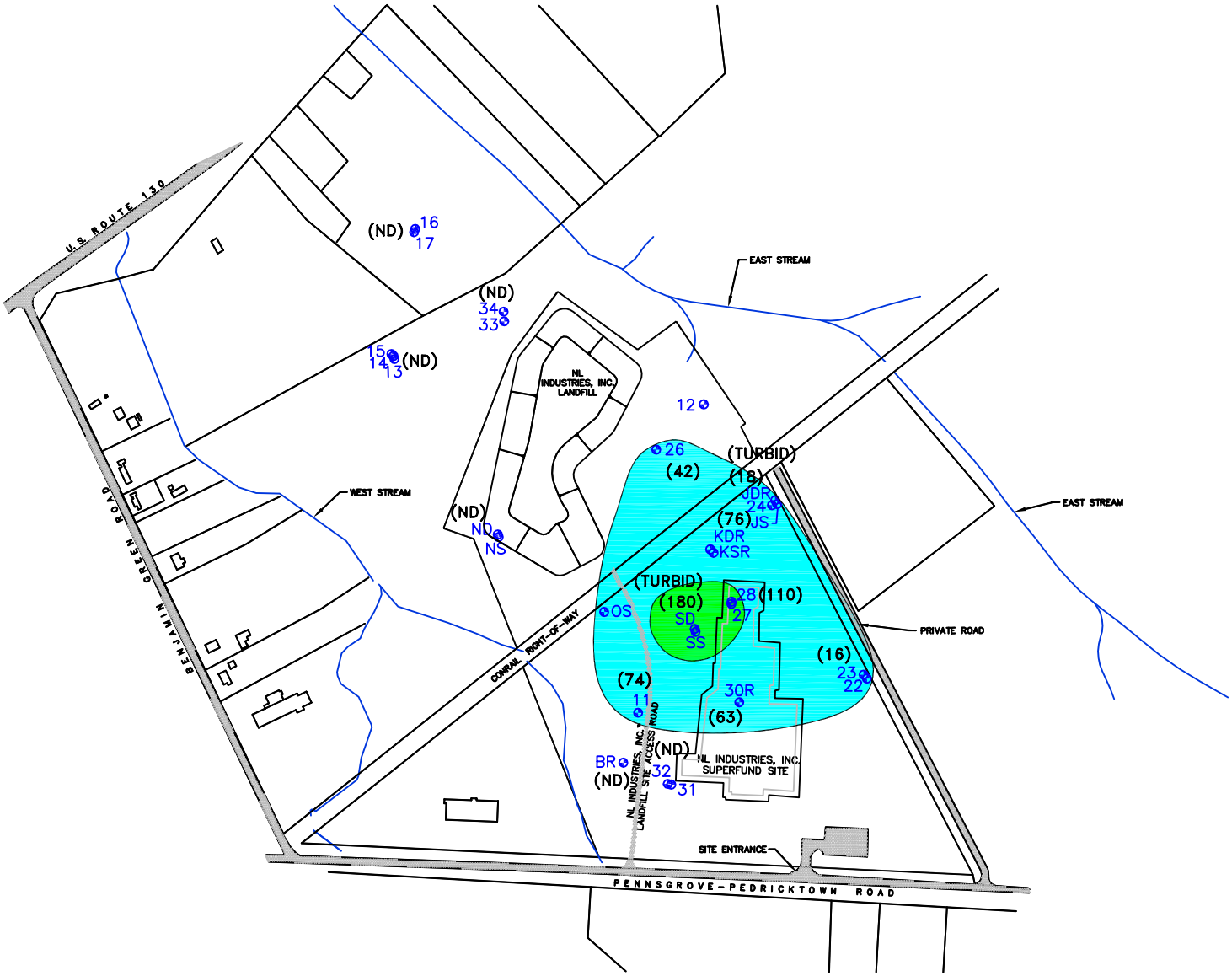


LEGEND:

- PROPERTY LINE
- STREAM
- 11 EXISTING WELL (APPROXIMATE)
- (J) RESULT IS GREATER THAN LABORATORY DETECTION LIMIT, BUT BELOW LABORATORY QUANTITATION LIMIT
- (ND) NOT DETECTED
- (4.9) CADMIUM CONCENTRATION IN ppb
- (DISS<RAO) DISSOLVED CADMIUM CONCENTRATION IS BELOW THE RAO
- (TURBID) SAMPLE HAD HIGH TURBIDITY MEASURED IN FIELD
- (NS) NOT SAMPLED
- CADMIUM CONCENTRATION, ≥100 ppb
- CADMIUM CONCENTRATION, 4 ppb≤ AND <100 ppb

0 200 400
SCALE IN FEET

CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Hickey Approved By: J.D. Ferris Prepared: 2/2/2011	Total Cd Distribution - Shallow Zone November 2010 NL Industries, Inc. Superfund Site Pedricktown, NJ	FIGURE 8 500081



LEGEND:

	PROPERTY LINE
	STREAM
11	EXISTING WELL (APPROXIMATE)
(J)	RESULT IS GREATER THAN LABORATORY DETECTION LIMIT, BUT BELOW LABORATORY QUANTITATION LIMIT
(ND)	NOT DETECTED
(4.9)	CADMIUM CONCENTRATION IN ppb
(DISS<RAO)	DISSOLVED CADMIUM CONCENTRATION IS BELOW THE RAO
(TURBID)	SAMPLE HAD HIGH TURBIDITY MEASURED IN FIELD
(NS)	NOT SAMPLED
	CADMIUM CONCENTRATION, ≥100 ppb
	CADMIUM CONCENTRATION, 4 ppb≤ AND <100 ppb

0 200 400
SCALE IN FEET

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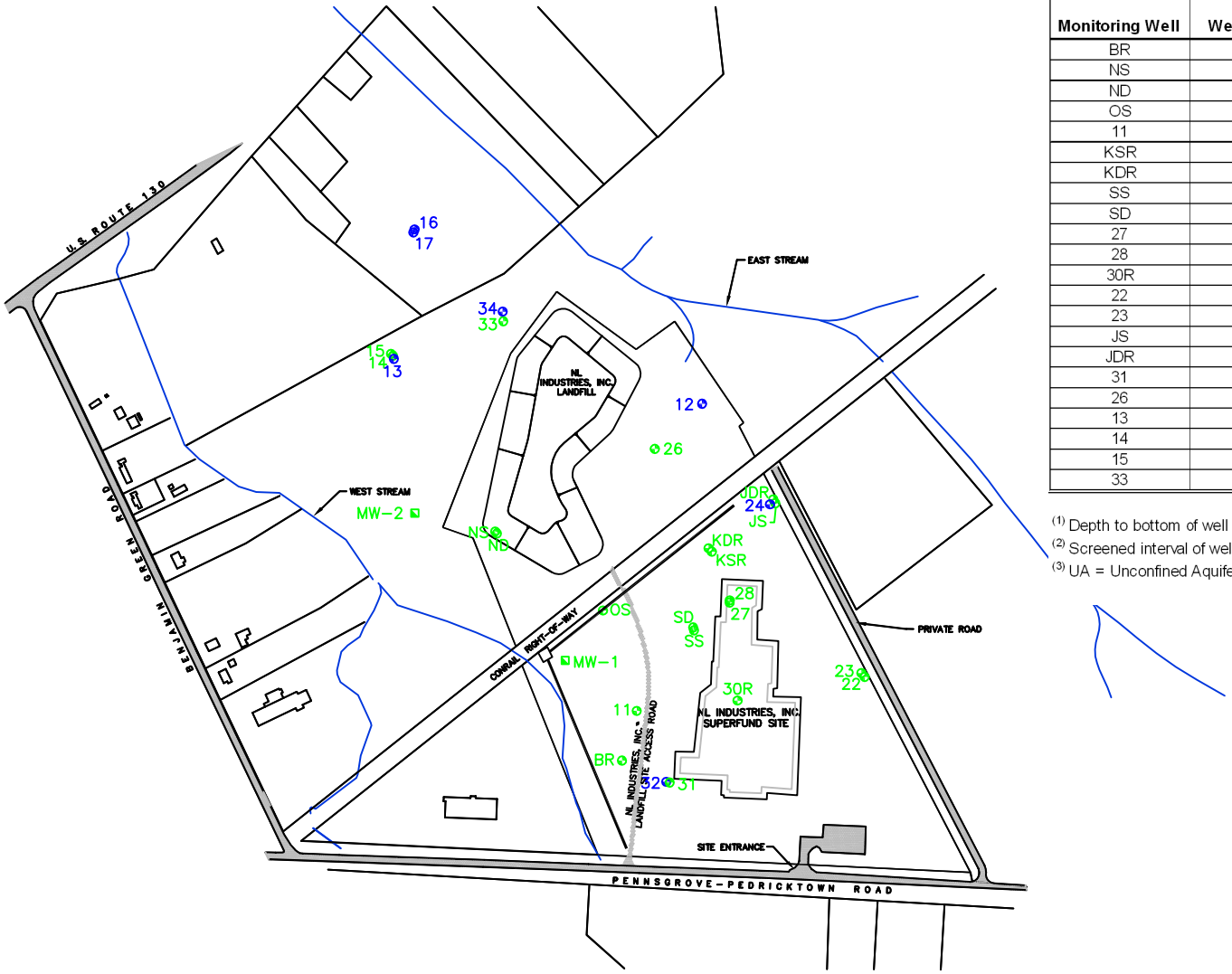
Total Cd Distribution - Deep Zone
November 2010
NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE
9
500082



Monitoring Well	Well Depth (1)	Screened Interval (2)	Aquifer Zone (3)	Monitored Area
BR	39	33 - 39	UA - Deep	western limits
NS	16.5	6.5 - 16.5	UA - Shalow	western limits
ND	24	14 - 24	UA - Deep	western limits
OS	21.3	6.3 - 21.3	UA - Shalow	western limits
11	54.1	34.1 - 54.1	UA - Deep	western limits
KSR	15	5 - 15	UA - Shalow	central area
KDR	24	14 - 24	UA - Deep	central area
SS	16.4	6.4 - 16.4	UA - Shalow	central area
SD	29.4	17.4 - 29.4	UA - Deep	central area
27	15	5 - 15	UA - Shalow	central area
28	30	20 - 30	UA - Deep	central area
30R	28.71	17 - 27	UA - Deep	central area
22	16	11 - 16	UA - Shalow	eastern limits
23	24	24 - 34	UA - Deep	eastern limits
JS	15.37	5 - 15	UA - Shalow	eastern limits
JDR	27.26	17 - 27	UA - Deep	eastern limits
31	15	5 - 15	UA - Shalow	southern limits
26	22	12 - 22	UA - Shalow	northern limts
13	115.7	95.7 -115.7	SCA	northern limts
14	46.6	26.6 - 46.6	UA - Deep	northern limts
15	25	10.0 - 25.0	UA - Shalow	northern limts
33	10	5 - 10	UA - Shalow	northern limts

(1) Depth to bottom of well in feet below top of casing (TOC).
(2) Screened interval of well in feet below ground surface.
(3) UA = Unconfined Aquifer

LEGEND:

- PROPERTY LINE
- STREAM
- 13 NON-MNA WELL
- 11 EXISTING MNA WELL
- MW-1 PROPOSED NEW MNA WELL LOCATION

0 200 400
SCALE IN FEET

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Last Revised: 2/1/2011

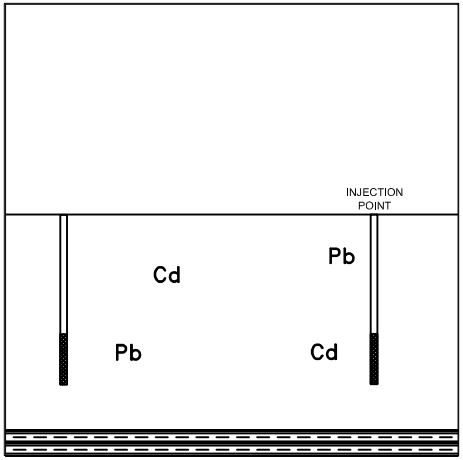
PROPOSED LOCATIONS FOR MNA GROUNDWATER MONITORING

NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

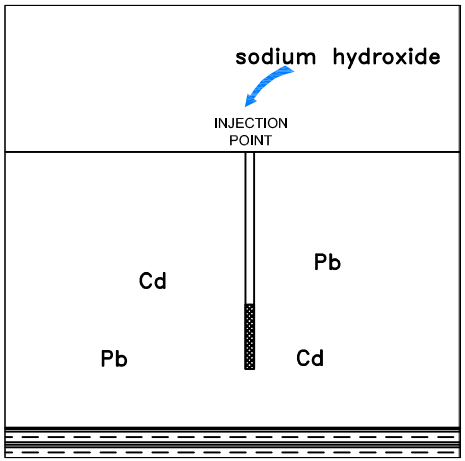
FIGURE
10
500083

Before reagent Injection

- Cd concentration = 149 ppb
- Pb concentration = 31 ppb
- PH = 3.08



Before reagent injection



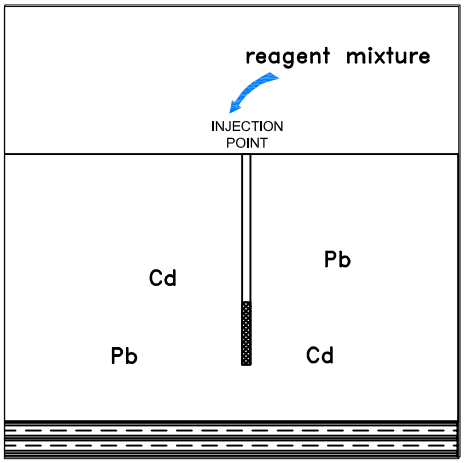
Stage 1 - PH Adjustment

Stage 1 - Adjust PH

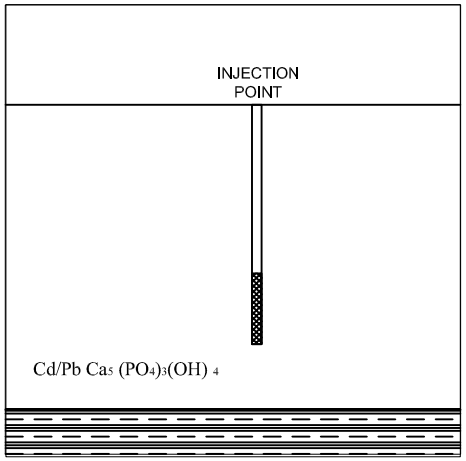
- An alkaline PH is necessary to stimulate metal phosphate formation. A 5% sodium hydroxide solution is introduced to adjust groundwater PH to approximately 8.5.

Stage 2 - Reagent Injection

- Mixture of sodium tri-polyphosphate and calcium chloride added to injection point.



Stage 2 - Reagent Injection



After reagent Injection

After Reagent Injection

- Cd & Pb groundwater concentrations not detected after reagent injection.
- Cd & Pb form metal phosphates (Cd/PbCa5(PO4)3(OH)4) becoming insoluble & inert.

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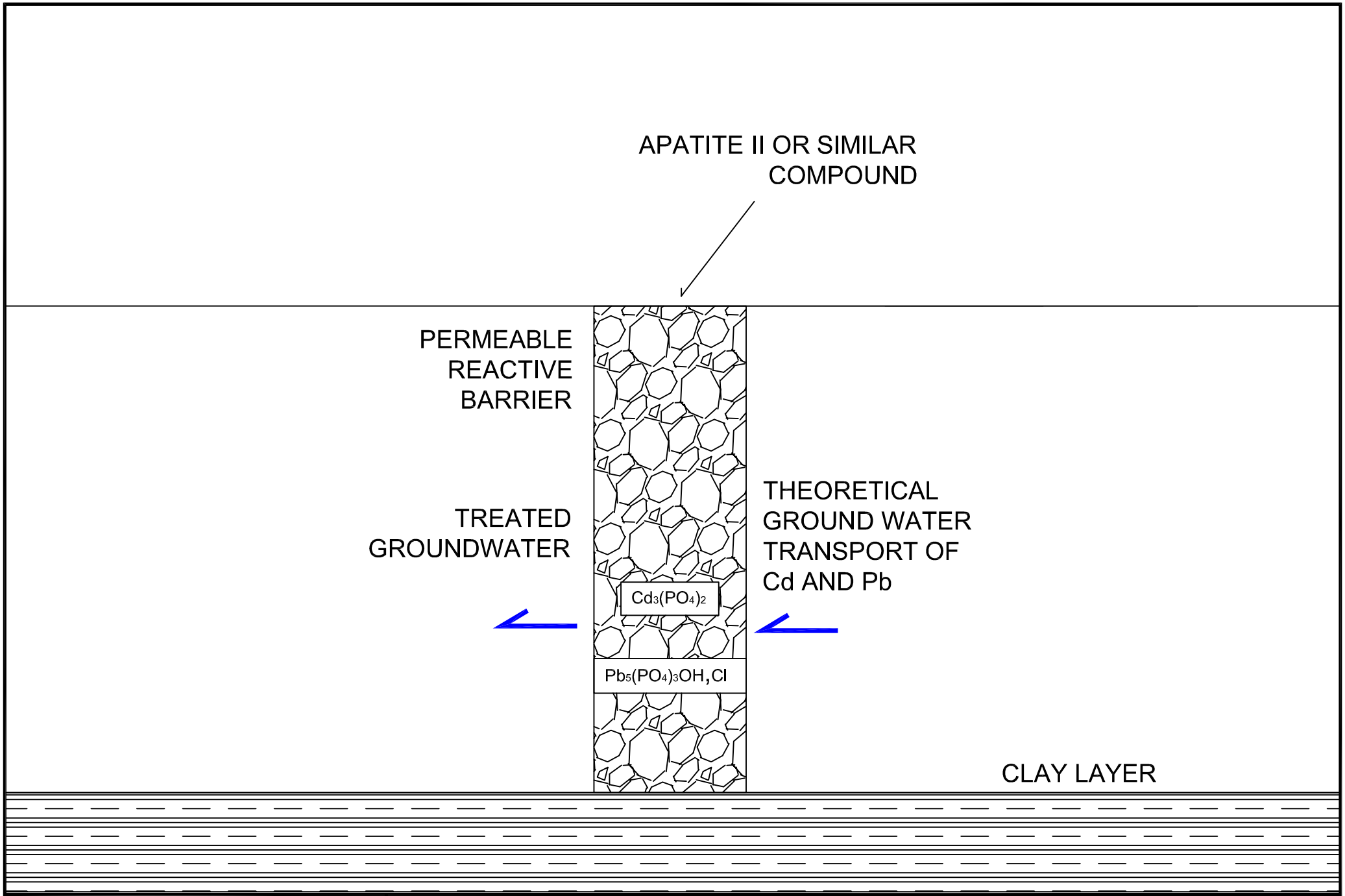
CONCEPTUAL APPLICATION OF REAGENT INJECTION ALTERNATIVE

NL Inustries, Inc. Superfund Site
Pedricktown, New Jersey

FIGURE

11

500084



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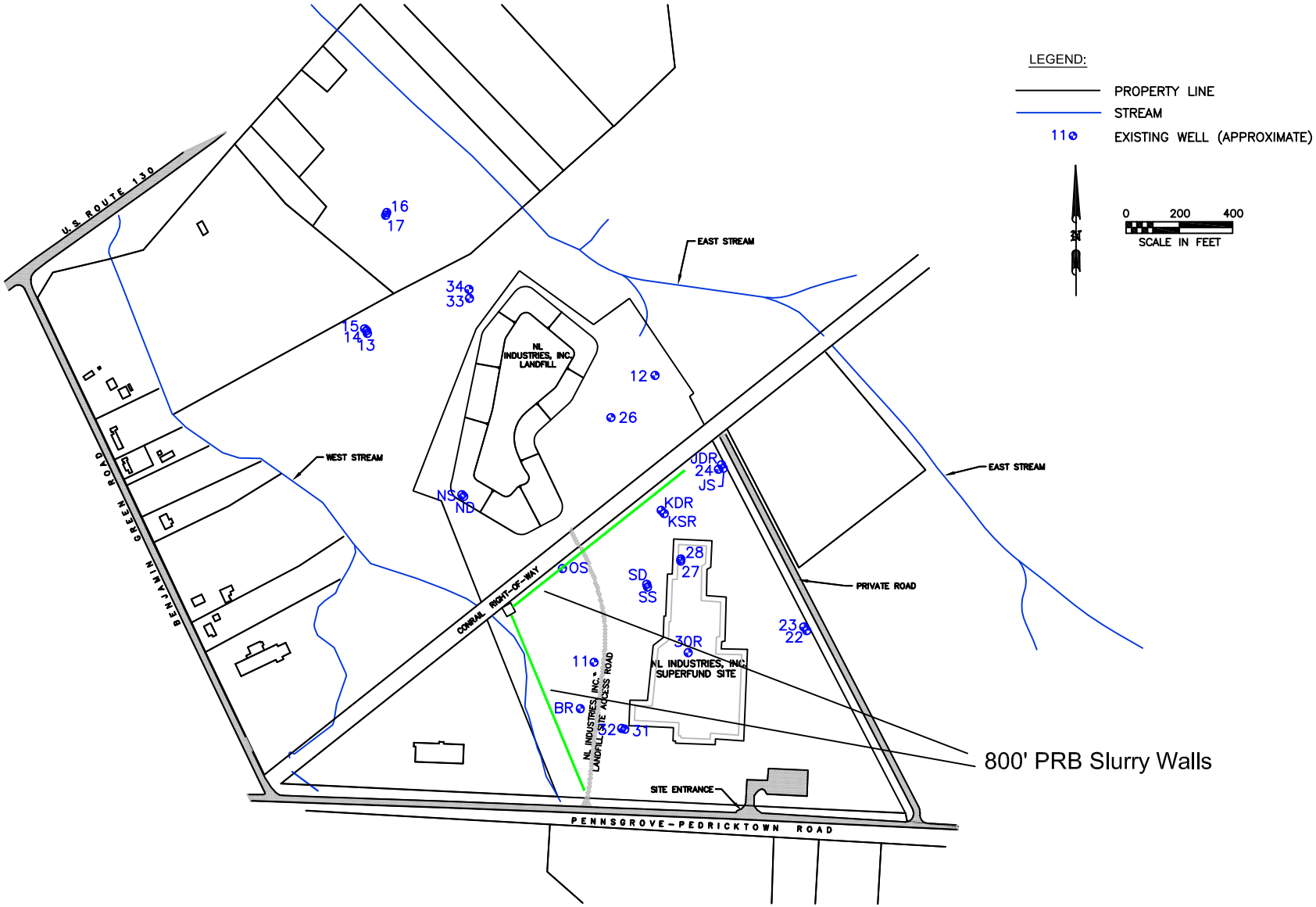
Prepared: 2/1/2011

CROSS SECTION OF A PERMEABLE REACTIVE BARRIER

NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

FIGURE 12

500085



CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Ballantine Approved By: J.D. Ferris Last Revised: 2/2/2011	CONCEPTUAL PERMEABLE REACTIVE BARRIER AND CONTAINMENT WALL LOCATION NL Industries, Inc. Superfund Site Pedricktown, New Jersey	FIGURE 13 500086

TABLES

Table 1
Monitoring Well Construction Details
NL Industries Superfund Site
Pedricktown, New Jersey

Monitoring Well	Casing Diameter	Well Depth [1]	Top Screen [2]	Bottom Screen [2]	Top of Casing Elevation [3]	Top Screen Elevation	Bottom Screen Elevation	Depth To Water [4]	Groundwater Elevation	Aquifer Zone [5]
24	2	73	68	73	13.13	-54.87	-59.87	12.22	0.91	FCA
12	4	78.2	58.2	78.2	11.79	-46.41	-66.41	10.79	1.00	FCA
13	4	115.7	95.7	115.7	11.59	-84.11	-104.11	11.62	-0.03	SCA
16	4	56.8	36.8	56.8	10.79	-26.01	-46.01	7.50	3.29	UA - Deep
11	4	54.1	34.1	54.1	9.72	-24.38	-44.38	4.68	5.04	UA - Deep
BR	4	39	33	39	9.74	-23.26	-29.26	5.60	4.14	UA - Deep
14	4	46.6	26.6	46.6	11.39	-15.21	-35.21	6.64	4.75	UA - Deep
23	2	24	24	34	14	-10	-20	8.54	5.46	UA - Deep
28	2	30	20	30	13.98	-6.02	-16.02	8.37	5.61	UA - Deep
32	2	30	20	30	14.22	-5.78	-15.78	8.82	5.40	UA - Deep
SD	2	29.4	17.4	29.4	12.33	-5.07	-17.07	6.90	5.43	UA - Deep
KDR	2	24	14	24	9.47	-4.53	-14.53	3.85	5.62	UA - Deep
30R	2	28.71	17	27	12.81	-4.19	-14.19	7.32	5.49	UA - Deep
JDR	2	27.26	17	27	13.01	-3.99	-13.99	7.37	5.64	UA - Deep
34	2	20	10	20	6.55	-3.45	-13.45	3.23	3.32	UA - Deep
ND	2	24	14	24	11.22	-2.78	-12.78	7.10	4.12	UA - Deep
26	2	22	12	22	11.86	-0.14	-10.14	6.53	5.33	UA - Deep
17	4	23	8.0	23	9.31	1.31	-13.69	4.60	4.71	UA - Shallow
15	4	25	10.0	25	11.32	1.32	-13.68	6.51	4.81	UA -Shallow
33	2	10	5	10	6.67	1.67	-3.33	3.39	3.28	UA -Shallow
22	2	16	11	16	14.16	3.16	-1.84	8.75	5.41	UA -Shallow
KSR	2	15	5	15	9.53	4.53	-5.47	3.96	5.57	UA -Shallow
SS	2	16.4	6.4	16.4	11.64	5.24	-4.76	6.17	5.47	UA -Shallow
OS	2	21.3	6.3	21.3	11.82	5.52	-9.48	6.77	5.05	UA -Shallow
NS	2	16.5	6.5	16.5	12.17	5.67	-4.33	7.91	4.26	UA -Shallow
JS	2	15.37	5	15	12.95	7.95	-2.05	7.31	5.64	UA -Shallow
27	2	15	5	15	13.49	8.49	-1.51	7.86	5.63	UA -Shallow
31	2	15	5	15	14.27	9.27	-0.73	6.56	7.71	UA - Shallow

Notes:
[1] Depth to bottom of well in feet below top of casing (TOC).
[2] Screened interval of well in feet below ground surface.
[3] TOC elevation in feet above mean sea level.
[4] Depth to water in feet below TOC, measured in November 2010.
[5] UA = Unconfined Aquifer , FCA = First Confined Aquifer, SCA = Second Confined Aquifer.

TABLE 2
Groundwater Data Summary
November 29, 2010 - December 3, 2010
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Parameter	Sample Identification																				Lowest NJ Standard	Source	EPAMCL
	11		12		13		DUP-100		14		15		16		DUP-103		17		22				
Inorganics (ug/L)																							
Total Cadmium by 200.8	**74.0**		2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	**3.7**		4	NJ GWQC	5
Total Cadmium by 6010B	**70.0**		0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	**3.9**	**J**	4	NJ GWQC	5
Dissolved Cadmium by 200.8	**70.0**		2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	2.0	U	**3.5**		4	NJ GWQC	5
Dissolved Cadmium by 6010B	**74.0**		0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	**4.2**	**J**	4	NJ GWQC	5
Total Lead by 200.8	**1.7**		1.2	U	1.2	U	1.2	U	**3.5**		1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	5	NJ GWQC	15 *
Total Lead by 6010B	**2.9**	**J**	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	**3.5**	**J**	**2.9**	**J**	**2.8**	**J**	5	NJ GWQC	15 *
Dissolved Lead by 200.8	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	5	NJ GWQC	15 *
Dissolved Lead by 6010B	2.8	U	**3.2**	**J**	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	2.8	U	5	NJ GWQC	15 *
Organics (ug/L)																							
Acetone	2.5	U	2.5	U J	2.5	U J	2.5	U J	12	U J	2.5	U J	2.5	U	2.5	U	2.5	U	2.5	U	6,000	NJ GWQC	NA
Benzene	0.1	U	**0.13**	**J**	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	NJ MCL	5
Bromodichloromethane	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	1	PQL	NA
2-Butanone	0.8	U	0.8	R	0.8	U R	0.8	R	0.8	R	0.8	R	0.8	U	0.8	U	0.8	U	0.8	U	300	NJ GWQC	NA
Carbon Disulfide	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	700	NJ GWQC	NA
Chloroform	**0.20**	**J**	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ GWQC	NA
Dibromochloromethane	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	NA
1,1-Dichloroethene	**0.67**	**J**	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	2	NJ MCL	7
1,1-Dichloroethane	**1.3**		**0.16**	**J**	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	50	NJ MCL	NA
cis-1,2-Dichloroethene	**4.7**		0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ MCL	70
1,4-Dioxane	0.9	U	**12**	**J**	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	NA	NA	NA
Methylene Chloride	0.2	U	0.2	U J	0.2	U J	0.2	U J	0.2	U	0.2	U J	0.2	U	0.2	U	0.2	U	0.2	U	3	NJ MCL	5
Tetrachloroethene	**1.6**		0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	1 (5 in ROD)
Toluene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	600	NJ GWQC	1,000
1,1,1-Trichloroethane	**1.9**		0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	30	NJ MCL	200
Trichloroethene	**0.48**	**J**	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	5
Vinyl Chloride	0.1	U	**7.7**		0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	2
Xylenes, Total	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	1,000	NJ MCL	10,000
General Chemistry																							
pH	**6.34**		**8.09**		**7.56**		NA		**4.71**		**5.31**		**6.25**		NA		**5.27**		**4.25**		NA		NA
Conductivity (mS/cm)	**1.41**		**0.64**		**0.54**		NA		**0.02**		**0.03**		**0.24**		NA		**0.04**		**0.16**		NA		NA
Temperature (deg. C)	**14.5**		**13.0**		**14.0**		NA		**14.9**		**15.8**		**13.3**		NA		**14.3**		**15.4**		NA		NA
ORP (mV)	**129**		**-22**		**-12**		NA		**164**		**172**		**-47**		NA		**187**		**15**		NA		NA
Turbidity (NTU)	**4.6**		**0.0**		**81.7**		NA		**200.0**		**5.7**		**31.5**		NA		**0.0**		**0.5**		NA		NA
Dissolved Oxygen (mg/L)	**0.00**		**0.00**		**0.00**		NA		**0.58**		**1.57**		**0.00**		NA		**0.00**		**0.00**		NA		NA

Notes:

J = The concentration is an estimated value.
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R = The results is unreliable/unusable.
NA = Not Applicable

[1] DUP-100 is a duplicate sample obtained from monitoring well 13.
[2] DUP-102 is a duplicate sample obtained from monitoring well 30R.
[3] DUP-103 is a duplicate sample obtained from monitoring well 16.
[4] Two rinsate blanks (RB-1 and RB-2) were collected to evaluate the effectiveness of field decontamination procedures.
* This concentration is an action level and not an MCL
The lowest NJ Criterion is the lowest value of the NJ Groundwater Quality Criterion (GWQC), NJ Maximum Contaminant Level (MCL), or the Practical Quantitation Limit (PQL).
The data shaded in gray represent lead concentrations analyzed by EPA Method 200.8 that are above the NJGWQC. Lead concentrations analyzed by EPA Method 6010B are not shaded because the results were affected by yttrium interference associated with the laboratory method.

TABLE 2
Groundwater Data Summary
November 29, 2010 - December 3, 2010
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

	Sample Identification																			
Parameter	23		24		26		27		28		30R		DUP-102		31		32		33		Lowest NJ Standard	Source	EPAMCL
Inorganics (ug/L)																							
Total Cadmium by 200.8	**16**		2.0	U	**42**		**7.7**		**110**		**63**		**62**		2.0	U	2.0	U	**2.0**	**J**	4	NJ GWQC	5
Total Cadmium by 6010B	**15**		0.9	U	**28**		**9.5**		**110**		**57**		**57**		**1.2**	**J**	0.9	U	**2.0**	**J**	4	NJ GWQC	5
Dissolved Cadmium by 200.8	**14**		2.0	U	**40**		**6.9**		**110**		**62**		**68**		2.0	U	2.0	U	**2.0**	**J**	4	NJ GWQC	5
Dissolved Cadmium by 6010B	**15**		0.9	U	**18**		**7.4**		**80**		**64**		**71**		0.9	U	0.9	U	**2.1**	**J**	4	NJ GWQC	5
Total Lead by 200.8	1.2	U	1.2	U	1.2	U	**20**		1.2	U	1.2	U	1.2	U	**150**		1.2	U	1.2	U	5	NJ GWQC	15 *
Total Lead by 6010B	**7.1**		2.8	U	2.8	U	**21**		2.8	U	**4.0**	**J**	**3.1**	**J**	**160**		2.8	U	2.8	U	5	NJ GWQC	15 *
Dissolved Lead by 200.8	1.2	U	1.2	U	1.2	U	**1.8**		1.2	U	1.2	U	1.2	U	**29**		1.2	U	1.2	U	5	NJ GWQC	15 *
Dissolved Lead by 6010B	2.8	U	2.8	U	**4.8**	**J**	**10**		**16**		2.8	U	2.8	U	**31**		2.8	U	2.8	U	5	NJ GWQC	15 *
Organics (ug/L)																							
Acetone	9.8	U	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U	2.5	U	2.5	U	2.5	U	2.5	U	6,000	NJ GWQC	NA
Benzene	0.1	U	**0.2**	**J**	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	NJ MCL	5
Bromodichloromethane	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	1	PQL	NA
2-Butanone	0.8	U	0.8	R	0.8	R	0.8	U	0.8	R	0.8	U	0.8	U	0.8	U	0.8	U	0.8	R	300	NJ GWQC	NA
Carbon Disulfide	0.2	U	0.2	U	0.2	U	0.2	R	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	700	NJ GWQC	NA
Chloroform	0.2	U	0.2	U	0.2	U	0.2	U	0.43	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ GWQC	NA
Dibromochloromethane	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	NA
1,1-Dichloroethene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	2	NJ MCL	7
1,1-Dichloroethane	0.1	U	**0.2**	**J**	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	50	NJ MCL	NA
cis-1,2-Dichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ MCL	70
1,4-Dioxane	0.9	U	**7.7**	**J**	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	NA	NA	NA
Methylene Chloride	0.2	U	0.2	U	0.2	U	0.2	U J	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	3	NJ MCL	5
Tetrachloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	1 (5 in ROD)
Toluene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	600	NJ GWQC	1,000
1,1,1-Trichloroethane	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	30	NJ MCL	200
Trichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	5
Vinyl Chloride	0.1	U	**6.9**		0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	2
Xylenes, Total	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	1,000	NJ MCL	10,000
General Chemistry																							
pH	**3.77**		**7.56**		**3.97**		**4.70**		**4.26**		**5.73**		NA		**6.31**		**6.32**		**5.44**		NA		NA
Conductivity (mS/cm)	**0.47**		**0.73**		**4.55**		**0.16**		**1.77**		**1.04**		NA		**0.09**		**0.31**		**1.29**		NA		NA
Temperature (deg. C)	**14.6**		**14.2**		**14.3**		**14.7**		**16.0**		**16.0**		NA		**14.1**		**14.9**		**13.6**		NA		NA
ORP (mV)	**452**		**18**		**226**		**265**		**170**		**194**		NA		**182**		**2**		**173**		NA		NA
Turbidity (NTU)	**2.1**		**4.9**		**5.2**		**16.7**		**0.8**		**0.0**		NA		**120.0**		**11.7**		**0.0**		NA		NA
Dissolved Oxygen (mg/L)	**0.00**		**0.00**		**0.00**		**0.51**		**0.00**		**0.00**		NA		**3.09**		**0.00**		**0.00**		NA		NA

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The data shaded in gray represent lead concentrations analyzed by EPA Method 200.8 that are above the NJGWQC. Lead concentrations analyzed by EPA Method 6010B are not shaded because the results were affected by yttrium interference associated with the laboratory method.

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November 29, 2010 - December 3, 2010
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

	Sample Identification																							
Parameter	34		JS		JDR		KSR		KDR		SS		SD		NS		ND		OS		Lowest NJ Standard	Source	EPAMCL
Inorganics (ug/L)																								
Total Cadmium by 200.8	2.0	U	**2.5**		**18**		2.0	U	**76**		**2.8**		**180**		2.0	U	2.0	U	**5.3**		4	NJ GWQC	5
Total Cadmium by 6010B	0.9	U	**2.6**	**J**	**20**		**2.1**	**J**	**68**		**2.0**	**J**	**160**		0.9	U	0.9	U	**4.4**	**J**	4	NJ GWQC	5
Dissolved Cadmium by 200.8	2.0	U	**2.2**	**J**	**18**		**2.0**	**J**	**70**		2.0	U	**190**		2.0	U	2.0	U	**4.9**		4	NJ GWQC	5
Dissolved Cadmium by 6010B	0.9	U	**2.4**	**J**	**18**		**2.0**	**J**	**52**		0.9	U	**38**		0.9	U	0.9	U	**4.4**	**J**	4	NJ GWQC	5
Total Lead by 200.8	**2.2**		1.2	U	1.2	U	1.2	U	1.2	U	**68**		**73**		**48**		**3.4**		**1100**		5	NJ GWQC	15 *
Total Lead by 6010B	**7.2**		2.8	U	2.8	U	2.8	U	5.6	U	**73**		56	U	**53**		2.8	U	**970**		5	NJ GWQC	15 *
Dissolved Lead by 200.8	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	1.2	U	**46**		**1.8**		1.2	U	**970**		5	NJ GWQC	15 *
Dissolved Lead by 6010B	2.8	U	2.8	U	**5.7**		**18**		**20**		**12**		**16**		2.8	U	2.8	U	**970**		5	NJ GWQC	15 *
Organics (ug/L)																								
Acetone	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U J	2.5	U	6,000	NJ GWQC	NA
Benzene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	**0.14**	**J**	0.1	U	0.1	U	0.1	U	1	NJ MCL	5
Bromodichloromethane	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	1	PQL	NA
2-Butanone	0.8	R	0.8	R	0.8	R	0.8	R	0.8	R	0.8	R	0.8	R	0.8	R	0.8	R	0.8	U	300	NJ GWQC	NA
Carbon Disulfide	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	**0.51**	**J**	0.2	U	0.2	U	0.2	U	700	NJ GWQC	NA
Chloroform	0.2	U	0.2	U	0.2	U	0.2	U	0.59	U	0.2	U	**2.2**		0.2	U	0.2	U	0.2	U	70	NJ GWQC	NA
Dibromochloromethane	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	NA
1,1-Dichloroethene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	2	NJ MCL	7
1,1-Dichloroethane	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	50	NJ MCL	NA
cis-1,2-Dichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ MCL	70
1,4-Dioxane	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	NA	NA	NA
Methylene Chloride	0.2	U	0.2	U J	0.2	U	0.2	U	0.2	U	0.2	U	0.25	U	0.2	U J	0.2	U J	0.2	U	3	NJ MCL	5
Tetrachloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	1 (5 in ROD)
Toluene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	**0.38**	**J**	0.1	U	0.1	U	0.1	U	600	NJ GWQC	1,000
1,1,1-Trichloroethane	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	30	NJ MCL	200
Trichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	5
Vinyl Chloride	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	2
Xylenes, Total	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	**0.76**	**J**	0.4	U	0.4	U	0.4	U	1,000	NJ MCL	10,000
General Chemistry																								
pH	**5.73**		**5.34**		**4.97**		**2.77**		**3.56**		**7.79**		**3.49**		**6.11**		**5.02**		**5.30**		NA		NA
Conductivity (mS/cm)	**2.31**		**0.04**		**0.28**		**0.20**		**4.02**		**0.90**		**33.20**		**0.19**		**1.49**		**1.21**		NA		NA
Temperature (deg. C)	**12.3**		**14.4**		**15.5**		**13.7**		**14.4**		**15.7**		**15.42**		**13.5**		**14.6**		**14.9**		NA		NA
ORP (mV)	**61**		**69**		**95**		**330**		**268**		**-57**		**210**		**151**		**34**		**99**		NA		NA
Turbidity (NTU)	**933.0**		**14.1**		**57.8**		**6.0**		**0.0**		**64.8**		**116**		**0.3**		**8.8**		**4.7**		NA		NA
Dissolved Oxygen (mg/L)	**0.00**		**0.00**		**0.00**		**0.20**		**0.00**		**0.00**		**0.00**		**0.91**		**0.00**		**0.00**		NA		NA

Notes:

J = The concentration is an estimated value. U = Parameter was not detected. UJ = Parameter no detected. The reporting limit is estimated

R = The results is unreliable/unusable. NA = Not Applicable

[1] DUP-100 is a duplicate sample obtained from monitoring well 13.

[2] DUP-102 is a duplicate sample obtained from monitoring well 30R.

[3] DUP-103 is a duplicate sample obtained from monitoring well 16.

[4] Two rinsate blanks (RB-1 and RB-2) were collected to evaluate the effectiveness of field decontamination procedures.

* This concentration is an action level and not an MCL

The lowest NJ Criterion is the lowest value of the NJ Groundwater Quality Criterion (GWQC), NJ Maximum Contaminant Level (MCL), or the Practical Quantitation Limit (PQL).

The data shaded in gray represent lead concentrations analyzed by EPA Method 200.8 that are above the NJGWQC. Lead concentrations analyzed by EPA Method 6010B are not shaded because the results were affected by yttrium interference associated with the laboratory method.

TABLE 2
Groundwater Data Summary
November 29, 2010 - December 3, 2010
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

	Sample Identification																
Parameter	BR		RB-1		RB-2		TB-1		TB-2		Lowest NJ Standard	Source	EPAMCL
Inorganics (ug/L)													
Total Cadmium by 200.8	2.0	U	2.0	U	2.0	U	NA		NA		4	NJ GWQC	5
Total Cadmium by 6010B	0.9	U	0.9	U	0.9	U					4	NJ GWQC	5
Dissolved Cadmium by 200.8	2.0	U	NA		NA		NA		NA		4	NJ GWQC	5
Dissolved Cadmium by 6010B	0.9	U	NA		NA						4	NJ GWQC	5
Total Lead by 200.8	**11.0**		1.2	U	1.2	U	NA		NA		5	NJ GWQC	15 *
Total Lead by 6010B	**13.0**		2.8	U	2.8	U					5	NJ GWQC	15 *
Dissolved Lead by 200.8	**1.5**		NA		NA		NA		NA		5	NJ GWQC	15 *
Dissolved Lead by 6010B	2.8	U	NA		NA						5	NJ GWQC	15 *
Organics (ug/L)													
Acetone	2.5	U	2.5	U J	4.5	U	**9.1**	**J**	**4.2**	**J**	6,000	NJ GWQC	NA
Benzene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	NJ MCL	5
Bromodichloromethane	0.9	U	**0.59**	**J**	0.9	U	0.9	U	0.9	U	1	PQL	NA
2-Butanone	0.8	U	0.8	R	**1.8**	**J**	0.8	R	0.8	U	300	NJ GWQC	NA
Carbon Disulfide	0.2	U	**1.7**		**0.24**	**J**	0.2	U	0.2	U	700	NJ GWQC	NA
Chloroform	0.2	U	**2.1**		0.2	U	0.2	U	0.2	U	70	NJ GWQC	NA
Dibromochloromethane	0.1	U	**0.16**	**J**	0.1	U	0.1	U	0.1	U	1	PQL	NA
1,1-Dichloroethene	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	2	NJ MCL	7
1,1-Dichloroethane	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	50	NJ MCL	NA
cis-1,2-Dichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	70	NJ MCL	70
1,4-Dioxane	0.9	U	0.9	U	0.9	U	0.9	U	0.9	U	NA	NA	NA
Methylene Chloride	0.2	U	0.2	U	0.2	U	**0.44**	**J**	0.2	U	3	NJ MCL	5
Tetrachloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	1 (5 in ROD)
Toluene	0.1	U	0.1	U	**0.56**	**J**	0.1	U	0.1	U	600	NJ GWQC	1,000
1,1,1-Trichloroethane	0.3	U	0.3	U	0.3	U	0.3	U	0.3	U	30	NJ MCL	200
Trichloroethene	0.2	U	0.2	U	0.2	U	0.2	U	0.2	U	1	NJ MCL	5
Vinyl Chloride	0.1	U	0.1	U	0.1	U	0.1	U	0.1	U	1	PQL	2
Xylenes, Total	0.4	U	0.4	U	0.4	U	0.4	U	0.4	U	1,000	NJ MCL	10,000
General Chemistry													
pH	**6.67**		NA		NA		NA		NA		NA		NA
Conductivity (mS/cm)	**0.46**		NA		NA		NA		NA		NA		NA
Temperature (deg. C)	**14.5**		NA		NA		NA		NA		NA		NA
ORP (mV)	**95**		NA		NA		NA		NA		NA		NA
Turbidity (NTU)	**1.8**		NA		NA		NA		NA		NA		NA
Dissolved Oxygen (mg/L)	**0.00**		NA		NA		NA		NA		NA		NA

Notes:

J = The concentration is an estimated value.
U = Parameter was not detected.
UJ = Parameter no detected. The reporting limit is estimated
R = The results is unreliable/unusable.
NA = Not Applicable

[1] DUP-100 is a duplicate sample obtained from monitoring well 13.
[2] DUP-102 is a duplicate sample obtained from monitoring well 30R.
[3] DUP-103 is a duplicate sample obtained from monitoring well 16.
[4] Two rinsate blanks (RB-1 and RB-2) were collected to evaluate the effectiveness of field decontamination procedures.
* This concentration is an action level and not an MCL
The lowest NJ Criterion is the lowest value of the NJ Groundwater Quality Criterion (GWQC), NJ Maximum Contaminant Level (MCL), or the Practical Quantitation Limit (PQL).
The data shaded in gray represent lead concentrations analyzed by EPA Method 200.8 that are above the NJGWQC. Lead concentrations analyzed by EPA Method 6010B are not shaded because the results were affected by yttrium interference associated with the laboratory method.

TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**11**									**12**							
Year	1983	1988	1989	1990	1997	1998	2004	2007	2010	1989	1990	1997	1998	2004	2007	2010	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	NM	NM	NM	NM	**47 JE**	**240**	**416**	**110 J**	**74**	NM	NM	ND	ND	ND	ND	ND	4
Dissolved Cadmium	NM	**134**	**210**	NM	**8 J**	**253**	**415**	**113 J**	**70**	ND	NM	NM	**0.9 B**	ND	ND	ND	4
Total Lead	**460**	NM	NM	NM	**25.2 J**	1.4 JB	4	ND	**1.7**	NM	NM	ND	ND	**4.9**	ND	ND	5
Dissolved Lead	NM	**6 J**	NM	NM	ND	ND	**5.1**	ND	ND	NM	**2.3**	NM	ND	ND	ND	ND	5
Volatile Organic Compounds (ug/L)																	
Total Organics	NM	NM	**5124**	**2974**	**1.52**	NM	**15**	**5.86**	**10.85**	NM	NM	**11.3**	NM	**3.7**	**9.3**	**19.99**	NA

Notes:
* = Original well damaged during the remedial action, replacement well data provided.
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
J = Value is approximate
B = Value was less than the contract-required LOD, but greater than the instrument LOD
E = Estimated value based on the presence of an interference

TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**13**		**14**		**15**						**16**		**17**				
Year	2007	2010	2007	2010	1989	1990	1997	2004	2007	2010	2007	2010	1989	1990	1997	2007	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	ND	ND	ND	ND	NM	NM	ND	NM	ND	ND	ND	ND	NM	NM	**2.3 JE**	ND	4
Dissolved Cadmium	ND	ND	ND	ND	ND	ND	**20 JE**	NM	ND	ND	ND	ND	ND	ND	NM	ND	4
Total Lead	ND	ND	ND	**3.5**	NM	NM	**4.5**	NM	ND	ND	ND	ND	NM	NM	**5.5 J**	ND	5
Dissolved Lead	ND	ND	ND	ND	NM	**2.1**	ND	NM	ND	ND	ND	ND	NM	1.6	NM	ND	5
Volatile Organic Compounds (ug/L)																	
Total Organics	ND	ND	ND	ND	NM	NM	ND	NM	ND	ND	**0.69**	ND	NM	NM	**1.9**	ND	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
J = Value is approximate
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**17**	**22**				**23**				**24**			**26**				
Year	2010	1998	2004	2007	2010	1998	2004	2007	2010	2004	2007	2010	1998	2004	2007	2010	**RAO**
Inorganic Compunds (ug/L)																	
Total Cadmium	ND	**92**	**15.6**	**7.3 J**	**3.7**	**12.9**	**74.8**	**25.8 J**	**16**	ND	ND	ND	ND	**31**	**13 J**	**42**	4
Dissolved Cadmium	ND	**86.2**	ND	**7.2 J**	**3.5**	**12.1**	ND	**26.7 J**	**14**	ND	ND	ND	**42 JB**	ND	**13 J**	**40**	4
Total Lead	ND	**1.9 B**	**5.7**	ND	ND	**1.6 B**	**3.6**	ND	ND	**4.9**	ND	ND	ND	**5.6**	**1.4 J**	ND	5
Dissolved Lead	ND	**4.9**	ND	ND	ND	**1.5 B**	ND	ND	ND	**4.3**	ND	ND	**49 JB**	ND	ND	ND	5
Volatile Organic Compounds (ug/L)																	
Total Organics	ND	NM	ND	ND	ND	NM	ND	ND	ND	**5.26**	**5.56**	**15**	NM	ND	ND	ND	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**27**				**28**				**30R***				**31**				
Year	1998	2004	2007	2010	1998	2004	2007	2010	1998	2004	2007	2010	1998	2004	2007	2010	**RAO**
Inorganic Compunds (ug/L)																	
Total Cadmium	**14.8**	**2.2 J**	**8.5**	**7.7**	**383**	**250**	**151**	**110**	**327**	**136**	**163 J**	**63**	ND	ND	**1.5 J**	ND	4
Dissolved Cadmium	**14.5**	ND	**7.1**	**6.9**	**360**	ND	**163**	**110**	**341**	ND	**169 J**	**62**	ND	ND	**1.0 J**	ND	4
Total Lead	**19.9**	**4.2**	**6.2**	**20**	**15.4**	**4.2**	ND	ND	**37.4**	**3.2**	ND	ND	ND	**34.3**	**20.6 J**	**150**	5
Dissolved Lead	**21**	ND	**3.3**	**1.8**	**13**	ND	ND	ND	**36.8**	ND	**1.6 J**	ND	ND	**2.8 J**	ND	**29**	5
Volatile Organic Compounds (ug/L)																	
Total Organics	NM	ND	ND	ND	NM	ND	ND	ND	NM	ND	ND	ND	NM	ND	ND	ND	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
J = Value is approximate
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**32**				**33**				**34**				**JS**				
Year	1998	2004	2007	2010	1998	2004	2007	2010	1998	2004	2007	2010	1998	2004	2007	2010	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	ND	ND	ND	ND	ND	**0.5 J**	**3.0 J**	**2.0 J**	ND	ND	ND	ND	**1.4 B**	**3.9 J**	**3.9 J**	**2.5**	4
Dissolved Cadmium	ND	ND	ND	ND	ND	**0.4 J**	ND	**2.0 J**	ND	ND	ND	ND	**1.5 B**	**1.5 J**	**3.0 J**	**2.2 J**	4
Total Lead	ND	**2.3 J**	ND	ND	**1.6 B**	ND	ND	ND	**8.6**	ND	**16.3**	**2.2**	ND	**4**	1.0 J	ND	5
Dissolved Lead	ND	ND	ND	ND	ND	ND	ND	ND	ND	**2.4 J**	ND	ND	ND	**3**	ND	ND	5
Volatile Organic Compounds (ug/L)																	
Total Organics	NM	ND	ND	ND	NM	ND	ND	ND	NM	ND	ND	ND	NM	ND	ND	ND	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
J = Value is approximate
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**JDR***							**KSR***						**KDR***			
Year	1983	1988	1997	1998	2004	2007	2010	1983	1988	1997	2004	2007	2010	1983	1988	1989	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	NM	NM	**193 J**	**200**	**14.8**	**54.5 J**	**18**	NM	NM	**63 J**	**15.1**	**7.8 J**	ND	NM	NM	NM	4
Dissolved Cadmium	NM	**103**	**7.1**	**207**	**12.6**	**60.8 J**	**18**	NM	**173**	**172**	**15.8**	ND	**2.0 J**	NM	**291**	**113**	4
Total Lead	**390**	NM	**4.1 B**	ND	**12.6**	ND	ND	**2560**	NM	**328**	**5**	ND	ND	**270**	NM	NM	5
Dissolved Lead	NM	**14**	ND	ND	**6.8**	ND	ND	NM	**3130**	ND	**4.1**	ND	ND	NM	**61 J**	**19 J**	5
Volatile Organic Compounds (ug/L)																	
Total Organics	NM	NM	**0.27**	NM	ND	ND	ND	NM	NM	ND	ND	ND	ND	NM	NM	NM	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
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NA = Not Applicable
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**KDR***					**SS**				**SD**							
Year	1990	1997	2004	2007	2010	1998	2004	2007	2010	1983	1988	1989	1990	1997	1998	2004	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	**103**	**16.5 J**	**97.1**	**141 J**	**76**	**22.7**	**105**	**10.6 J**	**2.8**	NM	NM	NM	NM	**237 JE**	**185**	**134**	4
Dissolved Cadmium	NM	**19.0 J**	**92.8**	**166 J**	**70**	**18.2**	ND	**11.8 J**	ND	NM	**1010**	**963**	**997**	NM	**169**	ND	4
Total Lead	**14**	ND	**11.9**	ND	ND	ND	**321**	**82.9**	**68**	**2960**	NM	NM	NM	**51.1 J**	**25.6 J**	**36.8**	5
Dissolved Lead	NM	ND	**11.2**	ND	ND	ND	ND	**13**	ND	NM	**294**	**84.0 J**	**56**	NM	**24.0 J**	ND	5
Volatile Organic Compounds (ug/L)																	
Total Organics	NM	ND	**0.96**	ND	ND	NM	**1.9**	ND	ND	NM	NM	**6**	**13**	**20**	NM	**17.93**	NA

Notes:
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RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**SD**		**NS**								**ND**				**OS**		
Year	2007	2010	1983	1988	1989	1997	1998	2004	2007	2010	1998	2004	2007	2010	1998	2004	**RAO**
Inorganic Compounds (ug/L)																	
Total Cadmium	**149 J**	**180**	NM	NM	NM	ND	**0.8 B**	**0.6 J**	ND	ND	**0.4 B**	ND	ND	ND	**4.7 B**	**1.4 J**	4
Dissolved Cadmium	**156 J**	**190**	NM	**9**	**4**	NM	ND	ND	ND	ND	**1.5 B**	ND	ND	ND	**2.9 B**	**1.4 J**	4
Total Lead	**31**	**73**	**1180**	NM	NM	**8.2**	**5.1 J**	**7.4**	**41.6 J**	**48**	ND	**18.8**	**22.2 J**	**3.4**	**476 J**	**456**	5
Dissolved Lead	**90.4**	**46**	NM	**45 J**	**10 J**	NM	ND	**2.3 J**	ND	**1.8**	ND	**10.6**	ND	ND	**6.8 J**	**94.9**	5
Volatile Organic Compounds (ug/L)																	
Total Organics	**5.23**	**3.99**	NM	NM	NM	ND	NM	ND	ND	ND	NM	**0.34**	**0.41**	ND	NM	ND	NA

Notes:
* = Original well damaged during the remedial action, replaced in 2004
RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
ND = Not detected above the laboratories limit of detection (LOD)
NM = Not Measured
NA = Not Applicable
J = Value is approximate
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TABLE 3
Historical Data Summary
NL Industries Superfund Site
Pedricktown, New Jersey

Well ID	**OS**		**BR**								
Year	2007	2010	1983	1988	1990	1997	1998	2004	2007	2010	**RAO**
Inorganic Compounds (ug/L)											
Total Cadmium	**3.9 J**	**5.3**	NM	**15**	NM	**13.5 E**	**16**	**1.3 J**	ND	ND	4
Dissolved Cadmium	**4.2 J**	**4.9**	NM	ND	NM	NM	**15**	**1.4 J**	ND	ND	4
Total Lead	**388**	**1100**	**250**	**18**	NM	**1.9 B**	ND	**5.6**	ND	**11**	5
Dissolved Lead	**320**	**970**	NM	**5.0 J**	NM	NM	**1.4 JB**	**3.9**	ND	**1.5**	5
Volatile Organic Compounds (ug/L)											
Total Organics	ND	ND	NM	NM	**89.3**	**79**	NM	ND	ND	ND	NA

Notes:
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RAO = Remedial Action Objective. RAO is the lowest value out of NJGWQS, NJMCL, or MCL as defined in the ROD.
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TABLE 4
Recommended Groundwater Monitoring Locations for MNA Remedy
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Monitoring Well	Well Depth [1]	Screened Interval [2]	Aquifer Zone [3]	Rationale
BR	39	33-39	UA	western limits
JS	15.37	5-15	UA	eastern limits
JDR	27.26	17-27	UA	eastern limits
KSR	15	5-15	UA	central area
KDR	24	14-24	UA	central area
NS	16.5	6.5-16.5	UA	western limits
ND	24	14-24	UA	western limits
OS	21.3	6.3-21.3	UA	western limits
SS	16.4	6.4-16.4	UA	central area
SD	29.4	17.4-29.4	UA	central area
11	54.1	34.1-54.1	UA	western limits
14	46.6	26.6-46.6	UA	northern limits
15	25	10-25	UA	northern limits
22	16	11-16	UA	eastern limits
23	24	24-34	UA	eastern limits
26	22	12-22	UA	northern limits
27	15	5-15	UA	central area
28	30	20-30	UA	central area
30R	28.71	17-27	UA	central area
31	15	5-15	UA	southern limits
33	10	5-10	UA	northern limts
MW-1[4]	TBD	TBD	UA	western limits
MW-2[4]	TBD	TBD	UA	western limits

Notes:
[1] Depth to bottom of well in feet below top of casing (TOC).
[2] Screened interval of well in feet below ground surface.
[3] UA = Unconfined Aquifer
[4] Monitoring wells to be installed at locations shown on Figure 10.

TABLE 5
Opinion of Probable Cost
(Capital Cost: Monitored Natural Attenuation Groundwater Sampling, One Event)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

CAPITAL COST SUMMARY	Quantity	Unit	Unit Cost/Time	Extended Cost	Notes
Groundwater Monitoring					
Labor	1	ea	$9,000.00	$9,000	
Analytical Costs	1	ea	$14,000.00	$14,000	*VOC+Tot/Dis pb & cd + WQ = $500 ea * 28 wells*
Equipment/Expenses	1	ea	$3,112.00	$3,112	
			subtotal	**$26,112**	
		Remediation/Oversight Costs		**$26,112**	
Engineering and Related Costs					
Groundwater Evaluation/Reporting	1	ls	$5,000	$5,000	
Regulatory Interaction	5.00%	ls		$250	
Contingency	15.00%	%		$788	
Inflation (3 %, 0 years)	0.00%	%/yrs	0	$0	
			subtotal	**$6,038**	Expect to start in 2012
MNA Work Plan	1	ls	$0	$0	Costs included on Table 6
Regulatory Interaction	10.00%	ls		$0	Not Required
Contingency	0.00%	%		$0	
Inflation (3 %, 0 years)	3.00%	%/yrs	1	$0	
			subtotal	**$0**	
		Engineering and Related Costs		**$6,038**	
TOTAL				**$32,150**	

Notes:
WQ = Water Quality Parameters

TABLE 6
Opinion of Probable Cost
(Present Worth: Monitored Natural Attenuation Groundwater Sampling for 30 Years)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Groundwater Monitoring Annual Cost	Qty	Unit	Unit Price	Inflation Rate*	Years of Inflation*	Extended Cost
Groundwater Monitoring Costs						
MNA Work Plan	1	one time only	$5,000	0.00%	0	$5,000
Install two (2) monitoring wells	1	one time only	$20,000	0.00%	0	$20,000
Groundwater Monitoring (quarterly)	4	event	$32,150	0.00%	0	$128,600
Groundwater Monitoring (semi-annual)	2	event	$32,150	0.00%	0	$64,300
Groundwater Monitoring (annual)	1	event	$32,150	0.00%	0	$32,150
						$250,050
Other						
Regulatory Interaction (work plan)	1	ls	$500	0.00%	0	$500
Regulatory Interaction (quarterly)**	4	ls	$3,215	0.00%	0	$12,860
Regulatory Interaction (semi-annual)**	2	ls	$3,215	0.00%	0	$6,430
Regulatory Interaction (annual)**	1	ls	$3,215	0.00%	0	$3,215
						$19,790
						$269,840

Present Worth Calculation		**Example**	**2012-2013 Mon. (quarterly)**	**2014-2016 Mon. (semi-annual)**	**2017-2041 Mon. (annual)**
Annual Inflation Rate:		0.1 (10% inflation)	0.035	0.035	0.035
Discount or Interest Rate: (annual compounding)		0.08 (8% interest rate)	0.05	0.05	0.05
Annual Cost Throughout Current Year (cost of activities performed in current year not adjusted for inflation during current year)		$100 (Estimated 1998 cost)	$166,960	$70,730	$35,365
Current Year		2003	2011	2011	2011
Year of First End-of-Year Payment		2005	2012	2014	2017
Year of Last End-of-Year Payment		2013	2013	2016	2041
Present Worth (Beginning of Current Year)		$1,006	**$326,799**	**$200,336**	**$686,069**
TOTAL PRESENT WORTH	**$1,213,204**				

Notes:
* If a unit rate is derived from a previous cost estimate, then it is adjusted for inflation to 2011 dollars. If the unit rate is based on current costs, then there is no adjustment for inflation.
** Estimated at 10% of One Monitoring Event cost.

TABLE 7
Treatability Study Data Summary
April 2007
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Parameter	Well Number												
	102*	31	JDR	JS	23	OS	SS	SD	NS	KDR	KSR	11	34
Inorganics													
Alkalinity (mg/L)	49	50	2	10	2	22	38	2	100	2	2	15	48
BOD (mg/L)	2	2	2	2	2	2	2	2	2	2	2	2	2
Chloride (mg/L)	4	4	7	3	7	6	43	3,000	2	49	3	37	44
COD (mg/L)	5	5	7	5	5	8	22	250	9	13	5	5	9
Calcium - dissolved (ug/L)	35,100	34,600	15,500	8,590	12,500	27,100	51,200	209,000	39,200	81,900	18,600	78,200	15,300
Calcium - total (ug/L)	38,200	31,300	11,800	8,370	11,600	24,700	47,500	199,000	36,700	78,600	16,500	72,200	14,000
Manganese - dissolved (ug/L)	81	61	437	30	675	231	516	8,170	7.0 J	3,830	110	2,210	2,580
Manganese - total (ug/L)	106	100	340	31	672	220	479	8,020	34	3,780	99	2,240	7,780
Iron - dissolved (ug/L)	709	474	1,890	267	114	7,710	23,400	294,000	18.8 B	77,500	18.8 B	18.8 B	27,500
Iron - total (ug/L)	3,150	2,910	2,700	736	344	7,830	23,200	287,000	1,420	76,300	423	19	N/A
Sulfate (mg/L)	46	41	220	17	210	220	110	9,800	41	4,600	86	780	16
Sulfide (mg/L)	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B	1 B
Organics													
TOC (mg/L)	3.12	3.11	3.76	2.56	1.37	4.46	11	26	4.9	4.06	1.56	0.4	5.19

J = Data indicates the presence of a compound that meets the identification criteria. The result is less than the quantitation limit but greater than zero. The concentration given is an approximate value.

B = Parameter was flagged in data validation because of laboratory contamination and are considered non-detects.

* 102 is a duplicate sample obtained from monitoring well 31.

N/A = Not Analyzed

ND = Non Detect

TABLE 8
Opinion of Probable Cost
(pH Adjustment, Reagent Injection and Injection Point Installation Capital Costs)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Capital Cost Summary	Quantity	Unit	Unit Cost/Time	Extended Cost	Notes
Remediation Costs					
Mobilization	1	ls	$2,000.00	$2,000	
Injection Pt Installation	12	ea	$3,000.00	$36,000	Average 20 feet deep
Reagent Injection Equipment	1	ls	$7,500.00	$7,500	tanks, tubing, pumps
pH Neutralization (one event)	1	ls	$2,000.00	$2,000	NaOH application (approx. 5,000 lbs)
Reagent Chemicals (quarterly for 1 year)	4	ea	$125,000.00	$500,000	cd vol = 25 mill gall/1000 gal * $5
Labor for reagent injection/pH neutralization	5	ea	$1,500.00	$7,500	2 people @ $150/hr, one 10 hr day
			subtotal	**$555,000**	
Oversight, Injection pt Installation	7	day	$1,000	$7,000	
Regulatory Interaction	10.00%	ls		$55,500	10% of Remediation subtotal.
			subtotal	**$62,500**	
Contingency	30.00%	%		$185,250	
Inflation (3 %, 1 years)	3.00%	%/yrs	1	$24,083	
			subtotal	**$209,333**	
	Remediation/Oversight Costs			**$826,833**	Expect to perform in 2012 to 2013
Engineering and Related Costs					
Pilot Study + Work Plan	1	ls	$50,000	$50,000	Expect to perform in 2012 to 2013
Regulatory Interaction	10.00%	ls		$5,000	
Contingency	30.00%	ls		$16,500	
Inflation (3 %, 1 years)	3.00%	%/yrs	1	$2,145	
			subtotal	**$73,645**	
Remedial Action Plan	1	ls	$10,000	$10,000	Plan for implementation of alternative
Regulatory Interaction	10.00%	ls		$1,000	10% of plan cost.
Contingency	30.00%	%		$3,300	
Inflation (3 %, 1 years)	3.00%	%/yrs	1	$429	
			subtotal	**$14,729**	Expect to perform in 2012-2013
	Engineering and Related Costs			**$88,374**	
TOTAL				**$915,207**	

TABLE 9
Opinion of Probable Cost
(Present Worth: Reagent Injection - Groundwater Sampling for 10 Years)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Groundwater Monitoring Annual Cost	Qty	Unit	Unit Price	Inflation Rate*	Years of Inflation*	Extended Cost
Groundwater Monitoring Costs						
MNA Work Plan	1	one time only	$5,000	0.00%	0	$5,000
Install two (2) monitoring wells	1	one time only	$20,000	0.00%	0	$20,000
Groundwater Monitoring (quarterly)	4	event	$32,150	0.00%	0	$128,600
Groundwater Monitoring (semi-annual)	2	event	$32,150	0.00%	0	$64,300
Groundwater Monitoring (annual)	1	event	$32,150	0.00%	0	$32,150
						$250,050
Other						
Regulatory Interaction (work plan)	1	ls	$500	0.00%	0	$500
Regulatory Interaction (quarterly)**	4	ls	$3,215	0.00%	0	$12,860
Regulatory Interaction (semi-annual)**	2	ls	$3,215	0.00%	0	$6,430
Regulatory Interaction (annual)**	1	ls	$3,215	0.00%	0	$3,215
						$19,790
						$269,840

Present Worth Calculation		**Example**	**2012-2013 Mon. (quarterly)**	**2014-2016 Mon. (semi-annual)**	**2017-2021 Mon. (annual)**
Annual Inflation Rate:		0.1 (10% inflation)	0.035	0.035	0.035
Discount or Interest Rate: (annual compounding)		0.08 (8% interest rate)	0.05	0.05	0.05
Annual Cost Throughout Current Year (cost of activities performed in current year not adjusted for inflation during current year)		$100 (Estimated 1998 cost)	$166,960	$70,730	$35,365
Current Year		2003	2011	2011	2011
Year of First End-of-Year Payment		2005	2012	2014	2017
Year of Last End-of-Year Payment		2013	2013	2016	2021
Present Worth (Beginning of Current Year)		$1,006	**$326,799**	**$200,336**	**$157,631**
TOTAL GROUNDWATER MON PRESENT WORTH	**$684,766**				

Notes:
* If a unit rate is derived from a previous cost estimate, then it is adjusted for inflation to 2011 dollars. If the unit rate is based on current costs, then there is no adjustment for inflation.
** Estimated at 10% of One Monitoring Event cost.

TABLE 9 Cont.
Opinion of Probable Cost
(Present Worth: Reagent Injection)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Present Worth Calculation		**Example**	**2012 Eng.**	**2013 Rem/Ovst**
Annual Inflation Rate:		0.1 (10% inflation)	0.035	0.035
Discount or Interest Rate: (annual compounding)		0.08 (8% interest rate)	0.05	0.05
Annual Cost Throughout Current Year (cost of activities performed in current year not adjusted for inflation during current year)		$100 (Estimated 1998 cost)	$88,374	$826,833
Current Year		2003	2011	2011
Year of First End-of-Year Payment		2005	2012	2013
Year of Last End-of-Year Payment		2013	2012	2013
Present Worth (Beginning of Current Year)		$1,006	**$87,112**	**$803,378**
TOTAL ENGINEERING COST PRESENT WORTH	**$890,489**			
TOTAL GROUNDWATER MONITORING PRESENT WORTH	**$684,766**			
TOTAL PRESENT WORTH	**$1,575,255**			

Notes:
* If a unit rate is derived from a previous cost estimate, then it is adjusted for inflation to 2011 dollars. If the unit rate is based on current costs, then there is no adjustment for inflation.
** Estimated at 10% of Operation and Maintenance cost.

Table 10
Present Worth - Pump and Treat Alternative with Discharge to Delaware River
NL Industries, Inc. Superfund Site
Pedricktown, NJ

Item[1]	Quantity	Units	Unit Cost	Extended Cost	Total Cost
DIRECT CAPITAL COSTS					
Site Preparation					
Mobilization/Site Preparation	1.00	LS	$7,500	$7,500	
Health and Safety Plan	1.00	LS	$1,000	$1,000	
Erosion/Sediment/Dust Control	1.00	LS	$5,000	$5,000	
Clear and Grub	0.25	ACRE	$4,000	$1,000	
Well Point System Startup-not required	1.00	LS	$0	$0	
Subtotal					**$14,500**
Outfall Construction for:	1.00	LS	$500,000	$500,000	
Delaware River Discharge (1.5 miles piping)					
Subtotal					**$500,000**
Purchased Treatment Plant Equipment (E)					
GW Recovery Pump (20 gpm)-existing wells	3.00	EA	$2,500	$7,500	
Equalization Tank (1,000 gallons)	1.00	EA	$1,250	$1,250	
Clarifier Feed Pump (25 gpm)	2.00	EA	$1,250	$2,500	
Mix Tank (1000 gallons)	1.00	EA	$1,250	$1,250	
Clarifier (50 gpm)-slant tray	1.00	EA	$9,500	$9,500	
Lime Feed System	1.00	LS	$6,250	$6,250	
Chemical Feed Systems	1.00	LS	$3,750	$3,750	
Filter Feed Sump Tank (1000 gallons)	1.00	EA	$1,250	$1,250	
Filter Feed Pump (50 gpm)	2.00	EA	$12,500	$25,000	
Multi Media Filter	1.00	EA	$9,500	$9,500	
Treated Water Tank (1000 gallons)	1.00	EA	$1,250	$1,250	
Backwash Pump (100 gpm)	2.00	EA	$2,500	$5,000	
Sludge Transfer System-not required	1.00	EA	$0	$0	
Sludge Thickener-not required	1.00	EA	$0	$0	
Decant Pump (50 gpm)-not required	1.00	EA	$0	$0	
Filter Press (.5 ton/day)-not required	1.00	EA	$0	$0	
Filtrate Pump (10 gmp)-not required	1.00	EA	$0	$0	
Ion Exchange Columns/Regen/Tanks/Pumps	1.00	LS	$43,750	$43,750	
Subtotal (E)					**$117,750**
Treatment Plant Components	% of (E)				
Installation	66.00%			$77,715	
Instrumentation and Controls	30.00%			$35,325	
Piping	66.00%			$77,715	
Electrical	25.00%			$29,438	
Building and Site Improvements	30.00%			$35,325	
Services/Utilities	70.00%			$82,425	
Subtotal					**$337,943**
VOC Pretreatment (MW-11)					
Recovery Well with pump	1.00	EA	$5,000	$5,000	
Air Stripper with sump tank and pump	1.00	EA	$30,000	$30,000	
Piping	500.00	LF	$30	$15,000	
Electrical	1.00	LS	$5,000	$5,000	
Pad/Building	1.00	LS	$25,000	$25,000	
Subtotal					**$80,000**
Discharge					
Piping	800.00	FT	$30	$24,000	
Earthwork	0.25	ACRE	$7,500	$1,875	
Piping End Treatments-included	1.00	EA	$0	$0	
Subtotal					**$25,875**
TOTAL DIRECT CAPITAL COSTS					**$1,076,068**
INDIRECT CAPITAL COSTS					
Contingency (25% +/-)				$269,017	
Engineering (15% +/-)				$161,410	
Administration (5% +/-)				$53,803	
TOTAL INDIRECT CAPITAL COSTS					**$484,230**
TOTAL CAPITAL COSTS					**$1,560,298**

Table 10
Present Worth - Pump and Treat Alternative with Discharge to Delaware River
NL Industries, Inc. Superfund Site
Pedricktown, NJ

Item[1]	Quantity	Units	Unit Cost	Extended Cost	Total Cost
ANNUAL OPERATING AND MAINTENANCE COSTS					
Treatment Plant Components					
Operating Labor-N2 Operator	1000.00	MANHR	$70	$70,000	
Maintenance (4% total capital)	1.00	LS	$62,412	$62,412	
System					
Inspection and Maintenance	1.00	LS	$2,000	$2,000	
Outfall Pipeline					
Inspection and Maintenance	1.00	LS	$500	$500	
Chemical Usage	1.00	LS	$17,500	$17,500	
Sludge Disposal	36.00	TON	$250	$9,000	
Ion Exchange Regen.					
Water Disposal	20000.00	GALLONS	$0.25	$5,000	
Electrical Requirement	80000.00	KW	$0.14	$11,200	
Quarterly Effluent Monitoring	4.00	EA	$3,000	$12,000	
Subtotal					**$189,612**
Groundwater Monitoring Program (see Tables 5 and 6 for cost detail)					
Present Worth for 30 yr Program	1.00	LS	$1,213,204	$1,213,204	
Present Worth for Groundwater Mon. O&M					**$1,213,204**
Present Worth of System O&M (30 years @ 5%)					**$2,914,904**
Present Worth of 30 Years of O&M					**$4,128,108**
TOTAL ESTIMATED REMEDIAL COST					**$5,688,406**

Notes:
1. The opinion of cost is based upon CSI experience, currently available data and the list of system components provided in *Final Feasibility Study, NL Industries, Inc. Site* [O'Brien & Gere, 1993].
2. As documented in *Phase II Groundwater Evaluation Technical Memorandum* [GeoSyntec, 2000], the area of impact in groundwater declined significantly between 1988 and 1998. Also, a groundwater extraction rate of 37 gallons per minute (gpm) was shown to effectively provide capture of groundwater sitewide. Therefore, the opinion of cost for the above system is based conservatively on a system throughput flow rate of 50 gpm.

TABLE 11
Opinion of Probable Cost
(Capital Cost: Permeable Reaction Barrier Construction Costs)
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

CAPITAL COST SUMMARY	Quantity	Unit	Unit Cost/Time	Extended Cost	Notes
PRB Construction					
Labor	1	ea	$972,000.00	$972,000	Laborers, operators and supervisors
Equipment	1	ea	$500,750.00	$500,750	Approx. 150 days in construction
Materials	1	ea	$2,560,000.00	$2,560,000	Approx 71,000 CF of Apatite II = $1.35 mllion
Admin Requirements	1	ea	$508,000.00	$508,000	Includes Mob/Demob
			subtotal	**$4,540,750**	
		Construction Costs		**$4,540,750**	
Oversight Costs					
Regulatory Interaction	5.00%	ls		$227,038	
Contingency	30.00%	%		$68,111	
Inflation (3 %, 1 years)	3.00%	%/yrs	0	$0	
			subtotal	**$295,149**	Expect to start in 2012
Remedy Design	1	ls	$50,000	$50,000	
Regulatory Interaction	5.00%	ls		$2,500	
Contingency	30.00%	%		$15,750	
Inflation (3 %, 0 years)	3.00%	%/yrs	0	$0	Costs provided in 2011 dollars
			subtotal	**$68,250**	
		Oversight/Design Costs		**$363,399**	
			TOTAL	**$4,904,149**	

APPENDIX A

Table F from 1994 Record of Decision

TABLE F
NL INDUSTRIES SITE
GROUND WATER ARARS

HAZARDOUS CONTAMINANT	NJMCL[1]	NJGWQS[2]	PQL[3]	MCL[4]
Organic (ppb)				
Acetone	-	700	NA	-
Bis-(2-ethylhexyl)phthalate	4	3	30	-
Chloroform	-	6	1	-
1,2-Dibromomethane	-	-	-	-
1,1-Dichloroethane	-	70	-	-
1,1-Dichloroethylene	2	1	2	7
1,2-Dichloropropane	5	0.5	1	5
Ethylbenzene	700	700	5	700
Naphthalene	-	-	-	-
N-Nitroso-di-n-propylamine	-	0.005	20	-
Tetrachloroethylene	1	0.4	1	5
Toluene	1,000	1,000	5	1,000
1,1,1-Trichloroethane	26	30	1	200
1,2,4-Trimethylbenzene	-	-	-	-
1,3,5-Trimethylbenzene	-	-	-	-
Vinyl Chloride	2	0.08	5	2
Xylene(s) (total)	44	40	2	10,000
o-		NA	1	-
m&p-		NA	2	

[1]New Jersey Maximum Contaminant Levels (NJMCLs) are expressed in ppb. (N.J.A.C 7:10-16.7) For any listed contaminant, the more stringent of the NJMCL, NJGWQS, or federal MCL applies.

[2]New Jersey Ground Water Quality Standards (NJGWQS) (N.J.A.C. 7:9-6) are expressed in parts per billion (ppb).

[3] The Practical Quantitation Levels (PQLs) are expressed in ppb. In accordance with N.J.A.C. 7:9-6.9(c), where a constituent standard (the criterion adjusted by the antidegredation policy and applicable criteria exemptions) is of a lower concentration than the relevant PQL, the Department shall not (in the context of an applicable regulatory program) consider the discharge to be causing a contravention of that constituent standard so long as the concentration of the constituent in the affected ground water is less than the relevant PQL.

[4]Federal Maximum Contaminant Levels (MCLs) are expressed in ppb. For any listed contaminant, the more stringent of the federal MCL, NJMCL, and the NJGWQS applies.

TABLE F (Cont'd)
NL INDUSTRIES SITE
GROUND WATER ARARS

HAZARDOUS CONTAMINANT	NJMCL[1]	NJGWQS[2]	PQL[3]	MCL[4]
Metals (ppb)				
Antimony	6	2	20	6
Arsenic (total)	50	0.02	8	50
Beryllium	4	0.008	20	4
Cadmium	5	4	2	5
Chromium (total)	100	100	10	100
Copper	1,300*	1,000	1,000	-
Cyanide	200	200	40	200
Lead (total)	15*	5	10	-
Mercury (total)	2	2	0.5	2
Nickel (soluble salts)	100	100	10	100
Selenium (total)	50	50	10	50
Silver	-	NA	2	-
Thallium	2	0.5	10	2
Zinc	-	5,000	30	-
Radiation (see footnotes 4 & 5 for units)				
Gross Alpha	15[5]	15[5]	-	15[5]
Gross Beta	4[6]	4[6]	-	4[6]

* New Jersey Action Level

[5]Federal MCL expressed in picocuries/liter (pC/l). From 40 CFR part 141.

[6]Federal MCL expressed in picocuries/liter (pC/l). From 40 CFR part 141.

APPENDIX B

Core Laboratory Report (Thin Section Petrography and X-Ray Diffraction, October 1998)

CORE LABORATORIES

PETROGRAPHIC ANALYSES

FOR

GEOSYNTEC CONSULTANTS
SOIL SAMPLES
NL INDUSTRIES PROJECT

File 198178
October 1998

Performed by:
Core Laboratories, Advanced Technology Center
Reservoir Geology/Stratigraphy Group
1875 Monetary Lane
Carrollton, Texas 75006
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PETROLEUM SERVICES

October 29, 1998

Jeff Moore
GeoSyntec Consultants
10015 Old Columbia Rd., Ste. A-200
Columbia, Maryland 21046

Subject:	**Petrographic Analyses**
Sample Type:	**Sand Soils**
Location:	**NL Industries, Pedricktown, New Jersey**
File Number:	**198178**

Dear Mr. Moore:

The enclosed study includes detailed thin section petrography and X-ray diffraction (XRD) analyses of four soil samples from NL Industries, Pedricktown, New Jersey. The main focus of this report is to document the presence or absence of any mineral matrices in the samples that may contain lead-bearing substances. A secondary focus of the report is to document the possible detection of lead-bearing substances. Table 1 shows the XRD data, and Table 2 contains the point-count results. Plates 1 through 4 display the thin section photomicrographs and descriptions. Two original copies of this report were prepared. You have received one report, and the other was sent to your colleague, Hal Tuchfeld, in California.

Thank you for selecting Core Laboratories to perform these analyses for GeoSyntec Consultants. Please feel free to contact us if you have any questions or comments concerning this report, or if we can be of further service.

Sincerely,

Drew L. Dickert

Drew L. Dickert
Senior Petrologist
Reservoir Geology/Stratigraphy Group
(972) 323-3998

PROJECT TEAM

Drew L. Dickert
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THIN SECTION PHOTOMICROGRAPHS AND DESCRIPTIONS

PLATE 1: Sample SV26072098; Depth 14 – 16 feet
PLATE 2: Sample SV28071698; Depth 12 – 16 feet
PLATE 3: Sample SV29071598; Depth 10 – 16 feet
PLATE 4: Sample SV40; Depth N.A.

DISCUSSION

Introduction

Core Laboratories' Reservoir Geology/Stratigraphy Group, Carrollton, Texas, performed a petrographic study on four soil samples from NL Industries, Pedricktown, New Jersey. The analyses performed were detailed thin section petrography (includes a point-count of 250 points) and bulk & clay X-ray diffraction (XRD). The purposes of this study are to describe the natural soil texture and composition, document the presence or absence of any mineral matrices in the samples that may contain lead-bearing substances, and identify any lead-bearing substances, if possible. Table 1 shows the XRD data, and Table 2 contains the point-count results. Plates 1 through 4 display the thin section photomicrographs and descriptions. The following discussion summarizes the findings. For ease of reference in the discussion, the sample names have been shortened to SV26, SV28, SV29, and SV40.

Sample Descriptions

The thin section analysis shows that all four soil samples are poorly sorted sands. SV26, SV28, and SV40 are silty sands, in which at least ten percent of the grains are silt sized. SV29 is a muddy sand, where clay matrix and silt together compose over ten percent of the sample. The muddy sand has the finest estimated average grain size (0.28 mm, excluding clay matrix), whereas the other sands have estimated average grain sizes between 0.36 and 0.40 millimeters. Most of the grains in each sample range from <0.01 to 2.5 millimeters in diameter. No pebbles (grains >4 mm) are present in the thin sections; however, traces of pebbles were noted in the jars containing SV26 and SV28, and minor amounts of pebbles in the SV40 sample jar. The individual grain shapes in each sample range from rounded to angular. Subrounded and subangular grains are predominant. Angular grains are mostly concentrated in the finer grain size fractions. Samples SV29 and SV40 seem to contain greater amounts of rounded grains than the other two samples. Grain compaction and natural pore systems could not be assessed, because these sands are unconsolidated and disaggregated in the thin sections. The uneven distribution of silt, clays, and heavy minerals in SV26, SV28, and SV40 could be wholly the result of sample preparation, or it may indicate the presence of some disrupted lamination.

The soil composition was measured two different ways. XRD analysis (Table 1) shows that three of the samples (SV 26, SV28, and SV40) contain 96 to 99 percent quartz, with small amounts of feldspars and clays. Sample SV29 contains only 83 percent quartz by XRD, with 11 percent clays and 5 percent feldspars. Point-count analysis (Table 2) shows similar proportions of quartz, feldspars, and clays, compared to Table 1. Most of the quartz occurs as individual mono- and poly-crystalline grains. The minor metamorphic rock fragments (0.4 – 2.4%) are mostly metaquartzites. Traces of quartz overgrowth cement are found on some grains (Plate 1B). Some of these overgrowths probably formed in-situ, but others may be relics from a recycled sandstone source. Small amounts of heavy minerals (magnetite/ilmenite, tourmaline, zircon, hornblende, etc.) and glauconite grains are also found in every sample. The muddy sand (SV29, Plate 3) contains common clay matrix. Samples SV28 and SV40 contain minor amounts of clay matrix, 2 percent and 3 percent by XRD, respectively. The thin

500120

sections also reveal a little more clay in SV40 than SV28, although this is not reflected in the point-count results because of the highly uneven distribution of clays in SV40. The clay minerals are mostly detrital, but they appear to be partially altered and recrystallized. XRD results reveal that the clay fractions consist of 60 to 78 percent kaolinite and 22 to 40 percent illite/mica (includes sericite). Tiny crystals and coatings of iron oxide and titanium oxide represent 1.2 to 4.0 percent of the thin sections by point-count. Traces of organic grain coatings are present in one sample (SV29). Rare amounts of dolomite occur within a few quartz grains (SV26 and SV28). XRD detected possible traces of lead phosphate in SV28 and SV40.

Conclusions

The main purpose of this study was to document the presence or absence of any mineral matrices that may contain lead compounds that could be interpreted to be contaminants from the seeping of lead-bearing fluids into the soil. As a secondary purpose, any lead-bearing substances detected were to be identified.

Some of the quartz and feldspar grains show signs of leaching (pitted grains; Plates 1A & 4A), but this can be present in natural soils and does not necessarily indicate damage from contaminating fluids. The thin sections reveal no mineral grains or crusts that are composed principally of lead compounds. Using polarized and reflected light microscopy, the minor amounts of dark coatings on grains and tiny crystals in the clay matrix (Plates 1-4B) are identified as mostly iron and titanium oxides. Many of these crystals are so small (<1-3 microns) that they cannot be adequately identified in thin section. If any lead compounds or elemental lead are present, they should be associated with these tiny crystals and the oxide coatings. Clay aggregates of kaolinite and illite/mica may be able to adsorb lead onto the clay crystal surfaces; however, these clay types are not noted for absorption of elements into their crystal structures.

The traces of lead phosphate reported by XRD in SV28 and SV40 are based on one peak in the diffraction pattern matching the primary peak for lead phosphate. In XRD analysis, separate mineral phases are recognized by distinct diffraction patterns containing a primary peak and secondary peaks for each mineral. The secondary peaks of some minerals can overlap primary peaks of other minerals. Also, relative peak heights are related to mineral concentration, and the secondary peaks for minerals present in small quantities are not generally detectable. Even the primary peaks for trace minerals are sometimes difficult to resolve from background noise. The peak identified to be a primary peak for lead phosphate does not seem to correspond to a secondary peak of any other component in the sample (if it did, the interpretation of lead phosphate would not be justified). Thus, the presence of small amounts of lead phosphate is a possibility, even though a distinct diffraction pattern for this compound is lacking (no secondary peaks). If lead phosphate is indeed present, one would expect it to be most prevalent in SV29, where clay matrix and iron and titanium oxide coatings are most common, but XRD does not show traces of lead phosphate for this sample.

This thin section and XRD study shows that mineral matrices that may contain lead-bearing substances are present. However, lead compounds, if present, are rare in these soil samples. These analyses are not sufficiently sensitive to completely affirm or deny the presence of rare amounts of lead in these samples.

ANALYTICAL PROCEDURES

Thin Section Preparation

Sample fractions are prepared for thin section analysis by first impregnating them with epoxy to augment sample cohesion and to prevent loss of materials during grinding. A blue dye was added to the epoxy to highlight the pore spaces. Each sample was mounted on a frosted glass slide and then cut and ground in water to an approximate thickness of 30 microns. The thin sections were examined using standard petrographic techniques.

X-ray Diffraction Analysis

X-ray diffraction analysis provides the identification and quantification of the rock-forming minerals present in the formation. Samples selected for bulk and clay X-ray diffraction analysis were dried and cleaned of obvious contaminants. Each sample was dried, weighed, placed in water and treated with a sonic cell disrupter. The resultant slurries were centrifuged to fractionate each fraction at 4 microns. The suspended <4 micron fraction was decanted and saved. The >4 micron fraction was dried and weighed to determine the percent of clay- and silt-sized materials. The suspended <4 micron fraction was suctioned onto a pure silver substrate to orient the clay-sized particles. The <4 micron fraction was analyzed in an air-dried state and then treated with ethylene glycol vapor for 24 hours and re-analyzed. The >4 micron fraction was milled and scanned on an X-ray diffractometer. The samples selected for bulk analysis only were also milled and scanned on the diffractometer. The resulting diffractograms were then analyzed for mineral content using a profile-fitting algorithm. The integrated areas from the profile-fitting algorithm were entered into a spreadsheet that contains correction coefficients for numerous minerals. These coefficients were obtained according to the adiabatic method outlined by Chung (1974a, 1974b, 1974c). The tabular data are reported in a weight percent format in Table 1.

REFERENCES

Chung, F.H. (1974) A new X-ray diffraction method for quantitative multicomponent analysis. Advances in X-ray Analysis, 17, 106-115.

Chung, F.H. (1974) Quantitative interpretation of X-ray diffraction patterns of mixtures. I. Matrix-flushing method for quantitative multicomponent analysis. Journal of Applied Crystallography, 7, 519-525.

Chung, F.H. (1974) Quantitative interpretation of X-ray diffraction patterns of mixtures. II. Adiabatic principle of X-ray diffraction analysis of mixtures. Journal of Applied Crystallography, 7, 526-531.

Folk, R.L. (1980) Petrology of Sedimentary Rocks. Hemphill Publishing Company, Austin, Texas, 184p.

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		Whole Rock Composition (weight %)										Relative Clay Abundance (Normalized to 100%)				
Sample ID	Depth	Quartz	K feldspar	Plagioclase	Calcite	Dolomite	Siderite	Pyrite	Pb phosphate	Hematite	*Total Clays*	Illite/Mica	Kaolinite	Chlorite	Smectite	Illite/ Smectite
SV26 7/20/98	14-16	99	0	Tr	0	Tr	0	0	0	0	*1*	31	69	0	0	0
SV28 7/16/98	12-16	96	1	1	0	Tr	0	0	Tr	0	*2*	40	60	0	0	0
SV29 7/15/98	10-16	83	3	2	0	1	0	0	0	Tr	*11*	22	78	0	0	0
SV-40	N/A	96	0	Tr	0	1	0	0	Tr	0	*3*	36	64	0	0	0

CORE LABORATORIES

Point-Count Tally Sheet

GeoSyntec Consultants
Sand Soil Samples
NL Industries Project

C.L. File No: 198178
Date: 27-Oct-98
Petrologist: D. Dickert

Table 2
Modal Percent

Sample ID		SV26	SV28	SV29	SV40
Quartz:	Monocrystalline	74.0	80.8	61.6	76.0
	Polycrystalline	17.6	10.8	7.2	17.2
	Total	**91.6**	**91.6**	**68.8**	**93.2**
Feldspars:	K-Feldspar	0.4	0.8	2.4	1.2
	Plagioclase	tr	tr	1.6	tr
	Total	**0.4**	**0.8**	**4.0**	**1.2**
Rock Fragments:	Crystalline Igneous		tr	0.8	tr
	Sedimentary	0.4	tr	4.0	0.4
	Metamorphic	1.2	0.8	2.4	0.4
	Chert/Chalcedony	tr	1.2	0.4	0.4
	Total	**1.6**	**2.0**	**7.6**	**1.2**
Accessory:	Biotite	tr		tr	tr
	Muscovite	tr	tr	1.6	tr
	Magnetite/Ilmenite	1.2	tr	0.4	0.4
	Tourmaline	0.4	tr	0.4	tr
	Zircon	tr	0.4	tr	tr
	Hornblende	tr	tr	0.4	tr
	Sphene	0.4		tr	
	Other Heavy Minerals	tr	tr	0.4	tr
	Glauconite	0.8	tr	0.4	tr
	Organic Debris	tr			
	Total	**2.8**	**0.4**	**3.6**	**0.4**
Matrix:	Detrital Clay	0.4	2.8	10.8	2.4
	Pseudomatrix				
	Total	**0.4**	**2.8**	**10.8**	**2.4**
Clays: (Authigenic)	Kaolinite	tr	tr		tr
	Chlorite		tr	tr	tr
	Sericite	tr	tr	tr	tr
	Undiff. Illite/Smectite	0.8	0.4	tr	0.4
	Total	**0.8**	**0.4**		**0.4**
Non-Clay Cements:	Quartz Overgrowths	0.8	0.4	0.8	tr
	Feldspar Overgrowths				
	Dolomite	tr	tr		
	Pyrite				
	Iron Oxide	0.8	0.4	2.4	tr
	Titanium Oxide	0.8	1.2	1.6	1.2
	Organic Coatings			0.4	
	Total	**2.4**	**2.0**	**5.2**	**1.2**
Porosity:	Not counted - disaggregated samples				
	Total				
Grand Total		**100.0**	**100.0**	**100.0**	**100.0**

THIN SECTION PETROGRAPHY

Plate 1A

31X

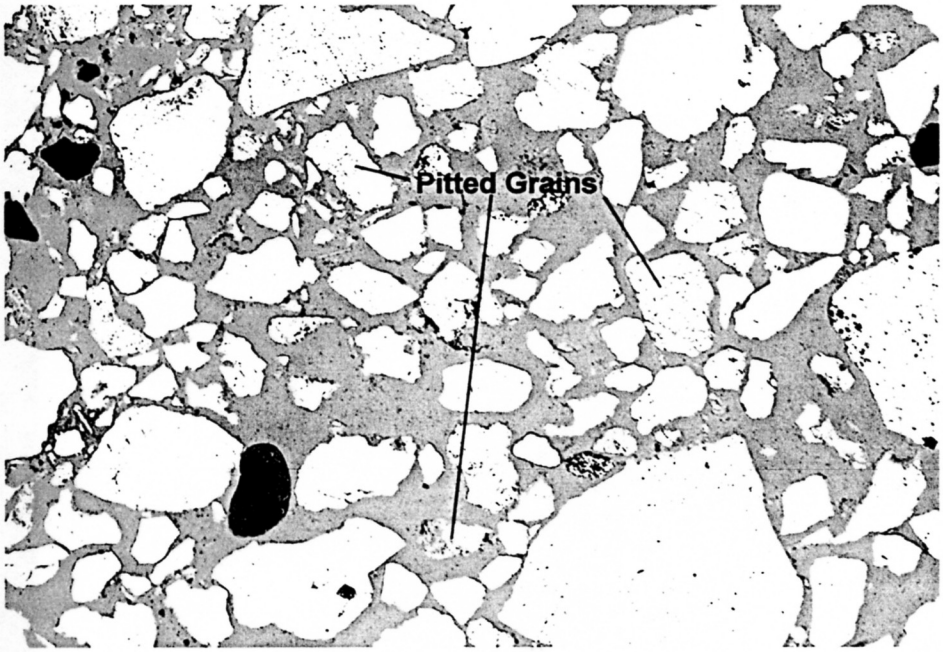
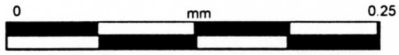
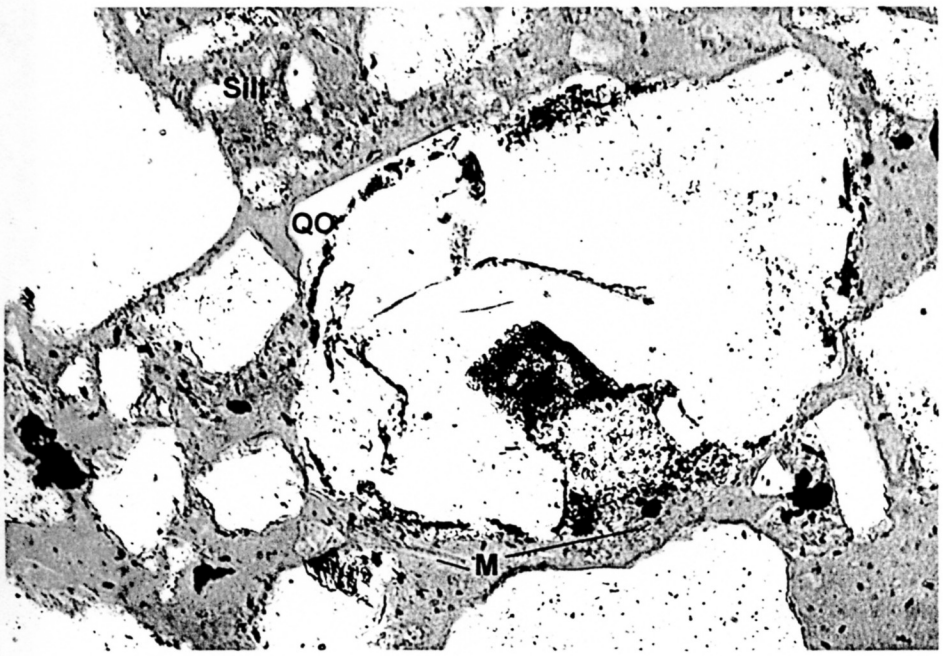


Plate 1B



200X



GeoSyntec Consultants
Soil Samples
NL Industries Project
Sample: SV26072098
Depth: 14 - 16 feet

Soil Type & Texture	
Classification (Folk)	Silty sand
Grain Size (mm)	Range = <0.01 - 2.54
(estimated)	Avg. = 0.40 (med. sand)
Grain Sorting	Poor
Grain Roundness	Rounded to angular
Compaction	Disaggregated
Structures	None evident

Composition (%)			
Detrital Grains		**Detrital Matrix**	
Mono. Qtz.	74.0	Clay	0.4
Poly. Qtz.	17.6	**Authigenic Clay**	
K-feldspar	0.4	Kaolinite	tr
Plagioclase	tr	Chlorite	
Igneous R.F.		Sericite	tr
Sedim. R.F.	0.4	Undiff. I/S	0.8
Meta. R.F.	1.2	**Cements (non-clay)**	
Chert	tr	Quartz O.G.	0.8
Biotite	tr	Feld. O.G.	
Muscovite	tr	Dolomite	tr
Heavy Min.	2.0	Pyrite	
Glauconite	0.8	Iron Oxide	0.8
Organics	tr	TiO_2	0.8
		Organic	

Photomicrograph Captions

Plate 1A: This soil sample consists of poorly sorted, silty sand. The white grains are nearly all quartz, but with small amounts of feldspar (mostly K-feldspar). Black grains in the upper-left and upper-right corners of the photo are magnetite/ilmenite. The well rounded, green grain in the lower-left quadrant is glauconite. Some quartz is slightly dissolved (pitted grains), as evidenced by traces of blue epoxy within the grains.

Plate 1B: A high-magnification view of the sample reveals dark-colored coatings on some grains and dark specks between grains. These dark brown to black materials are mostly iron oxide (hematite) and titanium oxide. No lead compounds are identified; however, traces of lead compounds may be associated with these dark crusts and specks. A quartz overgrowth (QO) is observed on top of a hematite grain coating. Tiny white grains between the larger grains are mainly quartz silt, along with small amounts of muscovite/sericite flakes (M).

CORELAB

THIN SECTION PETROGRAPHY

Plate 2A

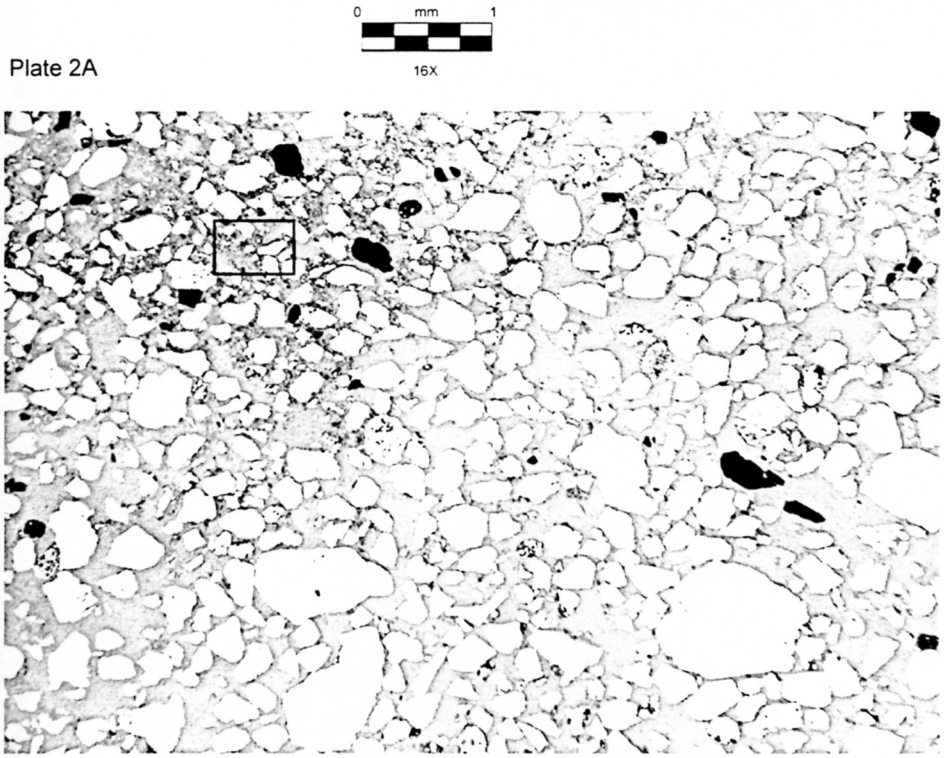
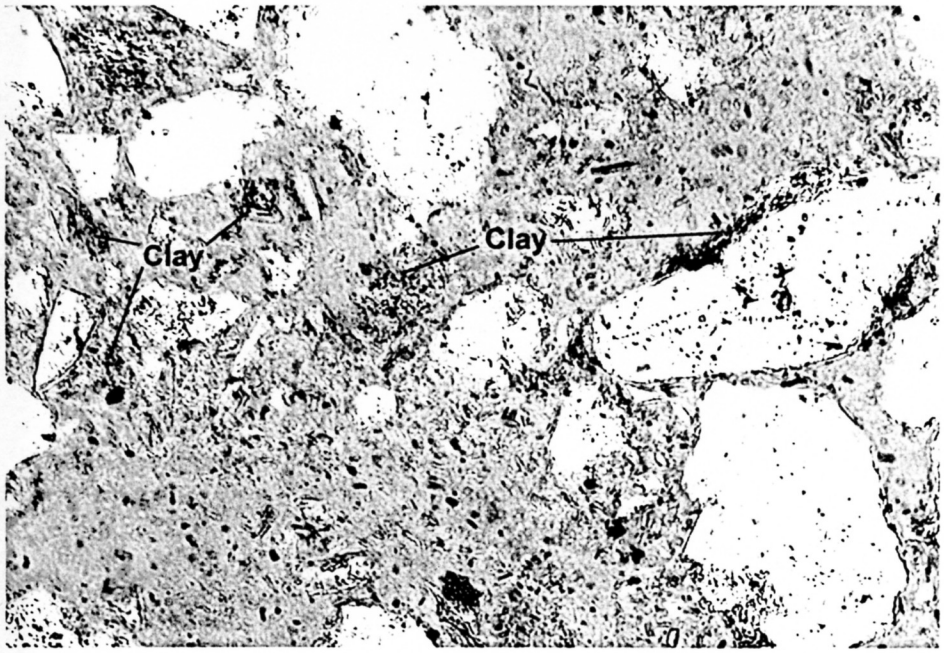


Plate 2B



GeoSyntec Consultants
Soil Samples
NL Industries Project
Sample: SV28071698
Depth: 12 - 16 feet

Soil Type & Texture

Classification (Folk)	Silty sand
Grain Size (mm)	Range = <0.01 - 2.18
(estimated)	Avg. = 0.38 (med. sand)
Grain Sorting	Poor
Grain Roundness	Rounded to angular
Compaction	Disaggregated
Structures	None evident

Composition (%)

Detrital Grains		**Detrital Matrix**	
Mono. Qtz.	80.8	Clay	2.8
Poly. Qtz.	10.8	**Authigenic Clay**	
K-feldspar	0.8	Kaolinite	tr
Plagioclase	tr	Chlorite	tr
Igneous R.F.	tr	Sericite	tr
Sedim. R.F.	tr	Undiff. I/S	0.4
Meta. R.F.	0.8	**Cements (non-clay)**	
Chert	1.2	Quartz O.G.	0.4
Biotite		Feld. O.G.	
Muscovite	tr	Dolomite	tr
Heavy Min.	0.4	Pyrite	
Glauconite	tr	Iron Oxide	0.4
Organics		TiO_2	1.2
		Organic	

Photomicrograph Captions

Plate 2A: This sample is very similar to the previous sample (Plate 1). A lower magnification is provided here, compared to Plate 1A, so that the silty texture of the sand is better observed (upper-left quadrant). Scattered dark grains are heavy minerals. The blackest grains are magnetite/ilmenite.

Plate 2B: The area within the black rectangle in Plate 2A is presented in this photomicrograph. The main difference between this sample and SV26072098 is that this sample contains greater (although minor) amounts of clay matrix (yellowish green). This intergranular to grain-coating clay contains many tiny specks of titanium and iron oxides (black). Some of this micron-sized material may include lead compounds, but this cannot be established with thin section analysis. XRD analysis reveals that the clays in this sample are kaolinite and illite/mica.

THIN SECTION PETROGRAPHY

Plate 3A

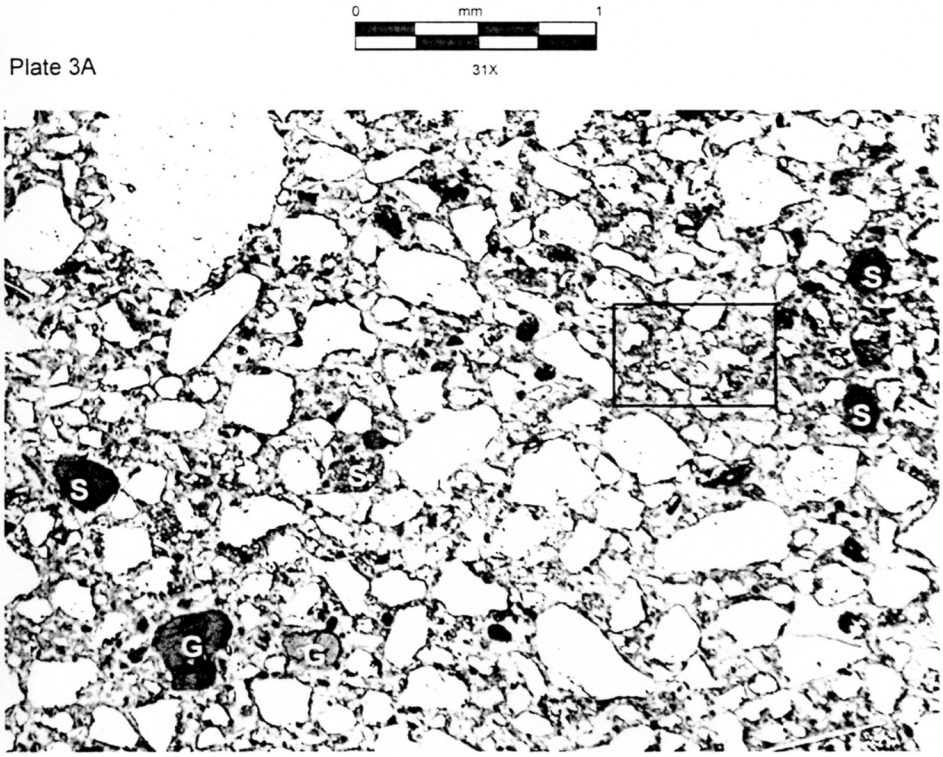
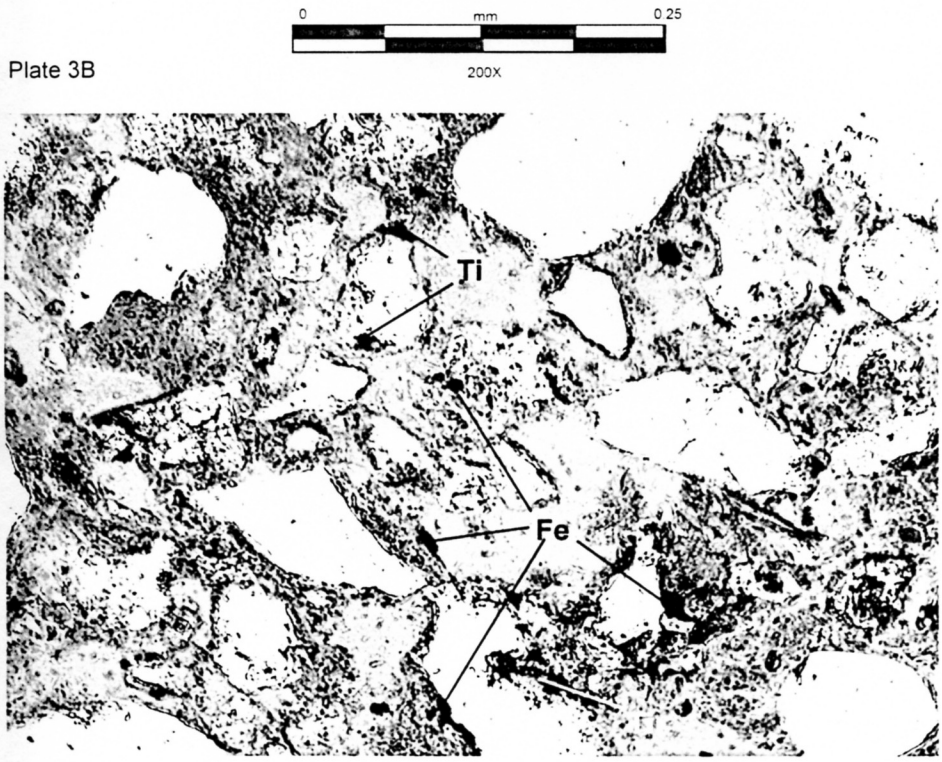


Plate 3B



GeoSyntec Consultants
Soil Samples
NL Industries Project
Sample: SV29071598
Depth: 10 - 16 feet

Soil Type & Texture	
Classification (Folk)	Muddy sand
Grain Size (mm)	Range = <0.01 - 2.02
(estimated)	Avg. = 0.28 (med. sand)
Grain Sorting	Poor
Grain Roundness	Rounded to angular
Compaction	Disaggregated
Structures	None evident

Composition (%)			
Detrital Grains		**Detrital Matrix**	
Mono. Qtz.	61.6	Clay	10.8
Poly. Qtz.	7.2	**Authigenic Clay**	
K-feldspar	2.4	Kaolinite	
Plagioclase	1.6	Chlorite	tr
Igneous R.F.	0.8	Sericite	tr
Sedim. R.F.	4.0	Undiff. I/S	tr
Meta. R.F.	2.4	**Cements (non-clay)**	
Chert	0.4	Quartz O.G.	0.8
Biotite	tr	Feld. O.G.	
Muscovite	1.6	Dolomite	
Heavy Min.	1.6	Pyrite	
Glauconite	0.4	Iron Oxide	2.4
Organics		TiO_2	1.6
		Organic	0.4

Photomicrograph Captions

Plate 3A: This is a poorly sorted, muddy sand sample. It is classified as muddy because of the common amounts of silt and clay occurring between the predominant sand grains. The white grains are mostly quartz, with minor amounts of K-feldspar and plagioclase. Various sedimentary argillaceous rock fragments (S) appear dark. Glauconite (G) grains are also noted. The one on the left appears orange due to oxidation.

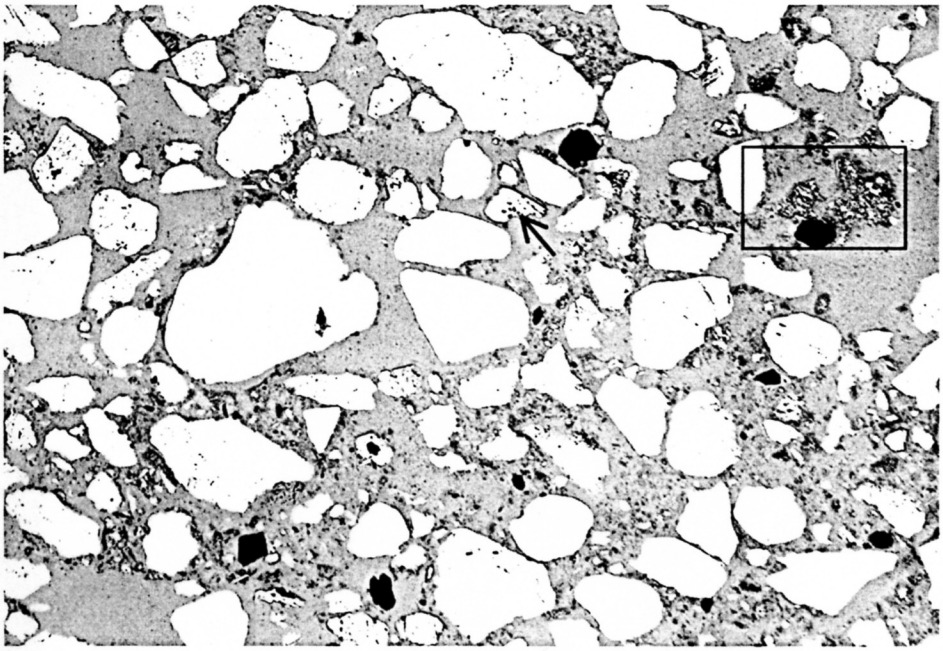
Plate 3B: The area within the black rectangle in Plate 3A is shown. This sample contains common amounts of clay matrix (greenish brown). This clay coats grains and fills pores. It consists of 78% kaolinite and 22% illite/mica, according to XRD analysis. Within the clay are dark-colored coatings and crystalline specks that are predominantly iron (Fe) and titanium (Ti) oxides. Micron-sized particles of lead compounds may possibly also be present within the clays and oxide coatings.

THIN SECTION PETROGRAPHY

0 mm 1

31X

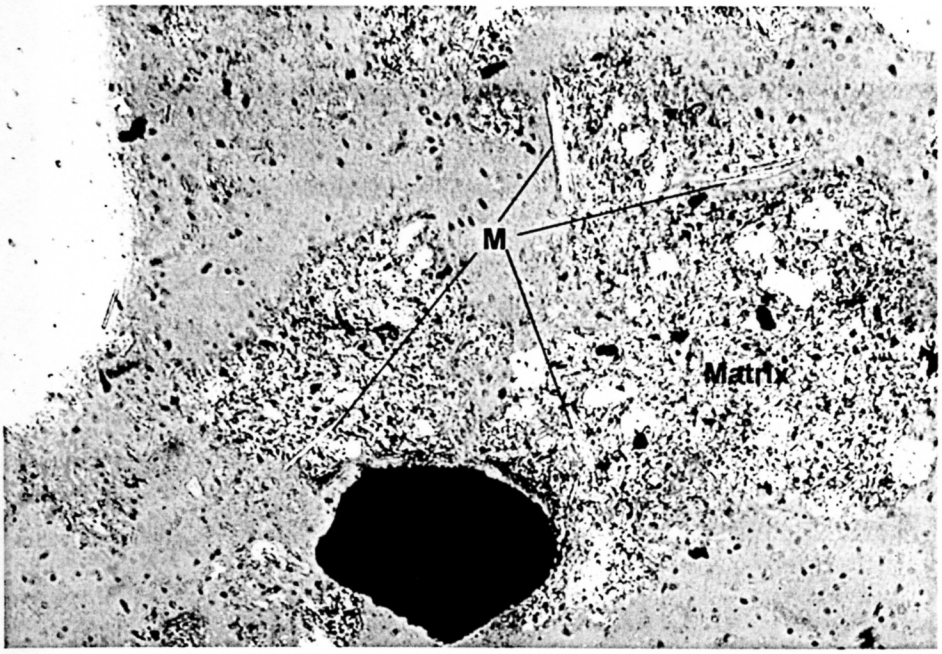
Plate 4A



0 mm 0.25

200X

Plate 4B



GeoSyntec Consultants
Soil Samples
NL Industries Project
Sample: SV40
Depth: N.A.

Soil Type & Texture	
Classification (Folk)	Silty sand
Grain Size (mm)	Range = <0.01 - 2.05
(estimated)	Avg. = 0.36 (med. sand)
Grain Sorting	Poor
Grain Roundness	Rounded to angular
Compaction	Disaggregated
Structures	None evident

Composition (%)			
Detrital Grains		**Detrital Matrix**	
Mono. Qtz.	76.0	Clay	2.4
Poly. Qtz.	17.2	**Authigenic Clay**	
K-feldspar	1.2	Kaolinite	tr
Plagioclase	tr	Chlorite	tr
Igneous R.F.	tr	Sericite	tr
Sedim. R.F.	0.4	Undiff. I/S	0.4
Meta. R.F.	0.4	**Cements (non-clay)**	
Chert	0.4	Quartz O.G.	tr
Biotite	tr	Feld. O.G.	
Muscovite	tr	Dolomite	
Heavy Min.	0.4	Pyrite	
Glauconite	tr	Iron Oxide	tr
Organics		TiO_2	1.2
		Organic	

Photomicrograph Captions

Plate 4A: Patches of silty clay matrix (light brown) are irregularly distributed in the thin section. This view shows an area where the matrix is relatively common. A slightly dissolved (pitted) feldspar grain is noted by the arrow. Black sand grains are ilmenite/magnetite.

Plate 4B: The portion of Plate 4A within the black rectangle is displayed. The black grain is probably magnetite that has an oxidized rim. The oxidation has stained the adjacent clay matrix brown. Most of the view features a patch of matrix consisting of detrital silt and clay. A few muscovite (M) flakes are part of the silt fraction. The numerous black specks in the matrix are titanium oxide, with traces of iron oxide and possibly other materials. If any lead compounds are present, they would be most likely to occur as very tiny crystals within this matrix. XRD analysis indicates the clay fraction of the matrix is kaolinite and illite/mica.

CORELAB

APPENDIX C

Toxscan, Inc. Laboratory Report (October 1998)

RECEIVED OCT 1 3 1998

ToxScan, Inc. 42 Hangar Way • Watsonville, CA 95076-2404 • (408) 724-4522 • FAX (408) 724-3188

October 08, 1998

ToxScan Number: T-16324

GeoSyntec Consultants
10015 Old Columbia Road, Suite A-200
Columbia, MD 21046

Attn: Jeffrey Moore

Project Name:	NL
Project Number:	ME0015-13
Date Sampled:	July 15, 1998 - September 23, 1998
Date Received:	August 14, 1998 - September 23, 1998
Matrix:	Soil Soil Extract

Please find the enclosed test results for the parameters requested for analyses. The samples were analyzed within holding time using the following methods:

Carbonate Cadmium by ICP/MS by EPA Method 200.8
Carbonate Lead by ICP/MS by EPA Method 200.8
Carbonate Lead by ICP/MS by EPA Method 200.8
Cation-Exchange Capacity by EPA Method 9081, conducted by Soil Control Lab
Extractable Cadmium by ICP/MS by EPA Method 200.8
Extractable Lead by ICP/MS by EPA Method 200.8
Extractable Lead by ICP/MS by EPA Method 200.8
Iron/Manganese Oxide/Hydroxide Cadmium by ICP/MS by EPA Method 200.8
Iron/Manganese Oxide/Hydroxide Lead by ICP/MS by EPA Method 200.8
Iron/Manganese Oxide/Hydroxide Lead by ICP/MS by EPA Method 200.8
Organic Cadmium by ICP/MS by EPA Method 200.8
Organic Lead by ICP/MS by EPA Method 200.8
Organic Lead by ICP/MS by EPA Method 200.8
[1] Particle Size Distribution by Plumb
Percent Solids by EPA Method 160.3
pH by EPA Method 9045B
Residual Cadmium by ICP/MS by EPA Method 200.8
Residual Lead by ICP/MS by EPA Method 200.8
Residual Lead by ICP/MS by EPA Method 200.8
Total Metals by ICP/MS (Cd,Pb) by EPA Method 6020

This cover letter is an integral part of the report.

[1] Russell H. Plumb, Jr.; Procedures for Handling and Chemical Analysis of Sediment and Water Samples, Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station; 1981.

ToxScan, Inc. 42 Hangar Way • Watsonville, CA 95076-2404 • (408) 724-4522 • FAX (408) 724-3188

October 08, 1998

ToxScan Number: T-16324

GeoSyntec Consultants
10015 Old Columbia Road, Suite A-200
Columbia, MD 21046

Attn: Jeffrey Moore

The samples were received intact and were handled with the proper chain-of-custody procedures. Appropriate QA/QC guidelines were employed during the analyses on a minimum of a 5% basis. QC results were within limits and are reported with or following the data for each analysis.

If you have any questions or require any additional information, please feel free to call.

Sincerely,

Philip D. Carpenter

Philip D. Carpenter, Ph.D.
President

Enclosures

This cover letter is an integral part of the report.

[1] Russell H. Plumb, Jr.; Procedures for Handling and Chemical Analysis of Sediment and Water Samples, Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station; 1981.

Client: GeoSyntec Consultants
Method: EPA Method(s) 200.8
Date Completed: 9/29/98
Matrix: Soil Extract
Units: mg/Kg

ToxScan Number: T-16324

Carbonate Metals

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910-12071598	16324-09	Cadmium	ND	0.1
		Lead	ND	0.1
SV2812-16071698	16324-10	Cadmium	ND	0.1
		Lead	0.17	0.1
SV071698-Dup	16324-11	Cadmium	ND	0.1
		Lead	0.14	0.1
SV26072098	16324-12	Cadmium	ND	0.1
		Lead	ND	0.1

ANALYTICAL CHEMISTS
and
BACTERIOLOGISTS
Approved by State of California

SOIL CONTROL LAB

42 HANGAR WAY
WATSONVILLE
CALIFORNIA
95076
USA

A Division of Control Laboratories Inc.

Tel: 831 724-5422
FAX: 831 724-3188

In any reference, please quote Certified Analysis Number appearing hereon.

130152-4-3344

ToxScan Inc.
42 Hangar Way
Watsonville, CA 95076

05 OCT 98

CERTIFIED ANALYTICAL REPORT

MATERIAL: Soil samples received 27 August 1998
IDENTIFICATION: T-16324, Quanterra
ID NUMBERS: 1/4-4/4-130152

Sample ID:	Cation Exchange Capacity (C.E.C.)
SV2910-12071598	3.57 meq/100 g dw
Dup	1.70 meq/100 g dw
SV2812-16071698	1.13 meq/100 g dw
Dup	0.89 meq/100 g dw
SV071698-Dup	0.91 meq/100 g dw
Dup	0.91 meq/100 g dw
SV26072098	2.72 meq/100 g dw
Dup	1.83 meq/100 g dw

The undersigned certifies that the above is a true and accurate report of the findings of this Laboratory.

Analyst

500133

Client: GeoSyntec Consultants
Method: EPA Method(s) 200.8
Date Completed: 9/29/98
Matrix: Soil Extract
Units: mg/Kg

ToxScan Number: T-16324

Extractable Metals

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910-12071598	16324-09	Cadmium	ND	0.1
		Lead	ND	0.1
SV2812-16071698	16324-10	Cadmium	ND	0.1
		Lead	ND	0.1
SV071698-Dup	16324-11	Cadmium	ND	0.1
		Lead	ND	0.1
SV26072098	16324-12	Cadmium	ND	0.1
		Lead	ND	0.1

Client: GeoSyntec Consultants
Method: EPA Method(s) 200.8
Date Completed: 9/29/98
Matrix: Soil Extract
Units: mg/Kg

ToxScan Number: T-16324

Iron/Manganese

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910-12071598	16324-09	Cadmium	ND	0.1
		Iron	120	0.1
		Lead	0.36	0.1
		Manganese	33	0.1
SV2812-16071698	16324-10	Cadmium	ND	0.1
		Iron	26	0.1
		Lead	ND	0.1
		Manganese	ND	0.1
SV071698-Dup	16324-11	Cadmium	ND	0.1
		Iron	28	0.1
		Lead	ND	0.1
		Manganese	ND	0.1
SV26072098	16324-12	Cadmium	ND	0.1
		Iron	34	0.1
		Lead	0.14	0.1
		Manganese	ND	0.1

Client: GeoSyntec Consultants
Method: EPA Method(s) 200.8
Date Completed: 9/29/98
Matrix: Soil Extract
Units: mg/Kg

ToxScan Number: T-16324

Bound Organic Metals

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910-12071598	16324-09	Cadmium	ND	0.1
		Lead	ND	0.1
SV2812-16071698	16324-10	Cadmium	ND	0.1
		Lead	ND	0.1
SV071698-Dup	16324-11	Cadmium	ND	0.1
		Lead	ND	0.1
SV26072098	16324-12	Cadmium	ND	0.1
		Lead	ND	0.1

Client:	GeoSyntec Consultants	ToxScan Number: 16324
Method:	Plumb	
Date Analyzed:	August 3 - September 8, 1998	
Matrix:	Sediment	

Client Sample ID: SV2910-12071598
Client Site ID:
ToxScan Lab ID: T-16324-05A

SIZE INTERVAL Phi	mm	INTERVAL WT (gm)	INTERVAL (%)	CUMULATIVE (%)
<-5	>32	0.00	0.0	0.0
-4	32-16	0.00	0.0	0.0
-3	16- 8	0.00	0.0	0.0
-2	8- 4	0.13	0.3	0.3
-1	4- 2	0.08	0.2	0.5
0	2- 1	0.16	0.4	0.9
1	1-0.5	2.26	5.3	6.2
2	0.5-0.25	12.57	29.4	35.6
3	0.25-0.125	16.85	39.5	75.1
4	0.125-0.062	8.01	18.8	93.9
5	0.062-0.031	1.23	2.9	96.7
6	0.031-0.016	0.41	1.0	97.7
7	0.016-0.008	0.29	0.7	98.4
8	0.008-0.004	0.16	0.4	98.7
9	0.004-0.002	0.08	0.2	98.9
>9	< 0.002	0.45	1.1	100

total wt	coarse wt	fine wt
42.7	40.1	2.6

% sand	% silt	% clay
93.9	4.9	1.3

GeoSyntec Consultants
Plumb
August 3 - September 8, 1998
Sediment

ToxScan Number: 16324

SV2812-16071698

T-16324-06A

INTERVAL WT (gm)	INTERVAL (%)	CUMULATIVE (%)
0.00	0.0	0.0
0.00	0.0	0.0
0.00	0.0	0.0
1.33	3.2	3.2
0.85	2.1	5.3
1.43	3.5	8.7
6.81	16.5	25.3
19.83	48.1	73.3
8.76	21.2	94.5
0.86	2.1	96.6
0.25	0.6	97.2
0.19	0.5	97.7
0.21	0.5	98.2
0.12	0.3	98.5
0.09	0.2	98.7
0.54	1.3	100

total wt	coarse wt	fine wt
41.3	39.9	1.4

% sand	% silt	% clay
96.6	1.8	1.5

c. 42 Hangar Way • Watsonville, CA 95076-2404 • (408) 724-4522 • FAX (408) 724-3188

Client:	GeoSyntec Consultants	ToxScan Number: 16324
Method:	Plumb	
Date Analyzed:	August 3 - September 8, 1998	
Matrix:	Sediment	

Client Sample ID: SV071698-Dup
Client Site ID:
ToxScan Lab ID: T-16324-07A

SIZE INTERVAL

Phi	mm	INTERVAL WT (gm)	INTERVAL (%)	CUMULATIVE (%)
<-5	>32	0.00	0.0	0.0
-4	32-16	0.00	0.0	0.0
-3	16- 8	0.00	0.0	0.0
-2	8- 4	3.01	7.0	7.0
-1	4- 2	1.30	3.0	10.0
0	2- 1	2.20	5.1	15.2
1	1-0.5	7.09	16.5	31.7
2	0.5-0.25	19.35	45.1	76.8
3	0.25-0.125	7.91	18.4	95.2
4	0.125-0.062	0.76	1.8	97.0
5	0.062-0.031	0.20	0.5	97.5
6	0.031-0.016	0.21	0.5	98.0
7	0.016-0.008	0.16	0.4	98.3
8	0.008-0.004	0.13	0.3	98.6
9	0.004-0.002	0.06	0.1	98.8
>9	< 0.002	0.53	1.2	100

total wt	coarse wt	fine wt
42.9	41.6	1.3

% sand	% silt	% clay
97.0	1.6	1.4

Client:	GeoSyntec Consultants	ToxScan Number: 16324
Method:	Plumb	
Date Analyzed:	August 3 - September 8, 1998	
Matrix:	Sediment	

Client Sample ID: SV26072098
Client Site ID:
ToxScan Lab ID: T-16324-08A

SIZE INTERVAL

Phi	mm	INTERVAL WT (gm)	INTERVAL (%)	CUMULATIVE (%)
<-5	>32	0.00	0.0	0.0
-4	32-16	0.00	0.0	0.0
-3	16- 8	0.00	0.0	0.0
-2	8- 4	8.39	18.9	18.9
-1	4- 2	0.22	0.5	19.4
0	2- 1	0.31	0.7	20.1
1	1-0.5	2.23	5.0	25.1
2	0.5-0.25	10.95	24.6	49.7
3	0.25-0.125	13.97	31.4	81.1
4	0.125-0.062	5.39	12.1	93.2
5	0.062-0.031	0.76	1.7	94.9
6	0.031-0.016	0.46	1.0	95.9
7	0.016-0.008	0.33	0.8	96.7
8	0.008-0.004	0.31	0.7	97.4
9	0.004-0.002	0.14	0.3	97.7
>9	< 0.002	1.02	2.3	100

total wt	coarse wt	fine wt
44.5	41.5	3.0

% sand	% silt	% clay
93.2	4.2	2.6

Client: GeoSyntec Consultants
Method: EPA Method(s) 160.3
Date Completed: 8/26/98
Matrix: Soil
Units: Percent

ToxScan Number: T-16324

Client Sample ID	ToxScan Lab ID	Analyte	Wet Wt. Sample Value	Wet Reporting Limit
SV2910 - 12071598	16324-05	Percent Solids	83	0.10
SV2812 - 16071698	16324-06	Percent Solids	82	0.10
SV071698 - Dup	16324-07	Percent Solids	84	0.10
SV26072098	16324-08	Percent Solids	80	0.10

Client: GeoSyntec Consultants
Method: EPA Method(s) 9045B
Date Completed: 9/3/98
Matrix: Soil
Units: units

ToxScan Number: T-16324

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910 - 12071598	16324-05	pH	7.3	0.10
SV2812 - 16071698	16324-06	pH	6.6	0.10
SV071698 - Dup	16324-07	pH	6.0	0.10
SV26072098	16324-08	pH	6.2	0.10

Client: GeoSyntec Consultants
Method: EPA Method(s) 200.8
Date Completed: 9/29/98
Matrix: Soil Extract
Units: mg/Kg

ToxScan Number: T-16324

Residual Metals

Client Sample ID	ToxScan Lab ID	Analyte	Sample Value	Reporting Limit
SV2910-12071598	16324-09	Cadmium	ND	0.1
		Lead	2.2	0.1
SV2812-16071698	16324-10	Cadmium	ND	0.1
		Lead	0.96	0.1
SV071698-Dup	16324-11	Cadmium	ND	0.1
		Lead	0.87	0.1
SV26072098	16324-12	Cadmium	ND	0.1
		Lead	1.6	0.1

Client: GeoSyntec Consultants
Method: EPA Method(s) 6020
Date Completed: 9/10/98
Matrix: Soil
Units: mg/Kg

ToxScan Number: T-16324

Total Metals

Client Sample ID	ToxScan Lab ID	Analyte	Wet Wt. Sample Value	Wet Reporting Limit
SV2910 - 12071598	16324-05	Cadmium	ND	0.10
		Lead	2.8	0.10
SV2812 - 16071698	16324-06	Cadmium	ND	0.10
		Lead	1.9	0.10
SV071698 - Dup	16324-07	Cadmium	ND	0.10
		Lead	2.3	0.10
SV26072098	16324-08	Cadmium	ND	0.10
		Lead	4.1	0.10

EXPLANATION OF ACRONYMS FOR PROJECT # T-16324

The following is a glossary for acronyms that may be used in this report.

Abbreviation	Definition
LCS	Laboratory Control Sample
MS	Matrix Spike
MSD	Matrix Spike Duplicate
NA	Not Applicable
ND	None Detected
REP	Replicate
RPD	Relative Percent Difference
SRM	Standard Reference Material
TOC	Total Organic Carbon

QC FOR PROJECT # T-16324

LABORATORY METHOD BLANK SUMMARY

Applicable Matrix: Sediment

Total Metals

Analyte	Amount	Reporting Limit mg/L	EPA Method Number
Cadmium	ND	0.10	6020
Iron	ND	1.0	7380
Lead	ND	0.10	6020
Manganese	ND	0.10	6020

QC FOR PROJECT # T-16324

LABORATORY PRECISION SUMMARY:

Matrix: Soil

Analyte	REP 1	REP 2	Units	RPD
pH				
16324-08	6.20	6.19	units	0

QC FOR PROJECT # T-16324

Concentrations of the following are in mg/Kg

SRM SUMMARY:

Matrix: Sediment

Total Metals

Analyte	Amount Found	Dilution	Corrected Value	SRM	Certified Value	% Recovery
Cadmium	0.0136	20	0.272	MESS-2	0.240	114
Lead	0.955	20	19.1	MESS-2	21.9	87

QC FOR PROJECT # T-16324

Concentrations of the following are in ug/L

SRM SUMMARY:

Matrix: Water

Total Metals

Analyte	Amount Found	Dilution	Corrected Value	SRM	Certified Value	% Recovery
Cadmium	24.0	5	120	ERA 9977	120	100
Iron	676	1	676	ERA 9977	667	101
Lead	128	5	641	ERA 9977	660	97
Manganese	18.6	5	93.0	ERA 9977	100	93

ERA 9977 = Environmental Resource Associates, WasteWatR Lot No. 9977

APPENDIX D

Current and Historical Groundwater pH Isopleths and Water Quality Data for 2004, 2007 and 2010

TABLE D-1
Historical General Water Chemistry Data Summary
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

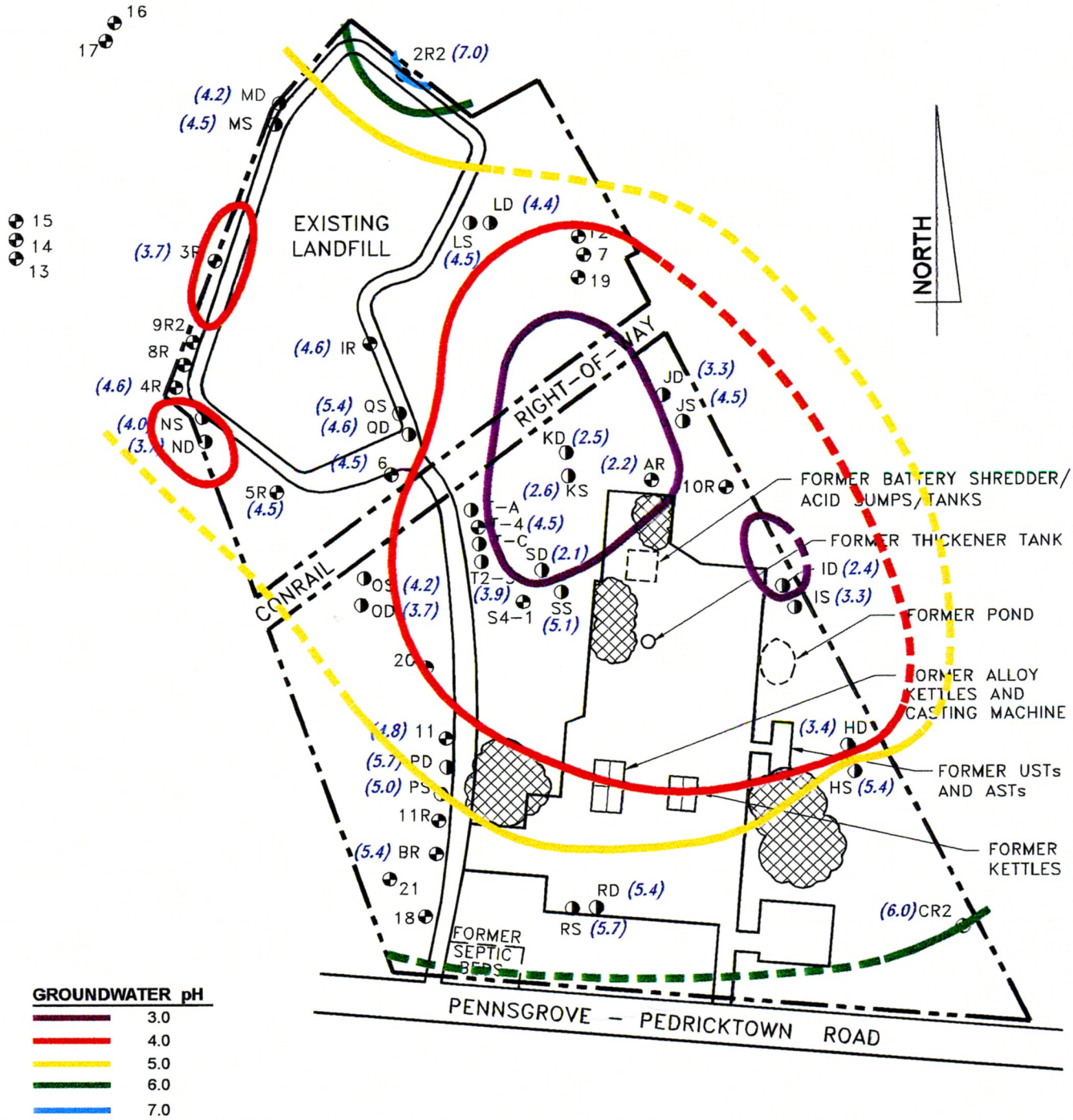
Monitoring Well	Oxidation-Reduction Potential (mv)				Turbidity (NTU)			Dissolved Oxygen (mg/L)		
	2004 *	2007	2010	Change (2004 - 2007)	2004 *	2007	2010	2004 *	2007	2010
BR	207	-302	95	-112	-10	8.5	1.8	10.04	0.00	0.00
JS	235	42	69	-166	8	40.8	14.1	8.08	1.65	0.00
JDR	253	385	95	-158	9	19.0	57.8	7.09	0.00	0.00
KSR	382	-54	330	-52	7	30.0	6.0	8	0.00	0.20
KDR	400	409	268	-132	0	20.3	0.0	8.88	0.00	0.00
NS	38	-80	151	113	9	46.8	0.3	10.34	1.99	0.91
ND	73	-45	34	-39	8	49.6	8.8	9.22	0.00	0.00
OS	53	-23	99	46	-10	18.0	4.7	9.83	0.00	0.00
SS	241	-126	-57	-298	6	11.7	64.8	7.81	0.00	0.00
SD	299	277	210	-89	7	2.1	116.0	5.73	0.00	0.00
11	258	274	129	-129	-10	5.3	4.6	9.62	0.00	0.00
12	89	-206	-22	-111	7	8.6	0.0	7.74	0.00	0.00
13	NM	46	-12	-58	NM	10.0	81.7	NM	0.00	0.00
14	NM	94	164	70	NM	11.6	200.0	NM	1.20	0.58
15	NM	259	172	-87	NM	19.0	5.7	NM	3.96	1.57
16	NM	-50	-47	3	NM	41.0	31.5	NM	0.00	0.00
17	NM	121	187	66	NM	33.5	0.0	NM	0.00	0.00
22	402	433	15.3	-386.7	3	4.7	0.5	6.46	0.00	0.00
23	427	140	452	25	1	3.0	2.1	6.61	0.00	0.00
24	125	19	18	-107	2	11.0	4.9	7.58	0.00	0.00
26	274	272	226	-48	1	12.5	5.2	6.35	0.00	0.00
27	266	-51	265	-1	1	14.0	16.7	6.62	4.36	0.51
28	299	298	170	-129	6	10.2	0.8	5.8	0.00	0.00
30R	161	190	194	33	28	9.6	0.0	7.65	0.00	0.00
31	97	103	182	85	1	28.0	120.0	10.34	1.00	3.09
32	60	-243	2	-58	1	33.0	11.7	9.52	0.00	0.00
33	116	104	173	57	9	11.5	0.0	7.92	0.00	0.00
34	42	-171	61	19	430	155.0	933.0	9.74	0.00	0.00

Notes:
* - 2004 data may be suspect due to freezing conditions.
Where 2004 data is unavailable, 2007 data was used to calculate difference in Oxidation-Reduction Potential and pH.

TABLE D-1
Historical General Water Chemistry Data Summary
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

Monitoring Well	pH				Conductivity (ms/cm)			Temperature (Deg. C)		
	2004 *	2007	2010	Change (2004 - 2007)	2004 *	2007	2010	2004 *	2007	2010
BR	5.74	5.61	6.67	0.93	46.2	1.65	0.46	10.5	13	14.49
JS	4.83	4.77	5.34	0.51	23.1	0.1	0.035	7.5	10	14.39
JDR	4.03	3.54	4.97	0.94	34.2	0.592	0.276	9.3	11.3	15.50
KSR	3.96	3.72	2.77	-1.19	63.3	0.293	0.197	8.1	10	13.73
KDR	2.95	2.99	3.56	0.61	982	10.6	4.02	9.9	11.64	14.38
NS	6.4	6.14	6.11	-0.29	34.1	0.286	0.186	7.6	9.3	13.54
ND	5.57	5.51	5.02	-0.55	131	0.72	1.49	10.4	11.6	14.56
OS	5.43	2.59	5.3	-0.13	74.6	0.9	1.21	10.1	10.9	14.92
SS	5.41	5.2	7.79	2.38	161	4.72	0.903	7.5	11.8	15.65
SD	3.15	3.15	3.49	0.34	2840	35.6	33.2	9.3	13.05	15.42
11	5.4	5.29	6.34	0.94	495	2.12	1.41	11.7	14.46	14.47
12	5.81	5.44	8.09	2.28	82.4	0.96	0.644	10	12.8	13.03
13	NM	4.87	7.56	2.69	NM	0.564	0.538	NM	13.7	14.00
14	NM	4.36	4.71	0.35	NM	0.144	0.024	NM	13.3	14.89
15	NM	4.29	5.31	1.02	NM	0.051	0.033	NM	11.1	15.78
16	NM	5.83	6.25	0.42	NM	0.203	0.238	NM	13.4	13.30
17	NM	5.22	5.27	0.05	NM	0.429	0.038	NM	9.7	14.30
22	3.87	3.83	4.25	0.38	46	0.215	0.161	9.2	12.46	15.36
23	3.42	3.64	3.77	0.35	135	5.2	0.47	9.4	13	14.60
24	5.93	5.71	7.56	1.63	53.6	0.647	0.727	10.8	14	14.22
26	3.89	3.98	3.97	0.08	361	3.32	4.55	9.4	11.58	14.31
27	4.6	5.26	4.7	0.1	62.3	0.465	0.159	6.6	11	14.70
28	3.93	3.84	4.26	0.33	282	0.992	1.77	8.8	11.7	16.03
30R	5.78	5.3	5.73	-0.05	171	1.99	1.04	11.6	12.82	16.04
31	6	6.05	6.31	0.31	33.1	0.188	0.087	9.6	11.75	14.10
32	6.09	5.85	6.32	0.23	33	1.99	0.305	11.9	13.2	14.90
33	5.68	5.23	5.44	-0.24	79.7	1.14	1.29	8	10.1	13.64
34	6.01	5.73	5.73	-0.28	222	2.35	2.31	9.7	12.2	12.30

Notes:
* - 2004 data may be suspect due to freezing conditions.
Where 2004 data is unavailable, 2007 data was used to calculate difference in Oxidation-Reduction Potential and pH.



NOTE: GROUNDWATER pH CONTOURS SHOWN ARE A REPRESENTATIVE COMPOSITE OF DATA FROM SHALLOW AND DEEP WELLS IN THE UNCONFINED AQUIFER.

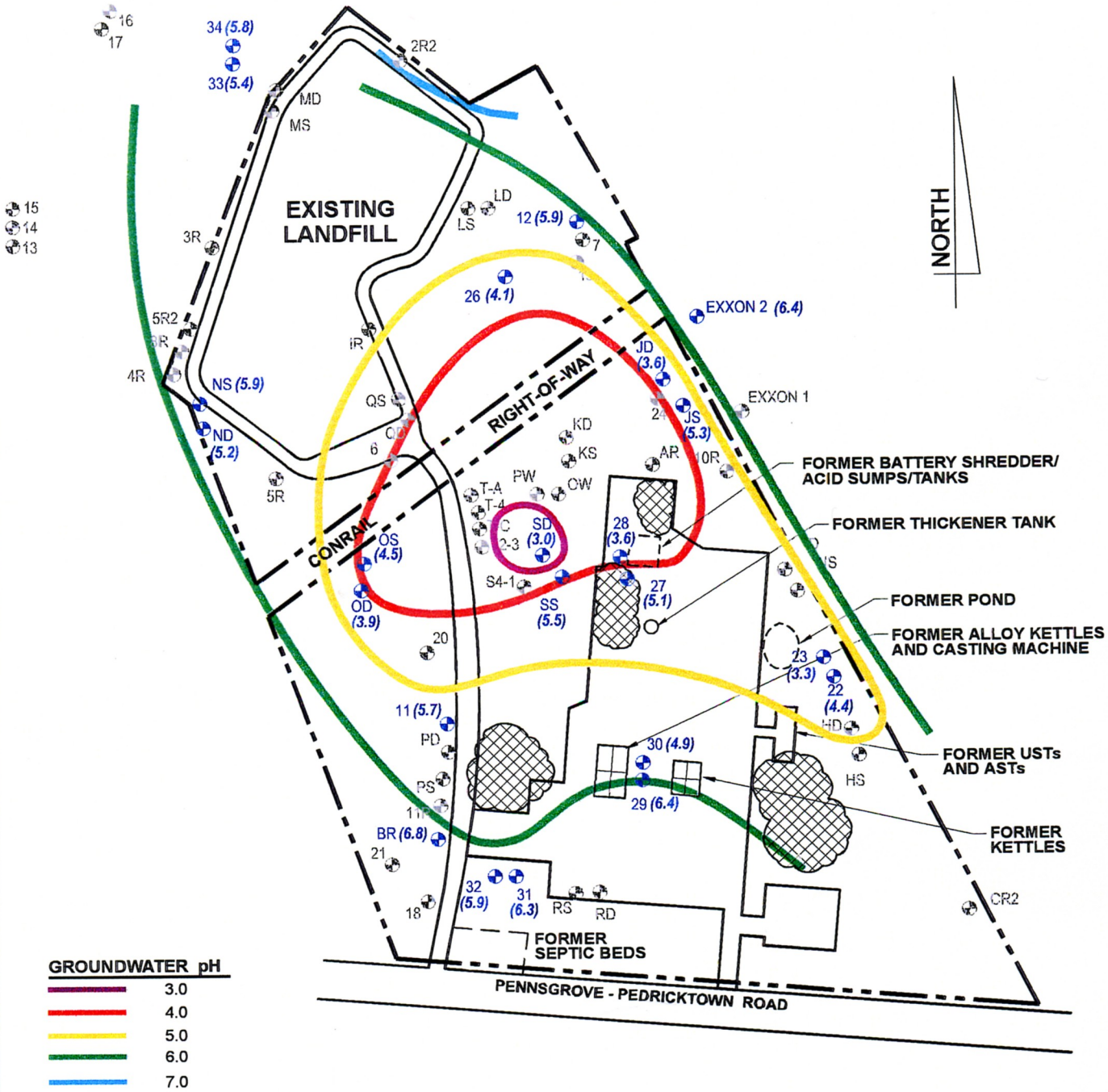
pH of Groundwater - 1983

NL Industries Site
Pedricktown, New Jersey

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	7-5
PROJECT NO.	ME0015-15
DOCUMENT NO.	-
FILE NO.	phs2-pH83

500153



NOTE: GROUNDWATER pH CONTOURS SHOWN ARE A REPRESENTATIVE COMPOSITE OF DATA FROM SHALLOW AND DEEP WELLS IN THE UNCONFINED AQUIFER.

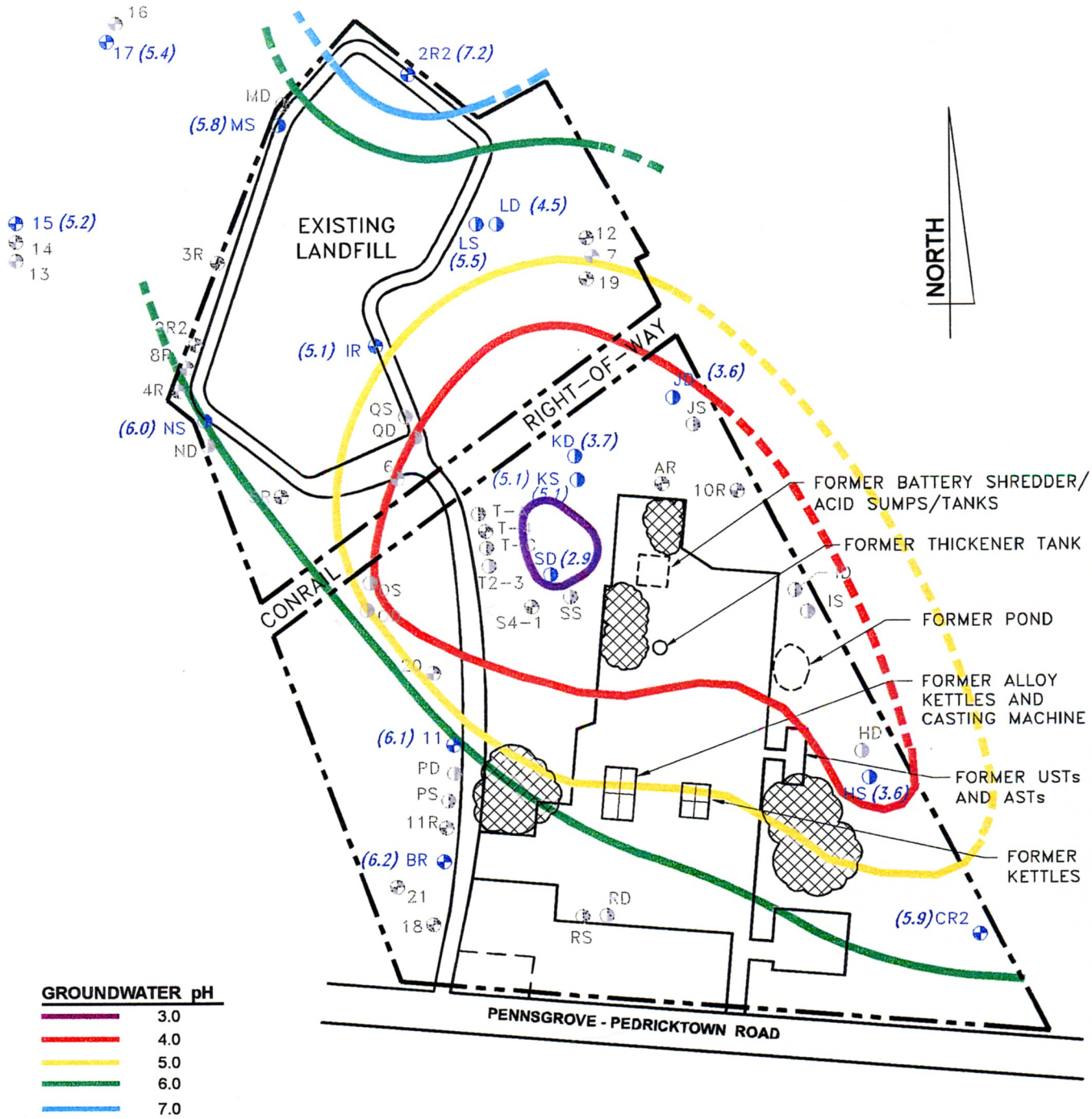
pH of Groundwater - 1998

NL Industries Site
Pedricktown, New Jersey

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	7-3
PROJECT NO.	ME0015-15
DOCUMENT NO.	-
FILE NO.	phs2-pH98

500154



LEGEND

RD	2" WELL (NESTED PAIR) & DESIGNATION
CR2	4" WELL & DESIGNATION
(4.5)	GROUNDWATER pH
	FORMER SLAG PILE LOCATION

NOTE: GROUNDWATER pH CONTOURS SHOWN ARE A REPRESENTATIVE COMPOSITE OF DATA FROM SHALLOW AND DEEP WELLS IN THE UNCONFINED AQUIFER.

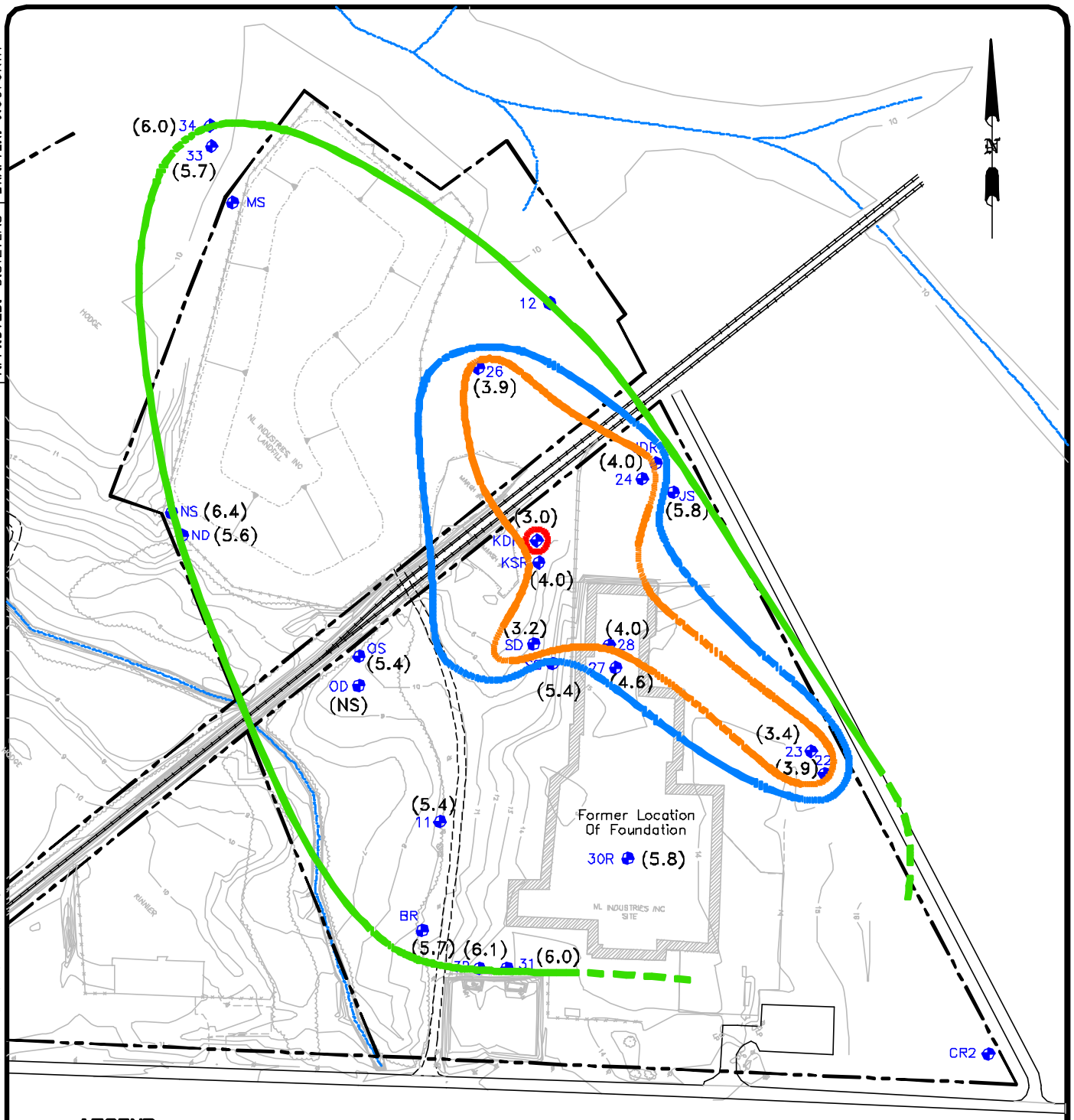
pH of Groundwater - 1997

NL Industries Site
Pedricktown, New Jersey

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	7-4
PROJECT NO.	ME0015-15
DOCUMENT NO.	-
FILE NO.	phs2-pH97

500155



LEGEND:

CR2 MONITORING WELL

pH 3

pH 4

pH 5

pH 6

0 150 300

SCALE IN FEET

CSI Environmental, LLC

918 Chesapeake Ave.
Annapolis, MD 21403
410-268-2765

Groundwater pH - 2004 Shallow Zone

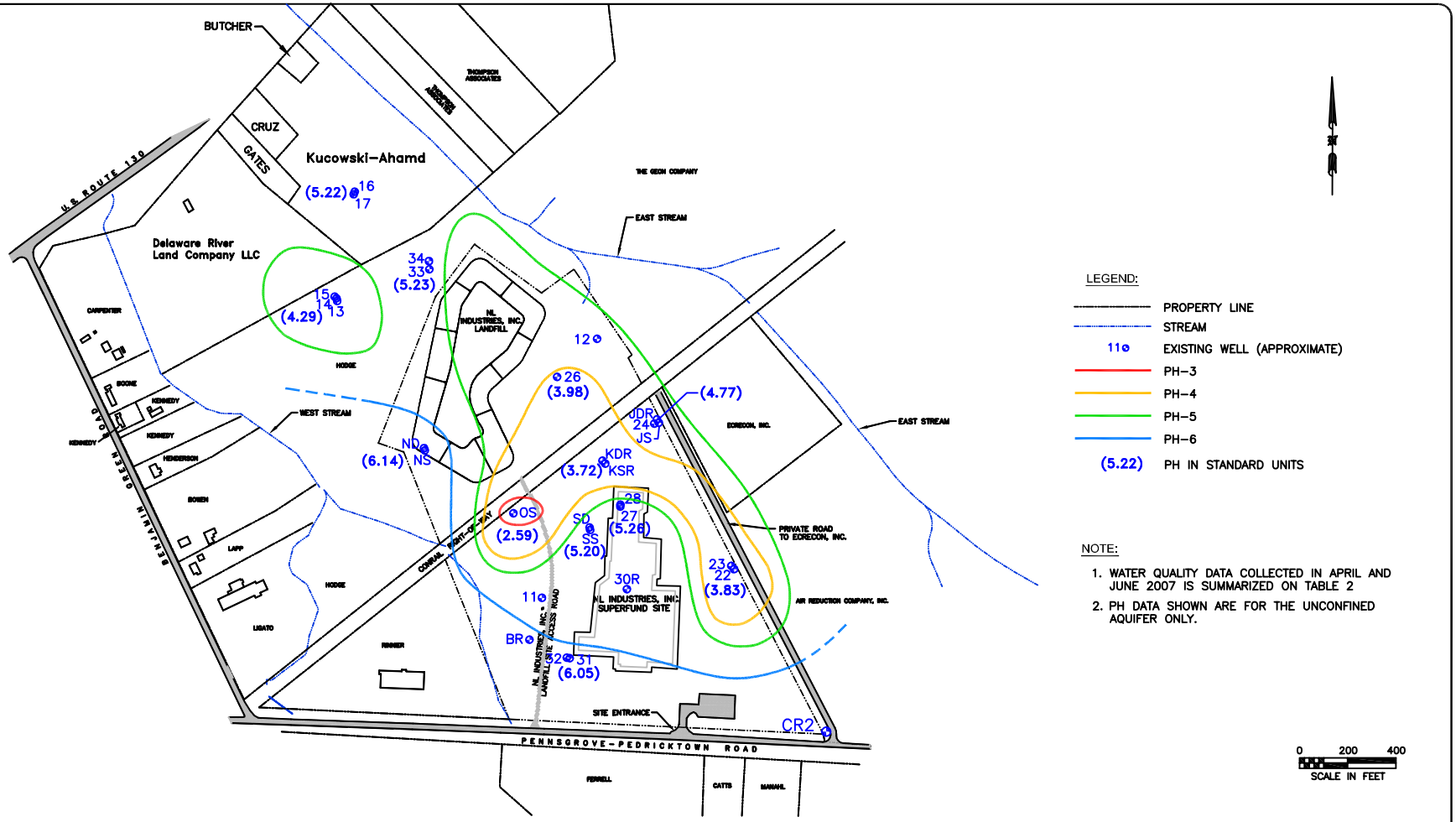
NL Industries Superfund Site
Pedricktown, New Jersey

FIGURE

3

500156

Date\Time : Wed, 14 Apr 2004 - 12:43pm | Path\Name : C:\LIBRARY\csi\NL\PH-CONC.dwg | APPROVED: C.STEVENS | DRAFTER: J.GOFORTH



CSI Environmental, LLC
918 Chesapeake Ave.
Annapolis, MD 21403
410–268–7261

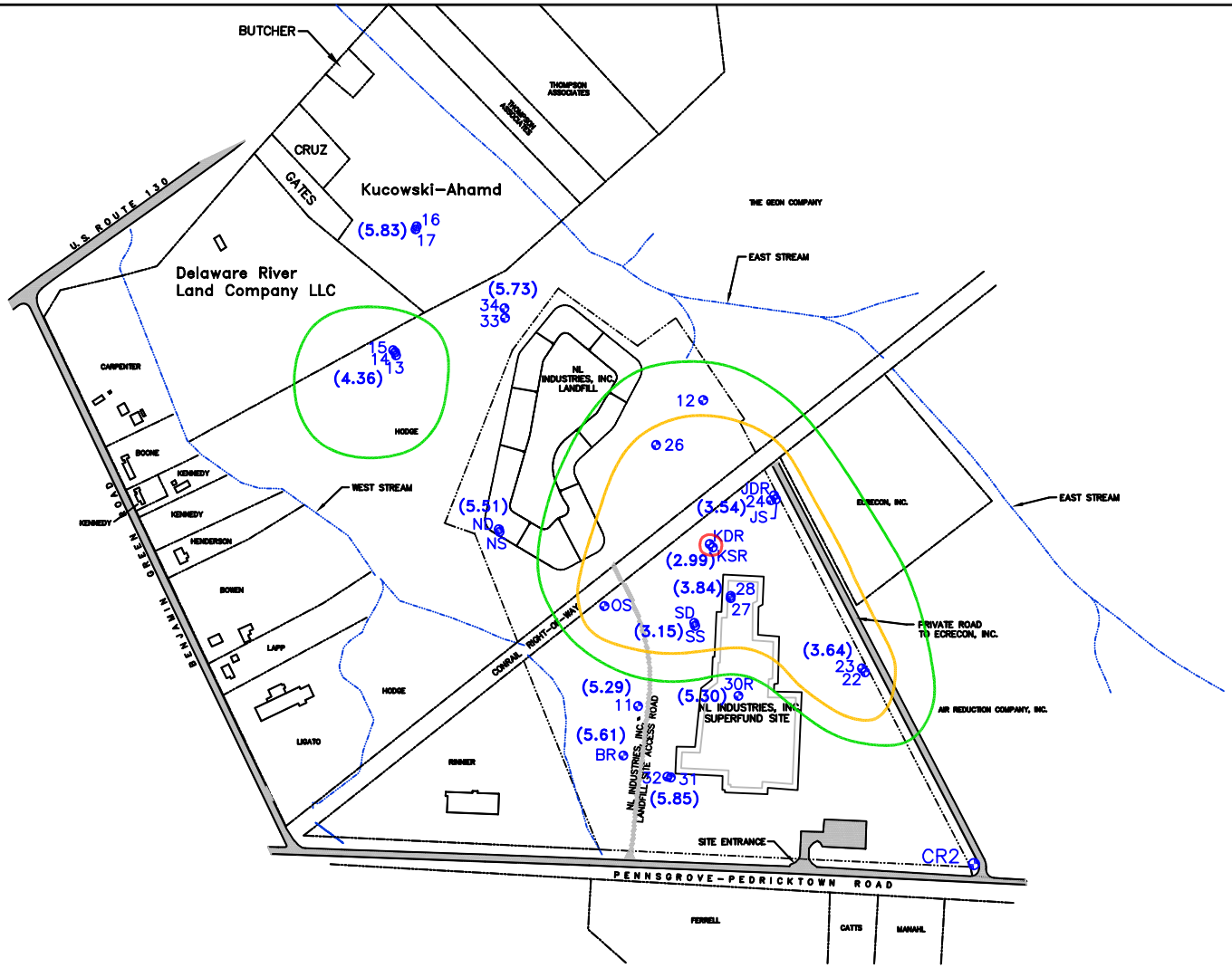
Groundwater PH - 2007
Shallow Zone

NL Industries Superfund Site
Pedricktown, New Jersey

FIGURE
3

DRAFTER: DRAFTER
APPROVED: MANAGER
CHECKED: CHECKER

500157



LEGEND:

- PROPERTY LINE
- STREAM
- 11 EXISTING WELL (APPROXIMATE)
- PH-3
- PH-4
- PH-5
- PH-6
- (5.22) PH IN STANDARD UNITS

NOTE:

1. WATER QUALITY DATA COLLECTED IN APRIL AND JUNE 2007 IS SUMMARIZED ON TABLE 2
2. PH DATA SHOWN ARE FOR THE UNCONFINED AQUIFER ONLY.

0 200 400
SCALE IN FEET

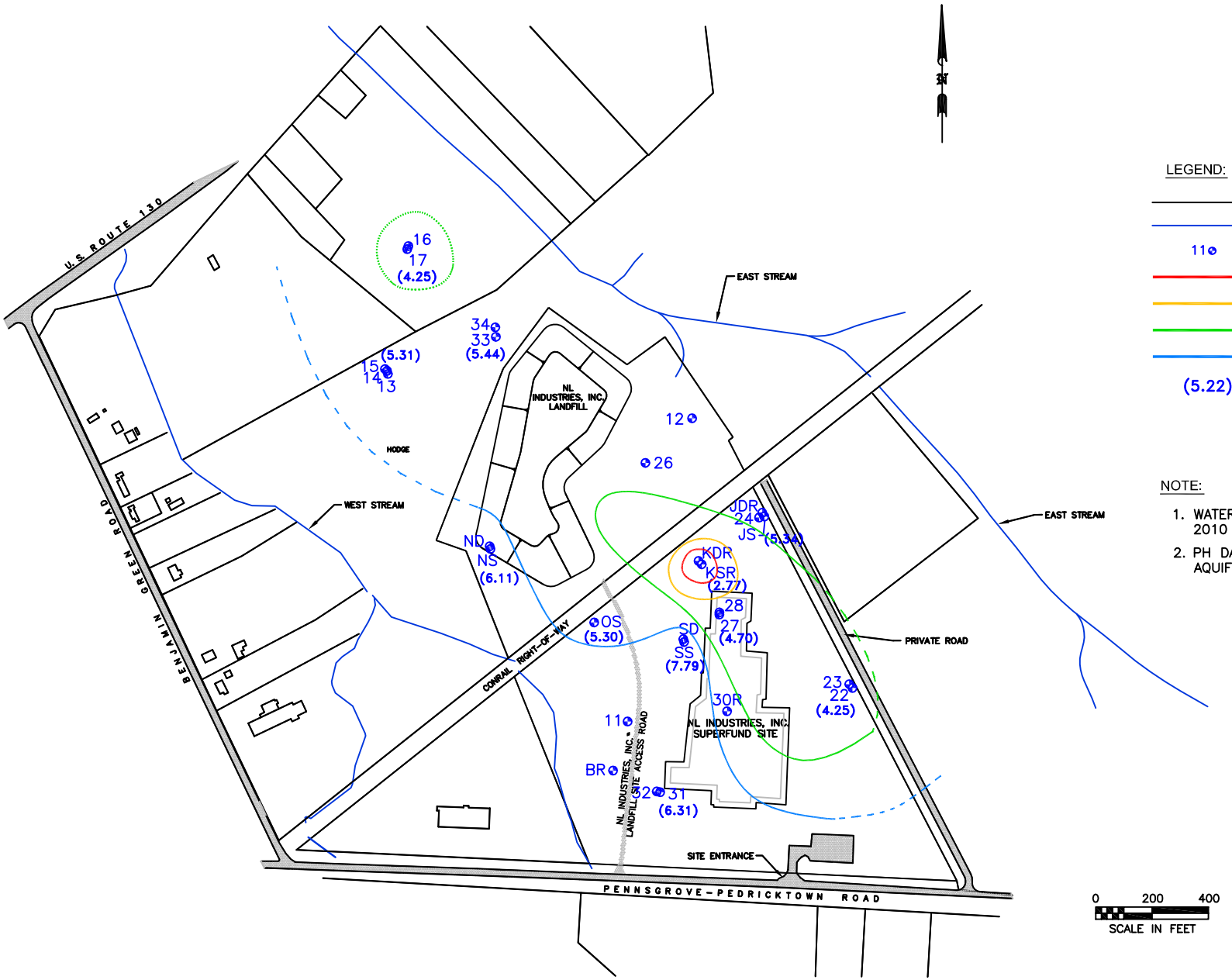
CSI Environmental, LLC
918 Chesapeake Ave.
Annapolis, MD 21403
410-268-7261

Groundwater PH - 2007
Deep Zone

NL Industries Superfund Site
Pedricktown, New Jersey

FIGURE 4

500158



LEGEND:

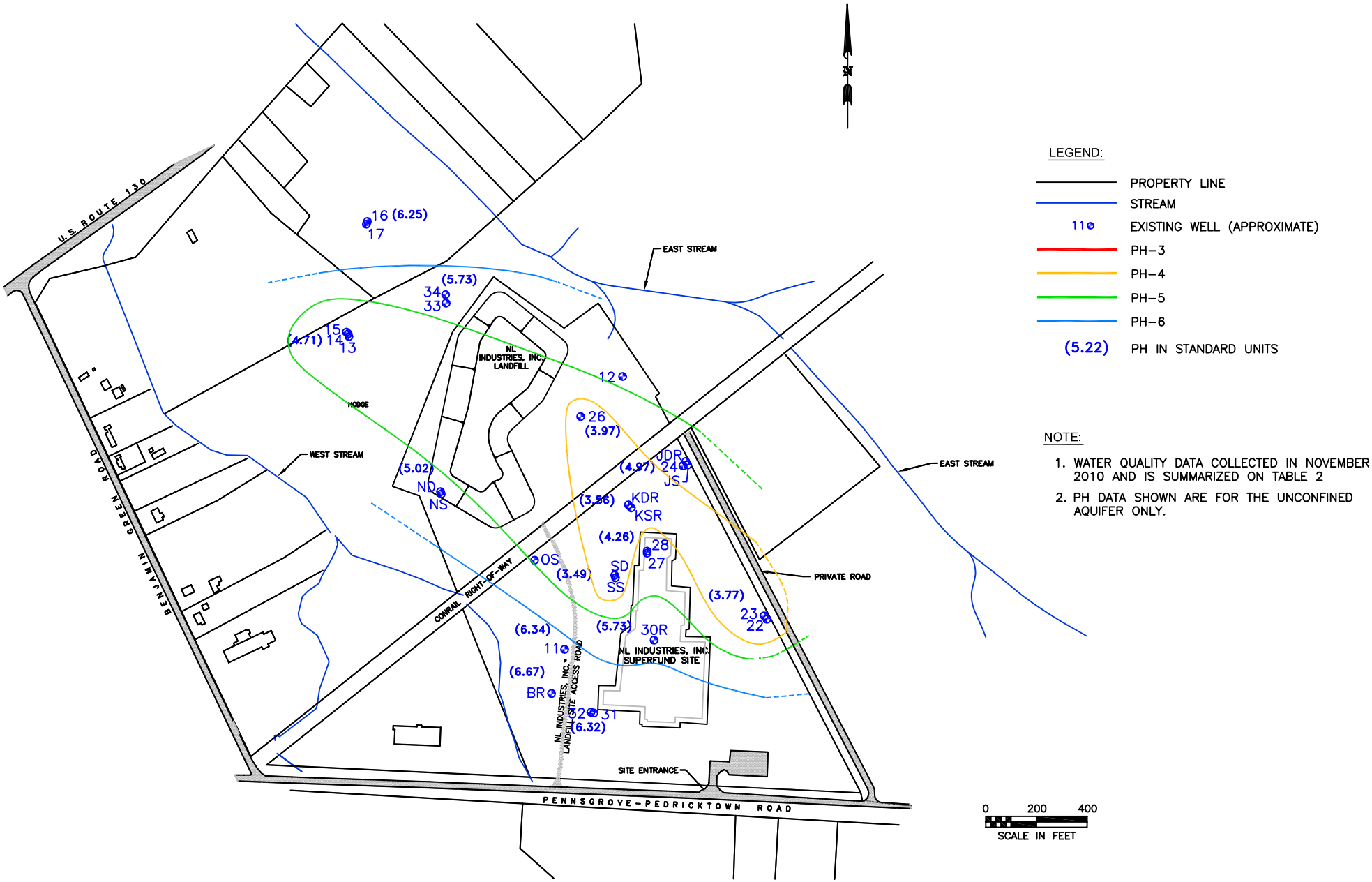
- PROPERTY LINE
- STREAM
- 11 EXISTING WELL (APPROXIMATE)
- PH–3
- PH–4
- PH–5
- PH–6
- (5.22) PH IN STANDARD UNITS

NOTE:

1. WATER QUALITY DATA COLLECTED IN NOVEMBER 2010 AND IS SUMMARIZED ON TABLE 2
2. PH DATA SHOWN ARE FOR THE UNCONFINED AQUIFER ONLY.

0 200 400
SCALE IN FEET

CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Hickey Approved By: J.D. Ferris Last Revised: 12/21/2010	Groundwater pH Distribution - Shallow Zone November 2010 NL Industries, Inc. Superfund Site Pedricktown, NJ	FIGURE 4 500159



CSI Environmental, LLC 918 Chesapeake Ave. Annapolis, MD 21403 410-268-2765	Drafter: M. Hickey Approved By: J.D. Ferris Last Revised: 12/21/2010	Groundwater pH Distribution - Deep Zone November 2010 NL Industries, Inc. Superfund Site Pedricktown, NJ	FIGURE 5 500160

APPENDIX E

Reagent Injection Bench Scale Treatability Study

WRT SERVICES, INC.

August 25, 2007

Mr. Jeff Moore
Senior Project Manager
Construction Services International, Inc.
918 Chesapeake Ave.
Annapolis, MD 21403

Re: NL Industries

Dear Jeff:

WRT Services conducted a laboratory bench study on behalf of CSI. The objective is to determine metal stabilization techniques for use at the NL Industries site, located in Pedricktown, NJ.

Background:

WRT Services was provided preliminary guidance for the bench tests as described in Section 3.3.3 Bench Scale Treatability Study, attached.

Water samples were obtained from four monitoring wells at the site. The samples were tested for:

Lead
Cadmium
Iron
Manganese
Calcium
COD
TOC
Sulfide
Chloride
Total Alkalinity
Total Hardness

The groundwater is contaminated with lead and cadmium. These metals form insoluble complexes with several anions, including sulfide, carbonate, and phosphate. The ultimate treatment objective is to precipitate the target metals in situ and immobilize them. This would eliminate the need for a pump and treat remediation system, at least with respect to metals removal.

Theory

Soluble metals are usually present in solution as mono, divalent, or trivalent cations. Most toxic soluble metals are present as divalent cations. These cations may be reacted with divalent anions and if their solubility product (K_{sp}) is exceeded, the reaction products precipitate from solution. A compound's solubility is proportional to its solubility Product: The smaller the solubility product, the less soluble the species.

Metal hydroxides, Me(OH), are generally two orders of magnitude more soluble than metal sulfides. Metal phosphates usually exhibit similar solubility products as metal sulfides. Note that rendering a metal insoluble does not necessarily immobilize the insoluble complex.

Metals may be immobilized by:

- Direct adsorption of a metal complex onto a substrate (i.e. the native rock)
- Incorporating the metal into a crystal lattice (interculation), and subsequent incorporation within the native rock.
- Interlocking the metal into a non-homogenous material such as concrete or glass (vitrification)

Metal sulfides tend to adsorb onto a substrate. Phosphate immobilization is somewhat more complex. A host crystal, such as calcium carbonate is formed in solution with the target metal. If the charge and atomic radius of the target metal is the proper size, the target metal is incorporated into the host crystal and simultaneously rendered insoluble and inert.

Test Considerations:

The test protocol suggests evaluating metal precipitation with three compounds: Carbonate, sulfide, or phosphate. However, cadmium carbonate has significantly higher solubility than either cadmium sulfide or cadmium phosphate. In fact cadmium carbonate it is more soluble than cadmium hydroxide. Metal hydroxide salts are generally not acceptable for in situ metal stabilization, so carbonate precipitation was eliminated from consideration.

There are other test design considerations with implications for a full scale remediation system.

Acidity/alkalinity:

From a practical viewpoint, high alkalinity and pH in excess of 7.0 are required for metal carbonate precipitation, adding to cost and application complexity. Metal phosphate precipitation also requires pH elevation, but alkalinity is not a consideration.

Safety and Toxicity:

If sodium sulfide is used for sulfide precipitation, then pH must be controlled to prevent evolution of explosive hydrogen gas. Sulfide precipitation conducted with organosulfur compounds is not subject to hydrogen gas evolution nor is pH control required.

Some organosulfur compounds, notably dithiocarbamates, are highly toxic to fresh water fish, so use of these reagents is avoided.

Cost:

Sodium sulfide is the least expensive sulfide precipitation reagent, but this was eliminated from consideration due to safety concerns.

Phosphate precipitation is not as simple as it may appear. The phosphate bearing reagent must supply the phosphate in the di-basic state. When metals form mono-basic salts with phosphate, the metal is adsorbed onto the face of the crystal, where it can be re-dissolved relatively easily. Thus, this will produce good laboratory results, but is not practical in real life applications. When metals are removed by crystalline formation with di-basic phosphate, the metals homogenously precipitate within the host crystal, effectively immobilizing the metals.

Tri-sodium polyphosphate (TSPP) was selected for use, rather than phosphorous acid, even though it is somewhat more expensive than phosphoric acid, to insure that cadmium and lead were removed as dibasic

phosphate salts. Tri-sodium polyphosphate also eliminates the safety concerns of handling strong mineral acid in field application.

Solubility Products:

$CdCO_3$	1×10^{-12}
$Cd(OH)_2$	7.2×10^{-15}
$Cd_3(PO_4)_2$	2.53×10^{-33}
CdS	3.6×10^{-29}
$Pb(OH)_2$	1.0×10^{-16}
PbS	3.4×10^{-28}
$Pb(PO_4)$	

Baseline Groundwater Chemistry

Sample Location		TDS ppm	pH	Cadmium ppb	Lead ppb	Iron ppm	Manganese ppm
Well	SD	28,500	3.08	149	31	294	8.0
Well	OS	5,400	3.09	4	388	8	0.2
Well	SS	767	5.25	11	83	24	0.5
Well	KDR	5,740	2.83	141	ND	78	4.0

Test Procedure:

Reagent Selection:

1. Tri-sodium phosphate (TSPP) was chosen to generate calcium phosphate in the presence of lead and cadmium.
2. Calcium chloride solution was used in conjunction with TSP to supply the calcium ion required to form calcium phosphate.
3. A 5% solution of sodium hydroxide was used for pH adjustment in all experiments requiring pH increase.
4. A liquid organosulfur compound, Trimercaptotriazine (TMT-15, manufactured by Degussa), was chosen to precipitate lead and cadmium. TMT was selected as the reagent because it has essentially no aquatic toxicity as use concentration.

Test matrix:

Three sets of tests were conducted on each sample point. The objective was to simultaneously precipitate cadmium and lead.

Test A: No pH adjustment.
Determine the dose of Trimercaptotriazine required for each sample.
The dose is determined by:
- Calculating the stoiciometric demand to precipitate all the known metals (iron, manganese, cadmium, and lead).
- Add TMT-15 at 1.5 times the stoiciometric requirement to compensate for any reagent demand from unknown metals.

Mix for 30 seconds at 120 rpm using a Phipps and Bird mechanical stirrer (gang stirrer).
Allow to stand and settle for five (5) minutes.
Filter through # 40 Whatman paper and retain filtrate for metals analysis
Acidify and refrigerate retained samples

Ship to Lancaster Laboratories for cadmium and lead determination.

Test B: Qualifiers:

1. Sulfide precipitation is usually conducted at mildly alkaline pH.
   Each groundwater was acidic: Several are strongly acidic.
   Determine if pH adjustment is required to augment sulfide precipitation

2. Iron and manganese create demand for sulfide reagent.
   Iron and manganese may be inexpensively precipitated by pH adjustment in excess of 8.0, using (inexpensive) sodium hydroxide.
   If iron is removed as iron hydroxide, the sulfide reagent can be preserved to precipitate the more soluble metals, cadmium and lead, at relatively lower cost.

Adjust pH to 8.5.
Add 30 ppm, active ingredient basis, of Trimercaptotriazine
Mix for 30 seconds at 120 rpm using a Phipps and Bird mechanical stirrer (gang stirrer).
Allow to stand and settle for five (5) minutes.
Filter through # 40 Whatman paper and retain filtrate for metals analysis
Acidify and refrigerate retained samples
Ship to Lancaster Laboratories for cadmium and lead determination.

Test C: Add 100 ppm of TSPP solution
Mix 30 seconds at 120 rpm
Add 200 ppm of Calcium Chloride solution
Mix for 30 seconds at 120 rpm
Adjust pH to 8.5 with sodium hydroxide solution
Mix for 30 seconds at 120 rpm.
Allow to stand and precipitate for five (5) minutes.
Filter through # 40 Whatman paper and retain filtrate for metals analysis
Acidify and refrigerate retained samples
Ship to Lancaster Laboratories for cadmium and lead determination.

Notes:

- Each test was conducted with 500 ml of sample, unless noted otherwise.
- Initially a 2:1 ratio of calcium to phosphate was selected to insure that the reaction was driven to completion. The desired crystalline end product is: $Ca_5(PO_4)_3(OH)_4$
- Calcium chloride dose modified to compensate for impact of iron phosphate formation.
- Each test was post treated with 10 ppm of anionic polyacrylamide copolymer to induce particle agglomeration and enhance filtration.

<u>Sample OS</u>:

Test A:

14.5 ppm of known metals present in sample

Dose with 0.1 ml of TMT-15 = 30 ppm active Trimercaptotriazine

Initial pH = 3.09
pH after TMT addition = 3.59

Test B: Adjust pH with 5% solution of sodium hydroxide

Add 1 cc of 5% sodium hydroxide: pH increases to 7.27
Add an additional 0.38 cc: pH = 8.52

Visible Pinfloc: Probably iron hydroxide

Add 0.1 cc of TMT-15 (30 ppm active ingredient): pH = 8.62

Stronger, more voluminous floc generated compared to Test A.

Test C: Add 2 cc of 5 % TSPP and mix: pH = 4.41
Add 1 cc of 5% $CaCl_2$ and mix: pH = 4.46
Increase pH to 8.5 with 5 % sodium hydroxide
Add 0.5 cc: pH =8.30
Increase dose to 0.58 cc: pH = 8.56

Pinfloc visible after pH adjustment.

Sample SS:

Test A:

TMT demand calculated at 458 ppm active ingredient

Note: Test volume = 700 ml.

Dose with 2.2 ml of TMT-15 = 471 ppm active Trimercaptotriazine
Mix

Initial pH = 5.25
pH after first TMT addition = 9.25

Creates suspended colloidal solids: Difficult to precipitate

Increase TMT dose by 1.0cc: Total concentration now = 685 ppm a.i.

Iron in filtrate = 6.70 ppm

Test B: Adjust pH with 5% solution of sodium hydroxide

Add 0.5 cc of 5% sodium hydroxide: pH = 5.45
Increase to 1 cc of 5% sodium hydroxide: pH increases to 9.25

Sample is not buffered.

Add 3.2 cc of TMT-15:

Colloidal, turbid solution: No pinfloc
Iron in filtrate = 1.80 ppm

Test C: Modify procedure: Add 1 pt of TSPP per part of iron in sample
Add 100 ppm of TSP to remove cadmium and lead.

Add 1.3 cc of 5 % TSPP (100 ppm) for cadmium and lead
Add 0.5 cc TSPP (30 ppm) for iron
Add 2.6 cc of 5% $CaCl_2$ and mix: pH = 6.35

Add 0.65 cc of 5 % sodium hydroxide: pH =9.26

Iron in filtrate = 0.33 ppm

Precipitates easily after anionic polymer addition:
Generates crystal clear water

Sample SD:

Test A:

TMT demand calculated at 1218 ppm active ingredient

Note: Test volume = 700 ml.

Dose with 22 ml of TMT-15 = 4714 ppm active Trimercaptotriazine
Mix

Massive, voluminous black floc
TMT: Metal ratio = 4:1: Too much TMT.

Initial pH = 3.04
pH after first TMT addition = 7.05

Note: Filtrate discolors: Reacts with nitric acid when sample is fixed: Indicates excess TMT.

Iron in sample reported as 296 ppm
Iron in filtrate = 135 ppm

Test B: Adjust pH with 5% solution of sodium hydroxide

Add 19.2 cc of 5% sodium hydroxide: pH = 8.48

Add 11 cc of TMT-15:

Iron in filtrate = 0.17 ppm

Test C: Modify procedure: Add 1 pt of TSPP per part of iron in sample
Add 100 ppm of TSP to remove cadmium and lead.

Add 8.4 cc of 5 % TSP pH = 3.33
Add 16.8 cc of 5% $CaCl_2$ and mix: pH = 3.22

Add 18.7 cc of 5 % sodium hydroxide: pH =8.54

Iron in filtrate = 3.20 ppm

Sample KDR:

Sample pH = 2.88
Sample iron = 52 ppm (GFR test) Reported as 78 ppm.

Volume for all three tests = 700 ml.

Test A:

TMT demand calculated at 770 ppm active ingredient

Dose with 4.5 ml of TMT-15 = 964 ppm active Trimercaptotriazine Mix

Large floc with clear water

pH after TMT addition = 4.70

Iron in filtrate = 13.5 ppm

Test B:

Add 3.25 cc of 5% sodium hydroxide: pH = 8.62

Add 3.8 cc of TMT-15: pH = 9.39

Iron in filtrate = 0.26 ppm

Test C:

Add 2.2 cc of 5 % TSPP (152 ppm) pH = 2.85
Add 2.9 cc of 5% $CaCl_2$ (200 ppm): pH = 2.84

Add 4.0 cc of 5 % sodium hydroxide: pH =8.75

Iron in filtrate = 0.18 ppm

Results:

Sample	Test	Cadmium ppm	Lead ppm
SS	Control	0.0091	0.0710
	Test A	0.0053	0.0263
	Test B	<0.0050	<0.0150
	Test C	<0.0050	<0.0150
KDR	Control	0.0793	<0.0150

	Test A	<0.0050	<0.0150
	Test B	<0.0050	<0.0150
	Test C	<0.0050	<0.0150
OS	Control	no test	no test
	Baseline	0.0040	0.3800
	Test A	0.0070	0.3200
	Test B	<0.0050	<0.0150
	Test C	<0.0050	<0.0150
SD	Control	0.1970	< 0.0750
	Test A	<0.0250	< 0.0750
	Test B	<0.0250	< 0.0750
	Test C	<0.0250	< 0.0750

Relative application costs:

Cost comparisons were made between:

Treatment A: Organosulfur
Treatment B: Organosulfur with pH adjustment
Treatment C: Trisodium polyphosphate

The results for Groundwater source SD and SS were evaluated.

- All three treatments worked effectively on Groundwater Source SD

- Trisodium Polyphosphate was more effective for removing lead and cadmium from Groundwater Source SS

Treatment cost per 1000 gal. of groundwater

Treatment	SD	SS
A: OrganoSulfur	$ 488	$ 11
B: Organosulfur with pH adjustment	$ 252	$ 72
C. Sodium Tripolyphosphate	$ 9	$ 1

Cost Basis:

Sodium tripolyphosphate supplied in dry bulk shipments at $ 42.00/CWT	($ 0.42/lb.)
Calcium chloride supplied in dry, bulk shipments at $ 182/ton:	($ 0.09/lb.)
Sodium hydroxide supplied in 330 gal. tote bin containers, at 25% solution strength at $ 14.25/CWT:	($ 0.1425/lb.)
Degussa TMT-15 supplied in semi-bulk, 275 gal. tote bin containers at:	($ 1.87/lb.)

Conclusion:

As expected both phosphate and sulfide precipitation remove cadmium and lead from solution.

The four test water sources each contain relatively low concentrations of lead and cadmium, which makes trend analysis somewhat difficult. Results with phosphate removal are more concise than with sulfide removal.

Cost wise, phosphate precipitation is clearly more effective than organosulfur. There are less expensive chemical sources of sulfide, however these have a host of application associated difficulties, as detailed within this report.

The study only addresses the issue of effective precipitation. One assumes that the lead and cadmium are interculated within the calcium phosphate crystalline lattice, and thus, effectively demobilized. Further study is required to verify this assumption.

Thank you for the opportunity to be of service to CSI, Inc. Please contact me with questions regarding this study.

Regards,

Gary Richards
WRT Services, Inc.

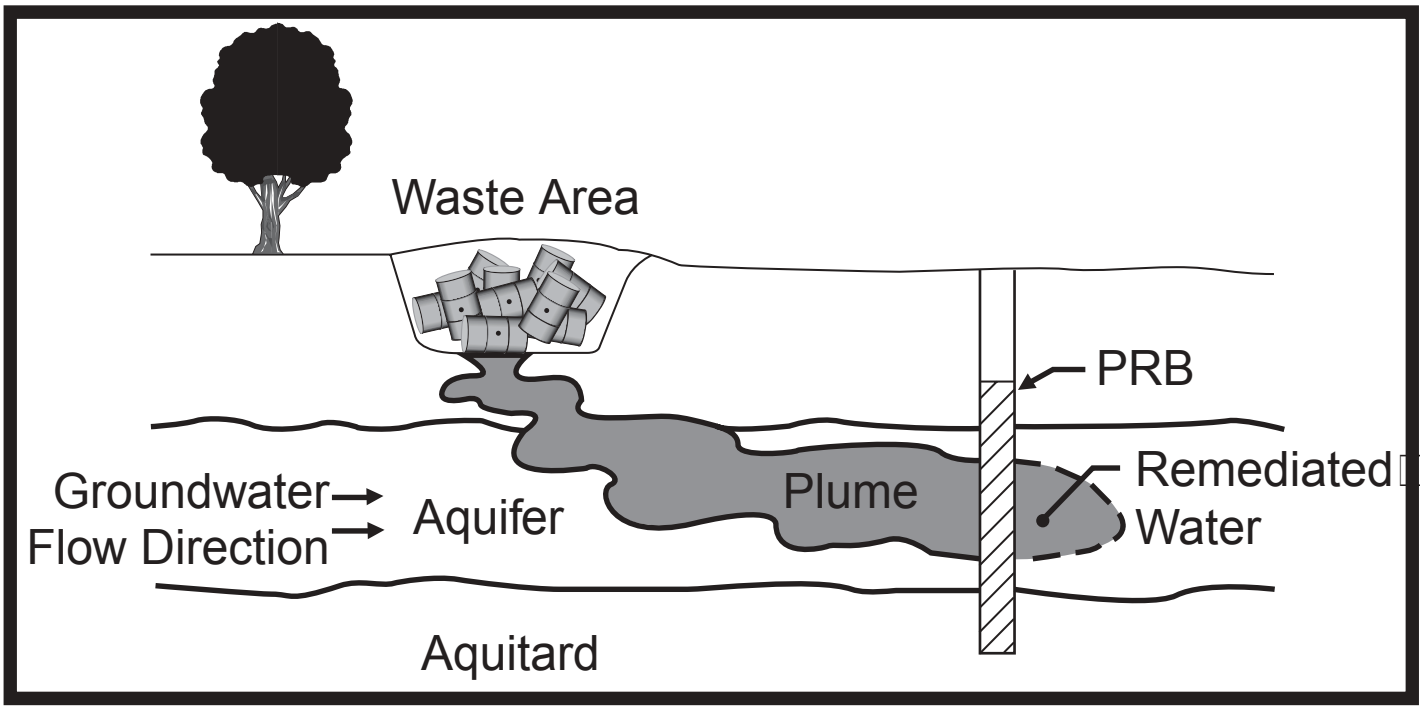
WRT Services, Inc. **1317 Pennsridge Court** **Downingtown, PA 19335**
Phone 610-873-6894 **Fax 610-873-3967** **WRT1997@aol.com**

APPENDIX F

Permeable Reactive Barrier Example Studies

United States
Environmental Protection
Agency

Field Applications of *In Situ* Remediation Technologies:
Permeable Reactive Barriers



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Field Applications of *In Situ* Remediation Technologies:

Permeable Reactive Barriers

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office
Washington, DC 20460

January 2002

Notice

This report was prepared by Environmental Management Support, Inc., 8601 Georgia Avenue, Suite 500, Silver Spring, MD 20910, under contract 68-W-00-084, Work Assignment 006, with the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. For more information about this project, contact: John Quander, U.S. EPA, Technology Innovation Office (5102G), 1200 Pennsylvania Avenue, N.W., Washington, DC 20460, Phone: 703-603-7198, e-mail: quander.john@epa.gov.

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Introduction

A permeable reactive barrier (PRB) contains or creates a reactive treatment zone oriented to intercept and remediate a contaminant plume. It removes contaminants from the groundwater flow system in a passive manner by physical, chemical or biological processes. Some PRBs are installed as permanent or semi-permanent units across the flow path of a contaminant plume. Some PRBs are installed as *in situ* reactors that are readily accessible to facilitate the removal and replacement of reactive media. Most have the reactive media installed or created in intimate contact with the surrounding aquifer material.

This report summarizes information about the use of PRBs for groundwater remediation at 47 sites in the United States, Canada, and selected locations abroad. PRB sites included were identified by the Remediation Technologies Development Forum (RTDF) Permeable Reactive Barriers Action Team members, and information was provided by the points-of-contact listed. The U.S. Environmental Protection Agency's (EPA) Technology Innovation Office has prepared this document to assist potential PRB users in making more informed decisions related to their respective sites.

Complete profiles of these sites are available on the Remediation Technologies Development Forum/Permeable Reactive Barriers Action Team's Internet site (*www.rtdf.org/public/permbarr/prbsumms/default.cfm*).

In addition to the site-by-site information included (pages 9-23), charts and graphs at the end of this section of the report summarize overall statistics concerning the sites profiled. For example, Figure 1 (page 4) shows that PRBs were used for full-scale cleanup at most of the sites profiled and provides a breakdown of these sites by the category of contaminants treated. Figure 2 (page 4) shows the breakdown of U.S., Canadian, and European sites profiled by contaminant groups. Figure 3 (page 5) illustrates that the profiles are almost evenly divided between Federal and private-sector sites, and Figure 4 (page 5) shows the types of barriers used at these sites. Figure 5 (page 6) illustrates that, while zero-valent iron (Fe^0) was the most frequently used reactive medium, a variety of other media or media mixtures are available and have been used in PRBs.

Internet versions of the PRB profiles are updated periodically as new information is received. Profile information for PRB sites that are currently not in the database may be submitted on-line at *www.rtdf.org/public/permbarr/prbsumms/default.cfm* by clicking on the "Submit New Profile" button at the top of the page.

The RTDF/PRB Action Team was established in 1995. Its members include representatives from government, academia, and the private sector working as partners to further public and regulatory acceptance of PRBs for remediating chlorinated solvents, metals, radionuclides, and other groundwater pollutants.

Figure 1

PRB Sites by Scale and Contaminant

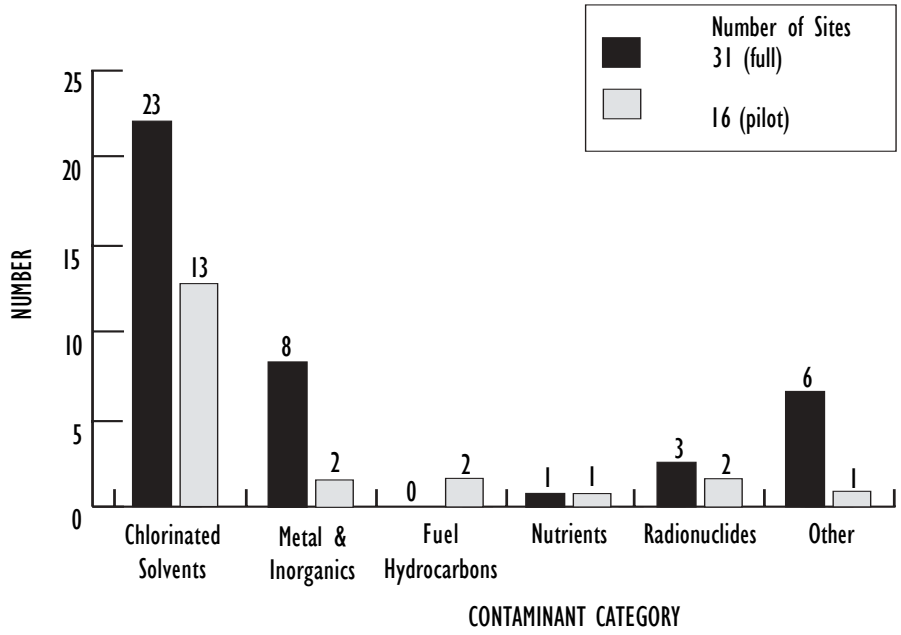


Figure 2

Profiled PRB Sites by Location and Contaminant

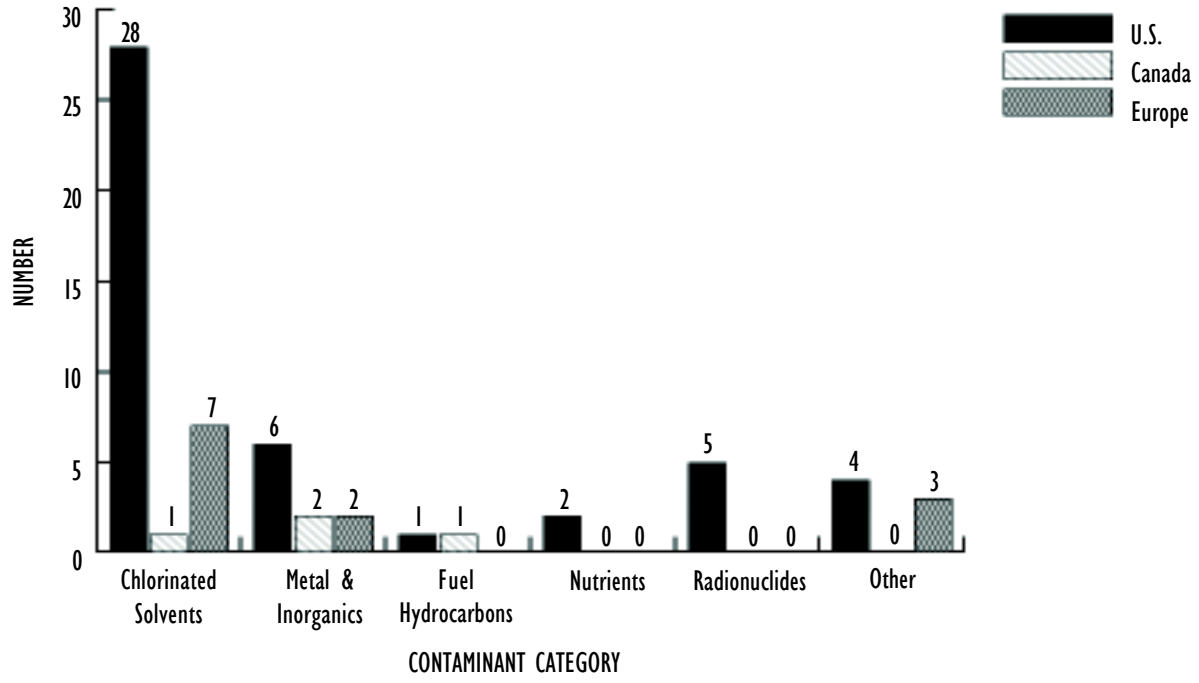


Figure 3

PRB Sites by Private and Government Sectors

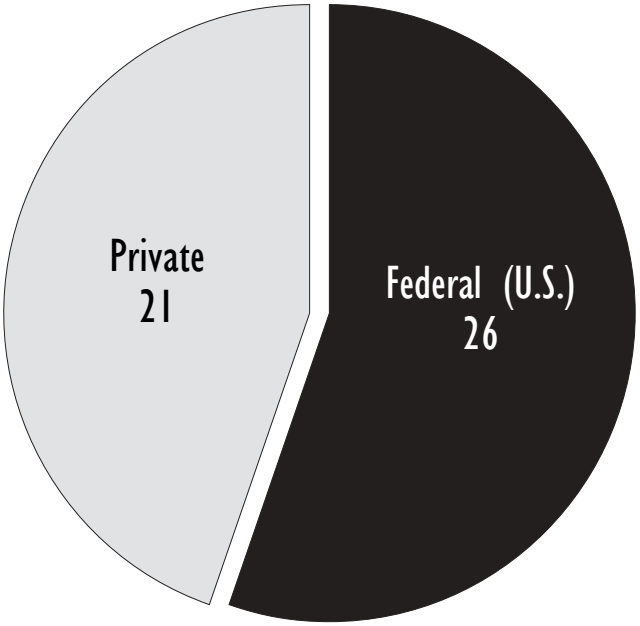


Figure 4

PRB Sites by Type of Barrier

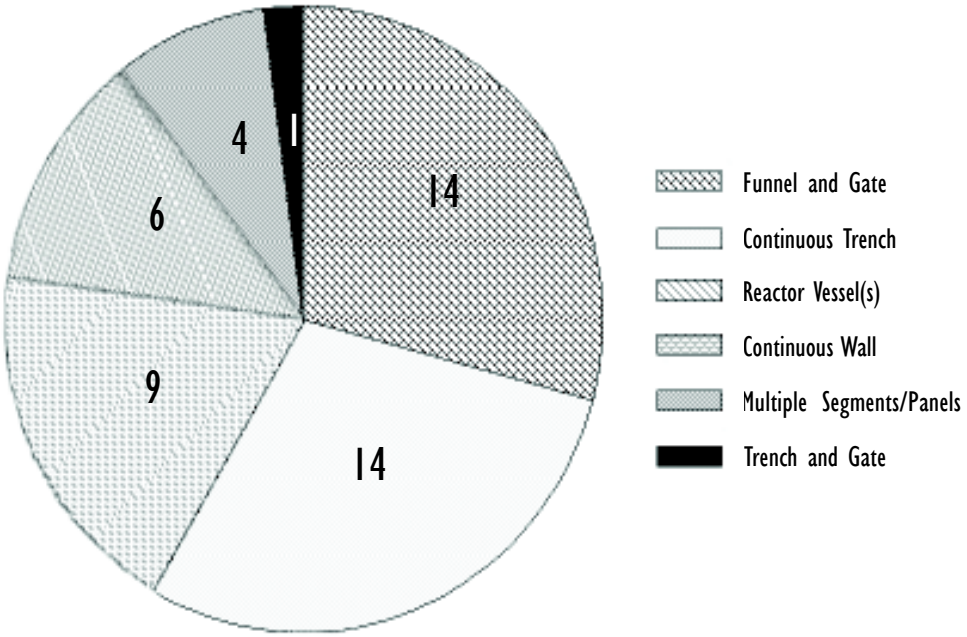
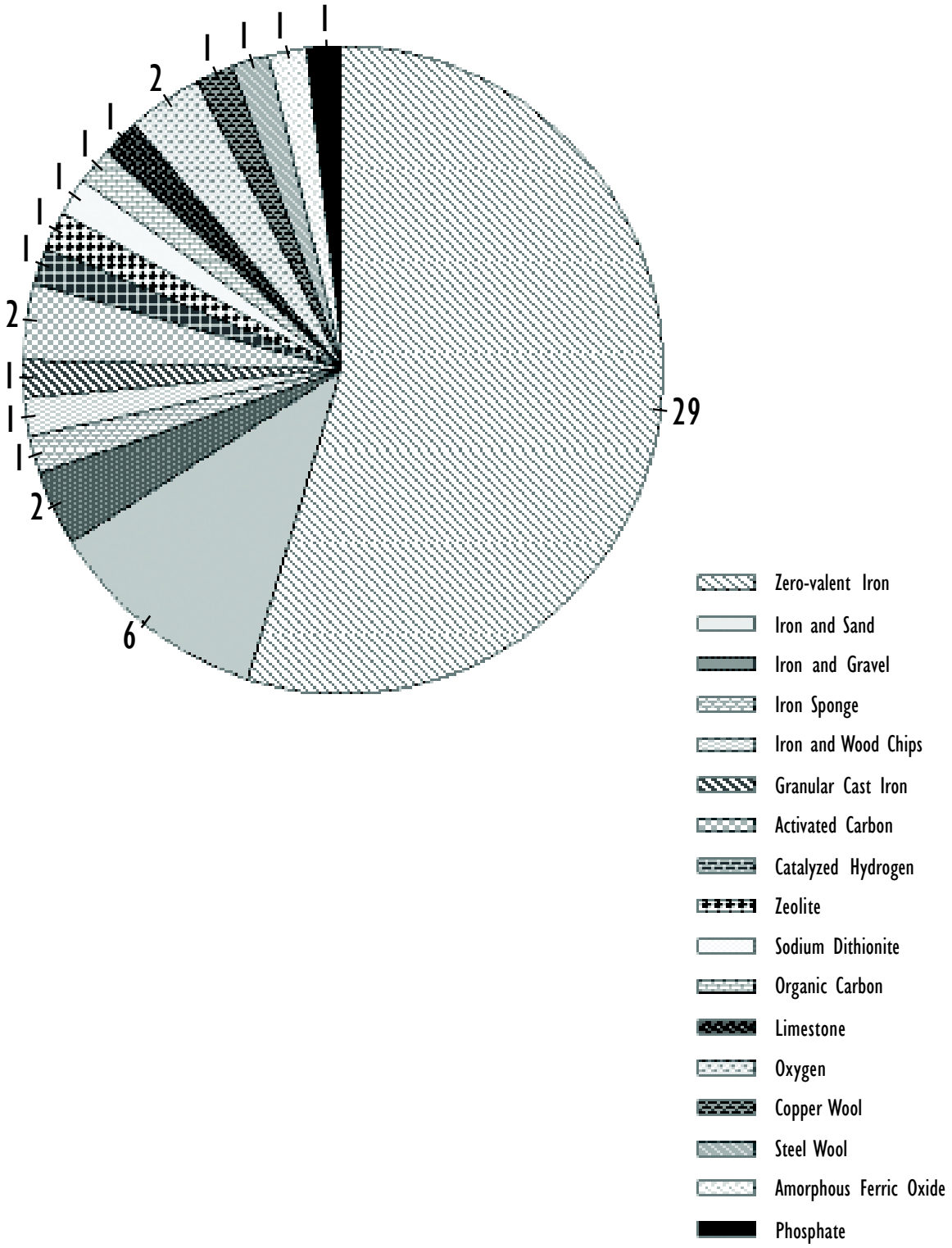


Figure 5

PRB Sites by Reactive Medium Used



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Abbreviations Used in This Document

AFO	amorphous ferric oxide
As	arsenic
bgs	below ground surface
BHC	alpha-hexachlorobenzene
Bq	Becquerel
BTEX	benzene, toluene, ethylbenzene, xylene
CaCO3	calcium carbonate
CB	cement bentonite
Cd	cadmium
Cr^{+6}	chromium, chromate
Cu	copper
DCA	dichloroethane
DCB	dichlorobenzene
DCE	dichloroethylene
DCM	dichloromethane
DDD	$(ClC_6H_4)_2CHCHCl_2$; an insecticide with properties similar to DDT
DDT	$C_{14}H_9C_{l5}$; a water-insoluble crystalline insecticide
DNAPL	dense nonaqueous-phase liquid
DSM	Deep Soil Mixing
Eh	Electrochemical Potential
Fe^0, ZVI	zero-valent iron
FeCO3	iron carbonate
Fe[OH]2	iron hydroxide
FeS	iron sulfide
Freon 11	trichlorofluoromethane
Freon 13	trichlorotrifluoroethane
Freon 113®	1,1,2-Trichloro-1,2,2-trifluorethane
ft	foot, feet
g	gram, grams
gpm	gallons per minute
HC	hydrocarbon
HDPE	high-density polyethylene
in	inch, inches
K	Kelvin
kg	kilograms
L	litre
MCB	chlorobenzene
MCL	Maximum Contaminant Level
mg	milligram, milligrams
Mn	manganese
mv	millivolts
Mo	molybdenum
Ni	nickel
O_2	oxygen
OU	operable unit
PAH	polynuclear aromatic hydrocarbon
Pb	lead
PCE	perchloroethylene, tetrachloroethylene
pCi	picoCuries
PO_4	bone char phosphate
PRB	permeable reactive barrier
s, sec	second, seconds

Se	selenium
Sr-90	strontium
Tc	technetium
TCA	trichloroethane
TCE	trichloroethylene
U	uranium
V	vanadium
VC	vinyl chloride
VOC	volatile organic compound
yd	yard, yards
Zn	zinc
µg	microgram, micrograms

Site Profile Summary

NOTE: Sites with more than 1 type of contaminant are listed under each appropriate contaminant category.

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Aircraft Maintenance Facility	Southern OR	1998	TCE	Funnel and Gate	$600 K	Fe^0		Dave Weymann Tel: 503-624-7200 Fax: 503-620-7658 Email: dweymann@emconinc.com
Caldwell Trucking	Northern NJ	1998	TCE	Hydraulic Fracturing, Permeation Infilling	$1.12 M	Fe^0	Only 60% degradation rate in groundwater; pursuing other measures	John Vidumsky Tel: 302-892-1738 Fax: 302-892-7641 Email: john.e.vidumsky@usa.dupont.com
Copenhagen Freight Yard	Copenhagen, Denmark	1998	*cis* 1,2-DCE, *trans*-DCE, TCE, PCE, VC	Continuous Trench	$235 K	Fe^0	effective treatment of upgradient concentration; part of plume migrated around barrier; conductivity decreased with time	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
F.E. Warren Air Force Base	Cheyenne, WY	1999	TCE, *cis* 1,2-DCE, VC	Trench Box	$2.617 M	Fe^0 and Sand	concentrations of contaminants reduced to non-detectable level	Ernesto J. Perez Tel: 307-773-4356 Fax: 307-773-4153 Email: Ernesto.Perez@ren.af.mil
Federal Highway Administration Facility	Lakewood, CO	1996	TCA, 1,1-DCE, TCE, *cis* 1,2-DCE	Funnel and Multiple Gate	$1 M	Fe^0	VOC concentrations increased in groundwater moving around south end of PRB and in area under PRB	J.H. Woll Tel: 303-716-2106 Fax: 303-969-5903 Email: jhwoll@road.cflhd.gov

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Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Former Dry-Cleaning Site	Rheine, Westphalia, Germany		PCE, *cis* 1,2-DCE	Continuous Wall	$160 K	Fe^0 Iron Sponge	significant reduction in concentration of contaminants	Dr. Martin Wegner Tel: 49-5131-4694-55 Fax: 49-5131-4694-90 Email: wegner@ mullundpartner.de
Former Industrial Site	Brunn am Gebirge, Austria	1999	PAH, Phenols, BTEX, HC, TCE, *cis* 1,2-DCE	Adsorptive Reactors with Hydraulic Barrier	$750 K	Activated Carbon	effective in forcing groundwater to enter PRB; level of contamination varies with groundwater level	Peter Niederbacher Tel: 43-2243-22844 Fax: 43-2243-22843 Email: niederbacher@ geol.at
Former Manufacturing Site	Seattle, WA	1999	PCE, TCE, *cis* 1,2-DCE, VC	Funnel and Gate	$350 K	Fe^0 Iron Filings	treatment efficiencies ranged from 65-99%; natural attenuation reducing concentrations before water reaches canal	Barry Kellems Tel: 206-324-9530 Fax: 206-328-5581 Email: barry.kellems@ hartcrowser.com
Former Manufacturing Site	Fairfield, NJ		1,1,1-TCA, PCE, TCE	Continuous Trench	$875 K	Fe^0	concentrations at center of plume decreased to near detection levels; pH increased, Eh decreased	Stephen Tappert Tel: 973-383-2500 Fax: 973-579-0025 Email: stappert@ trccos.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Haardkrom Site	Kolding, Denmark	1999	TCE, CR^{+6}	Continuous Trench	$358 K	Fe^0	design not effective in controlling contaminants along PRB; working on resolving problems	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Industrial Site	SC	1997	TCE, *cis* 1,2-DCE, VC	Continuous Trench	$400 K	Fe^0	consistent decrease in concentration levels downgradient; upgradient levels remain variable	Steven Schroeder Tel: 864-281-0030 Fax: 864-287-0288 Email: steve.schroeder@rmtinc.com
Industrial Site	Coffeyville, KS	1996	TCE, 1,1,1-TCA	Funnel and Gate	$400 K	Fe^0	concentration in iron zone below MCLs; no determination made of groundwater velocity through system	Greg Somermeyer Tel: 970-493-3700 Fax: 970-493-2328 Email: gsomermeyer@thermoretec.com
Industrial Site	Belfast, Northern Ireland	1995	TCE, *cis* 1,2-DCE	Slurry Wall Funnel *in situ* reaction vessel	$375 K	Fe^0	overall 99.7% reduction in contaminant levels through reaction vessel	Dale Haig Tel: 44-115-9456544 Fax: 44-115-9456540 Email: Dhaigh@GOLDER.com
Intersil Semiconductor Site	Sunnyvale, CA	1995	TCE, *cis* 1,2-DCE, VC, Freon113®	Funnel and Gate	$1 M	Fe^0	concentrations below cleanup goals in wells within wall; groundwater contained on site until mounding dissipates	Carol Yamane Tel: 415-434-9400 Fax: 415-434-1365 Email: cyamane@geomatrix.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Kansas City Plant	Kansas City, MO	1998	*cis* 1,2-DCE, VC	Continuous Trench	$1.5 M	Fe^0	samples from wells north and south of PRB indicate inconsistencies in levels; high zone of conductivity; PRB rendered ineffective upon ordered resumption of pumping well	Steve Cline Tel: 423-241-3957 Fax: 423-576-8646 Email: qc2@ornl.gov
Lowry Air Force Base	CO	1995	TCE	Funnel and Gate	$530 K	Fe^0	chlorinated hydrocarbons degraded within first ft of wall; all analytes degraded 2 ft into wall	William A. Gallant Tel: 303-452-5700 Fax: 303-452-2336 Email: gallabil@versar.com
Rocky Flats Environmental Technology Site (East Trenches Plume)	Golden, CO	1999	TCE, PCE, Carbon tetrachloride, Chloroform, *cis* 1,2-DCE, Methylene chloride	Reaction Vessels	$1.3 M	Fe^0 and Pea Gravel	except for methylene chloride, concentrations routinely non-detectable	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov
Rocky Flats Environmental Technology Site (Mound Site)	Golden, CO	1998	VC, 1,1-DCE, *cis* 1,2-DCE, TCE, PCE, U, Chloroform Carbon tetrachloride,	Reaction Vessels	$590 K	Fe^0	concentrations non-detectable in effluent samples; U concentration below stream standards; low cost, effective technology	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Full Scale								
Seneca Army Depot Activity	Romulus, NY	1999	TCE, *cis* 1,2-DCE	Continuous Trench	$450 K	Fe^0 and Sand	100% removal of TCE; removal of *cis* 1,2-DCE less than expected - will require added iron	Michael Duchesneau Tel: 781-401-2492 Fax: 781-401-2492 Email: michael.duchesneau@parsons.com
Shaw Air Force Base	Sumter, SC	1998	TCA, DCA, DCE, VC	Continuous Wall Trenches	$1.065 M	Fe^0, Iron Filings	significant reductions in TCA, DCA and DCE; VC increases at PRB, but biodegrades sufficiently	Richard Roller Tel: 803-895-9991 Fax: 803-895-5103 Email: richard.roller@shaw.af.mil
Somersworth Sanitary Landfill Superfund Site	Somersworth, NH	2000	PCE, TCE, *cis* 1,2-DCE, VC	Continuous Wall	$2.2 M	Fe^0 and Sand	groundwater monitoring indicates PRB working as designed	Tom Krug Tel: 519-822-2230 Fax: Email: tkrug@geosyntec.com
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Watervliet Arsenal	Watervliet, NY	1999	VOCs	Continuous Trench	$391 K	Fe^0 and Concrete Sand	monitoring indicates walls meeting projected goals	Grant A. Anderson Tel: 410-962-6645 Fax: 410-962-7731 Email: grant.a.anderson@nab02.usace.army.mil

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Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
Alameda Point	Alameda, CA	1997	*cis* 1,2-DCE, VC, TCE, BTEX	Funnel and Sequenced Gate		Fe^0, O	excellent results for VOCs at high concentrations; almost complete degradation at low concentrations; biosparge zone supported aerobic degradation of VC & *cis* 1,2-DCE	Mary Morkin Tel: 925-943-3034 ext. 203 Fax: 925-943-2366 Email: mmorkin@geosyntec.com
Area 5, Dover Air Force Base	Dover, DE	1998	PCE, TCE, DCE	Funnel and Gate	$800 K	Fe^0	PRB functioned as designed, capturing plume and reducing contaminants below target levels; iron zone more efficient than pyrite zone in removing DO	Alison Lightner Tel: 850-283-6306 Fax: 850-283-6064 Email: alison.lightner@tyndall.af.mil
Borden Aquifer	Ontario, Canada	1991	TCE, PCE	Continuous Trench	$30 K (reactive material and labor donated)	Fe^0	PRB reduced TCE by 90% and PCE by 86%; low calcium carbonate after 5 years indicates at least another 5 yrs of operation	Stephanie F. O'Hannesin Tel: 519-746-2204 Ext. 235 Fax: 519-764-2209 Email: sohannesin@eti.com
Cape Canaveral Air Station	Cape Canaveral, FL	1998	TCE, DCE, VC	Continuous Walls with Overlapping Panels	$809 K	Fe^0		Jerry Hansen Tel: 210-536-4353 Fax: 210-536-4330 Email: jerry.hansen@hqafcee.brooks.af.mil

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
DuPont	Oakley, CA		Carbon tetrachloride, Chloroform, Freon 11, Freon 113	Vertically Oriented Hydraulic Fracturing	$1.15 M	Granular cast iron	No problems except at recovering an intact core of emplaced PRB at 120 ft.; alternative methods being explored	Stephen H. Shoemaker Tel: 704-362-6638 Fax: 704-362-6636 Email: Stephen.H. Sheomaker@ USA.DuPont.com
DuPont	Kinston, NC	1999	TCE	Continuous Jetted Wall with Overlapping Panels	$200 K	Granular Fe^0	TCE mass reduced by 95%; 13 of 16 geoprobe locations indicate non-detectable levels of TCE; negotiating with state to shut down pump & treat system affecting velocity through PRB	Richard C. Landis Tel: 302-892-7452 Fax: 302-892-7641 Email: Richard.C.Landis@ USA.DuPont.com
Launch Complex 34, Cape Canaveral Air Force Station	Cape Canaveral, FL	1999	TCE, *trans* DCE, *cis* 1,2-DCE	Vibrating Caissons filled with Fe^0, followed by Deep Soil Mixing	$220 K	Fe^0	TCE and daughter products non-detectable within wall and declining in downstream wells, except for VC	Debra R. Reinhart Tel: 407-823-2156 Fax: 407-823-5483 Email: reinhart@ mail.ucf.edu
Massachusetts Military Reservation CS-10 Plume	Falmouth, MA	1998	PCE, TCE	Hydraulic Fracturing	$160 K	Fe^0		Robert W. Gillham Tel: 519-888-4658 Fax: 519-746-1829 Email: rwgillha@ sciborg.uwaterloo.ca

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Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
Moffet Federal Airfield	Mountain View, CA	1996	TCE, *cis* 1,2-DCE, PCE	Funnel and Gate	$540 K	Fe^0	principal contaminants reduced to below maximum levels within 2-3 ft of gate	Chuck Reeter Tel: 805-982-0469 Fax: 805-982-4304 Email: creeter@fesc.navy.mil
SAFIRA Test Site	Bitterfeld, Germany	1999	Benzene, MCB, o-DCB, p-DCB, TCE, *cis* 1,2-DCE, *trans* 1,2-DCE	Vertical Well Shafts and Horizontal Wells	11 M Deutsh Mark	Hydrogen-activation Systems with and without Paladium Catalyst	pilot tests indicate promising results; project ends 6/02, expected to be extended	Dr. Holger Weiss Tel: +49-341-235-2060 Fax: +49-341-235-2126 Email: weiss@pro.ufz.de
Savannah River Site TNX Area	Aiken, SC	1997	TCE, *cis* 1,2-DCE, CT, Nitrate	GeoSiphon Cell	$119 K (phase I)	Fe^0	Phases I & II indicate that changing siphon line accelerates flow rates inducing accelerated cleanup; use limited to areas of shallow ground water	Mark Phifer Tel: 803-725-5222 Fax: 803-725-7673 Email: mark.phifer@srs.gov
U.S. Coast Guard Support Center	Elizabeth City, NC	1996	Cr^{+6}, TCE	Continuous Trench	$675 K	Fe^0	Cr continues to be removed as expected; TCE, *cis* 1, 2-DCE, and VC below MCL for most wells; plume seems to have dipped after wall installation	Robert W. Puls Tel: 580-436-8543 Fax: 580-436-8706 Email: puls.robert@epa.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Chlorinated Solvents - Pilot Scale								
X-625 Groundwater Treatment Facility, Portsmouth Gaseous Diffusion Plant	Piketon, OH	1996	TCE	Horizontal Well		Fe^0	TCE reduced to below 5µg/L; hydraulic conductivity of iron media reduced due to mineral precipitation	Thomas C. Houk Tel: 614-897-6502 Fax: 614-897-3800 Email: uk9@ornl.gov
Metals & Inorganics - Full Scale								
100D Area, Hanford Site	Hanford, WA	1997	Cr^{+6}	Injection	$480 K (wall- $5 M)	Sodium dithionite	aqueous chromate reduced below 8µg/L; plan calls for remaining cells to be treated	Jonathan S. Fruchter Tel: 509-376-3937 Fax: 509-372-1704 Email: john.fruchter@pnl.gov
Chalk River Laboratories	Ontario, Canada	1998	Sr-90	Wall and Curtain	$300 K	Clinoptilolite (zeolite)	PRB retained 100% of contaminant since installed; leakage beneath steel cut-off wall compensated for by controlling flow	David R. Lee Tel: 613-584-8811 Ext. 4710 Fax: 613-584-1221 Email: leed@aecl.ca
Former Mill Site	Monticello, UT	1999	U, As, Mn, Se, V	Funnel and Gate	$800 K	Fe^0	PRB effective in reducing contaminants; concentration of iron increases as groundwater passes through the PRB	Don Metzler Tel: 970 248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com

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Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Metals & Inorganics - Full Scale								
Haardkrom	Kolding, Denmark	1999	TCE, CR^{+6}	Continuous Trench	$358 K	Fe^0	design not effective in controlling contaminants along PRB; working on resolving problems	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Nickel Rim Mine Site	Sudbury, Ontario, Canada	1995	Ni, Fe, Sulfate	Cut and Fill	$30 K	Organic Curtain	decrease in concentration of all contaminants; PRB converted aquifer from acid-producing to acid-consuming	David W. Blowes Tel: 519-888-4878 Fax: 519-746-5644 Email:
Rocky Flats Environmental Technology Site (Solar Ponds Plume)	Golden, CO	1999	Nitrate, U	Reaction Vessels	$1.3 M	Fe^0 and Wood Chips	although system does not collect and treat all groundwater in plume, surface water standards are met in nearby creek	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov
Tonolli Superfund Site	Nesquehoning, PA	1998	Pb, Cd, As, Zn, Cu	Continuous Trench		Limestone		John Banks Tel: 215-814-3214 Fax: 215-814-3002 Email: banks.john-d@epa.gov
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Metals & Inorganics - Pilot Scale								
Bodo Canyon	Durango, CO	1995	As, Mo, Se, U, V, Zn	Collection Drain Piped to Underground Treatment System	$380 K	Fe^0, Copper Wool, Steel Wool	only 1 of 4 PRBs ran for 3 years reducing concentrations of wide variety of contaminants	Don Metzler Tel: 970-248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com
U.S. Coast Guard Support Center	Elizabeth City, NC	1996	Cr^{+6}, TCE	Continuous Trench	$675 K	Fe^0	Cr continues to be removed as expected; TCE, *cis* 1,2-DCE, and VC below MCL for most wells; plume seems to have dipped after wall installation	Robert W. Puls Tel: 580-436-8543 Fax: 580-436-8706 Email: puls.robert@epa.gov
Fuel Hydrocarbons - Pilot Scale								
Alameda Point	Alameda, CA	1997	*cis* 1,2-DCE, VC, TCE, BTEX	Funnel and Sequenced Gate		Fe^0, O	excellent results for VOCs at high concentrations; almost complete degradation at low concentrations; biosparge zone supported aerobic degradation of VC & *cis* 1,2-DCE	Mary Morkin Tel: 925-943-3034 ext. 203 Fax: 925-943-2366 Email: mmorkin@geosyntec.com

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Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Fuel Hydrocarbons - Pilot Scale								
East Garrington	Alberta, Canada	1995	BTEX	Trench and Gate	$67.2 K	O_2	plume captured and treated; no contaminants detected off-site	Marc Bowles Tel: 403-247-0200 Fax: 403-247-4811 Email: mbowles@calgary.komex.com
Nutrients - Full Scale								
Y-12 Site, Oak Ridge National Laboratory	Oak Ridge, TN	1997	U, Tc, Nitric acid	Funnel and Gate, Continuous Trench	$1 M	Fe^0	efficient and cost-effective method of removing this combination of contaminants	Baohua Gu Tel: 423-574-7286 Fax: 423-576-8543 Email: b26@ornl.gov
Nutrients - Pilot Scale								
Savannah River Site TNX Area	Aiken, SC	1997	TCE, *cis* 1,2-DCE, Nitric acid, Carbon tetrachloride	GeoSiphon Cell	$119 K (phase I)	Fe^0	Phases I & II indicate that changing siphon line accelerates flow rates inducing accelerated cleanup; use limited to areas of shallow ground water	Mark Phifer Tel: 803-725-5222 Fax: 803-725-7673 Email: mark.phifer@srs.gov
Radionuclides - Full Scale								
Former Mill Site	Monticello, UT	1999	U, As, Mn, Se, V	Funnel and Gate	$800 K	Fe^0	PRB effective in reducing contaminants; concentration of iron increases as groundwater passes through the PRB	Don Metzler Tel: 970 248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Radionuclides - Full Scale								
Rocky Flats Environmental Technology Site (Solar Ponds Plume)	Golden, CO	1999	Nitrate, U	Reaction Vessels	$1.3 M	Fe^0 and Wood Chips	although system does not collect and treat all groundwater in plume, surface water standards are met in nearby creek	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov
Y-12 Site, Oak Ridge National Laboratory	Oak Ridge, TN	1997	U, Tc, Nitric acid	Funnel and Gate, Continuous Trench	$1 M	Fe^0	efficient and cost-effective method of removing this combination of contaminants	Baohua Gu Tel: 423-574-7286 Fax: 423-576-8543 Email: b26@ornl.gov
Radionuclides - Pilot Scale								
Bodo Canyon	Durango, CO	1995	As, Mo, Se, U, V, Zn	Collection Drain Piped to Underground Treatment System	$380 K	Fe^0, Copper Wool, Steel Wool	only 1 of 4 PRBs ran for 3 years reducing concentrations of wide variety of contaminants	Don Metzler Tel: 970-248-7612 Fax: 970-248-6040 Email: d.metzler@gjo.doe.com
Fry Canyon Site	Fry Canyon, UT	1997	U	Funnel and Gate	$170 K	Fe^0, AFO, PO_4	3 barriers each using different media - Fe^0 and PO_4 remove >99% of incoming U; AFO PRB reached chemical break-through	David N. Naftz, PhD Tel: 801-975-3389 Fax: 801-975-3424 Email: dlnaftz@usgs.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Other Organic Contaminants - Full Scale								
Former Industrial Site	Brunn am Gebirge, Austria	1999	PAH, Phenols, BTEX, HC, TCE, *cis* 1,2-DCE	Adsorptive Reactors with Hydraulic Barrier	$750 K	Activated Carbon	effective in forcing groundwater to enter PRB; level of contamination varies with groundwater level	Peter Niederbacher Tel: 43-2243-22844 Fax: 43-2243-22843 Email: niederbacher@geol.at
Marzone Inc./ Chevron Chemical Co.	Tifton, GA	1998	BHC, *beta*-BHC, DDD, DDT, xylene, ethylbenzene, lindane, methyl parathion	Funnel and Gate	$750 K	Activated carbon	concentrations for effluent have been below detection levels	Annie Godfrey Tel: 404-562-8919 Fax: 404-562-8896 Email: godfrey.annie@epa.gov
Rocky Flats Environmental Technology Site (East Trenches Plume)	Golden, CO	1999	TCE, PCE, Carbon tetrachloride, Chloroform, *cis* 1,2-DCE, Methylene chloride	Reaction Vessels	$1.3 M	Fe^0 and Pea Gravel	except for methylene chloride, concentrations routinely non-detectable	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov
Rocky Flats Environmental Technology Site (Mound Site)	Golden, CO	1998	VC, 1,1-DCE, *cis*-1,2-DCE, TCE, PCE, Chloroform, U Carbon tetrachloride	Reaction Vessels	$590 K	Fe^0	concentrations non-detectable in effluent samples; U concentration below stream standards; low cost, effective technology	Annette Primrose Tel: 303-966-4385 Fax: 303-966-5180 Email: Annette.Primrose@rfets.gov

Name	Location	Installation Date	Contaminants	Construction Type	Design/ Installation Cost	Reactive Media	Results	Point of Contact
Other Organic Contaminants - Full Scale								
Vapokon Petrochemical Works	Sonderso, Denmark	1999	PCE, TCE, TCA, DCA, DCE, DCM, BTEX	Funnel and Gate	$940 K	Fe^0	most compounds degraded at expected rates; daughter products degraded in anoxic plume; upgradient concentrations increased possibly due to low velocities	Peter Kjeldsen Tel: +45 45251561 Fax: +45 45932850 Email: pk@er.dtu.dk
Watervliet Arsenal	Watervliet, NY	1999	VOCs	Continuous Trench	$391 K	Fe^0 and Concrete Sand	monitoring indicates walls meeting projected goals	Grant A. Anderson Tel: 410-962-6645 Fax: 410-962-7731 Email: grant.a.anderson@nab02.usace.army.mil
Other Organic Contaminants - Pilot Scale								
SAFIRA Test Site	Bitterfeld, Germany	1999	Benzene, MCB, o-DCB, p-DCB, TCE, *cis* 1,2-DCE, *trans* 1,2-DCE	Vertical Well Shafts and Horizontal Wells	11 M Deutsch Mark	Hydrogen-activation Systems with and without Paladium Catalyst	pilot tests indicate promising results; project ends 6/02, expected to be extended	Dr. Holger Weiss Tel: +49-341-235-2060 Fax: +49-341-235-2126 Email: weiss@pro.ufz.de

Lessons Learned

The following lessons learned are based on a review of all of the site profiles. They are organized according to the major phases of the remediation process. Visit ***www.rtdf.org/public/permbarr/prbsumms/default.cfm*** and check the profiles indicated in parentheses for more detailed information.

Site Characterization

At least 5 sites reported that it is important to conduct extensive characterization in the pre-planning phase. Specifically, it is important to detail the hydrogeology (Kansas City, Fry Canyon), topography (Fry Canyon), seasonal conditions (Oak Ridge), and presence of or proximity to potential obstacles (Tonolli, Chalk River).

Planning and Coordination

Several sites reported that careful planning (F.E. Warren) and coordination are critical to the success of a PRB project. Planning factors that were addressed include site layout, sequencing of the work, and selection and placement of equipment and materials (Brunn am Gebirge, Fry Canyon). Three sites addressed the issue of structuring the project so that the methods and design are flexible enough to respond to changing conditions (Chalk River, Bodo Canyon, Tonolli).

At this stage, it is also important to coordinate plans with state agencies (Fairfield, NJ) and subcontractors (Chalk River). This ensures a better understanding of the project by all interested parties.

Design and Construction

Groundwater Geochemistry and Flow

Groundwater geochemistry (FHWA) and velocity/flow are common concerns during the design and construction phases.

- Groundwater modeling is recommended as a design tool during this stage in order to avoid potential flaws (Watervliet).
- Awareness of the geochemistry can include the impact of high concentrations of inorganic compounds (Copenhagen) or affect of O_2 on microbial activity (Brunn am Gebirge).
- Groundwater velocity/flow can impact the time required to complete flushing (Industrial Site, SC) or the wall design and efficiency (Watervliet).
- The variability of velocities can affect monitoring and incomplete treatment (Seneca).
- When hydraulic conditions change seasonally, groundwater migration patterns may change (Oak Ridge).
- Reduced hydraulic conductivity of bedrock fractures coupled with shallow gradients in the vicinity of a PRB may result in a diversion of groundwater flow (Caldwell).
- Gravity flow may be considered the most effective when the natural contours of a hillside can be utilized (Rocky Flats), but groundwater at one site was reported to have moved laterally through reactive media before it moved downgradient (Monticello).

Reactive Media

Some sites performed tests comparing a variety of reactive media (Bodo Canyon, Fry Canyon) to the most commonly used media, Fe^0. A number of sites had problems with hydraulic conductivity and incomplete treatment of contaminants attributed to the concentration (Seneca) and amount or distribution of reactive media (Chalk River, Caldwell).

Other Media or Materials

Other media or materials in or around the PRB have been found to affect PRBs.

- A pea gravel zone upgradient of a PRB can result in precipitation of minerals and partial treatment of target contaminants (Intersil).
- The addition of phosphorous can increase the degradation rate (East Garrington).
- The presence of guar can increase biological activity (Oak Ridge). Guar gum gel introduced at low temperature and high pH may slow enzymatic degradation after placement in PRB (Caldwell).
- The use of bentonite slurry may make it difficult to control movement of slurry (Fry Canyon).
- The presence of chloride is not a good indication of effectiveness of dechlorination for all sites (Industrial Site, SC).

Tools and Construction Methods

The following observations were made regarding tools and construction methods:

- The use of appropriate tools and construction methods allow for better surfaces and flow patterns for groundwater (Fry Canyon).
- The system should be constructed to allow for gas venting (Bodo Canyon, Marzone).
- The length of trench box should be minimized to reduce slope failure (Rocky Flats).
- Backfill specifications should be rigorously followed (Rocky Flats).

Other Considerations

Other design and construction considerations might include:

- The impact of other remediation technologies. For example, groundwater flow and plumes at a site that has been subjected to pump and treat need time to return to non-pumping conditions (Kansas City).
- Daughter products may affect the width and retention time required to treat groundwater (Shaw).
- A funnel and gate system was selected at one site because it offered less impact on the surrounding community (Marzone).
- In placing monitoring wells, consideration should be given to no-flow areas (Fry Canyon) and the need for additional wells in areas with unanticipated variability in contaminant concentrations and groundwater velocity (Seneca).

Operations and Maintenance

Monitoring and testing of groundwater conditions, contaminants, reactive media, and materials during and after construction help ensure that the systems operate effectively. Therefore, it is important that operations and maintenance be carefully considered during site characterization, planning and design (Rocky Flats).

Cost

Observations on PRB costs include:

- Reaction vessels cost about 1/4 of a baseline pump and treat system (Rocky Flats).
- A continuous trench system is a cost effective installation with a high degree of confidence (Industrial Site, SC).
- The bio-polymer construction method is effective and economical for a large PRB (Somersworth).
- A wall and curtain construction performs well and involves relatively low cost for routine monitoring and adjustment (Chalk River).

Field Results From the Use of a Permeable Reactive Wall. O. Kiilerich, J. W. Larsen, and C. Nielsen. Paper on Copenhagen Freight Yard, Denmark, Site presented at the Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 2000.

Environmental Cleanup Plan and Quality Project Plan, Spill Site 7 Interim Remedial Action. U.S. Air Force and Montgomery Watson. Spill Site 7 Interim Remedial Action, F.E. Warren Air Force Base, Cheyenne, WY, Jan. 1999.

Quarterly Monitoring Reports. U.S. Air Force and Earthtech. Quarterly Monitoring Reports from May 2000 - Feb. 2001 for F.E. Warren Air Force Base, Cheyenne, WY.

"1,200-Foot Permeable Reactive Barrier in Use at the Denver Federal Center." Alex Caruana. *Ground Water Currents*, No. 27, Mar. 1998. (Available through http://clu-in.org)

Numerical Simulation of Geochemical Reactions at a Zero-Valent Iron Wall Remediation Site. G.P. Curtis, P.B. McMahon. 1998 American Geophysical Union Spring Meeting, 26-29 May, Boston, MA, 1998.

Successful Remediation of Solvent Contaminated Ground Water using a Funnel and Gate Constructed by Slurry Trench Methods (Industrial Site Seattle, WA). Steven Day, et al. Presented at 2001 International Containment and Remediation Technology Conference and Exhibition, June 10-13, 2001, Orlando, FL.

"Business and Technical Objectives Not A Barrier - Meet the Wall" (Industrial Site, Fairfield, NJ). Stephen E. Tappert, Leigh E. Finn. *Massachusetts Environment*, Dec. 1998.

Permeable Reactive Barrier Installation-Fairfield, NJ. Presentation Materials, RTDF Permeable Reactive Barriers Action Team Meeting, Nov. 17-19, 1998.

Demonstration Program on Reactive Barrier Technologies Using Zero-Valent Iron (Haardkrom, Denmark). P. Kjeldsen and I. A. Fuglsang. FZK/TNO International Conference on Contaminated Soil, Leipzig, Germany, Sept. 18-22, 2000.

"Reactive Treatment Zones: Concepts and a Case History." Stephan A. Jefferis, Graham H. Norris. *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater-Phase III. Session on Treatment Walls and Permeable Reactive Barriers*, No. 229. 66-76. EPA/542/R-98/003, 1998.

"Reactive Barrier System Reduces TCE in Northern Ireland Installation." Dale Haigh. *Water Online*, Aug. 1997. (Available at http://news.wateronline.com/case-studies/CS707292.html)

The Feasibility of Permeable Reactive Barriers for in Situ Groundwater Treatment: the Sunnyvale "Iron Wall" and Beyond. S.D. Warner. Subsurface Barrier Technologies Conference: Engineering Advancements and Application Considerations for Innovative Barrier Technologies, Tucson, AZ, Jan. 1998.

"Considerations for Monitoring Permeable Ground-Water Treatment Walls." Scott D. Warner, Carol L. Yamane, John D. Gallinatti, Deborah A. Hankins. *Journal of Environmental Engineering*, 124:6, 524-529, 1998.

"Technical Update: the First Commercial Subsurface Permeable Reactive Treatment Zone Composed of Granular Zero-Valent Iron." Scott D. Warner, Carol L. Yamane, N.T. Bice, F.S. Szerdy; J. Vogan, D.W. Major,

D.A. Hankins. *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*, Battelle Press, Columbus, OH. 145-150, 1998.

Final, Reactive Wall Demonstration Project Technical Report, Lowry AFB, Colorado. Versar, Inc. / Dames & Moore. Air Force Center for Environmental Excellence, Brooks AFB, TX, Sept. 1997. (Available through Defense Technical Information Center or National Technical Information Center.)

Final Proposed Action Memorandum For The East Trenches Plume (Rocky Flats Environmental Technology Site). Rocky Mountain Remediation Services, LLC (RMRS). RF/RMRS-98-258, 1999.

Final Mound Site Plume Decision Document (Rocky Flats Environmental Technology Site). U.S. Department of Energy, Rocky Flats Environmental Technology Site. RF/RMRS-97-024, Sept. 1997.

Feasibility Memorandum for Groundwater Remediation Alternative Using Zero-Valent Iron Reactive Wall at the Ash Landfill, Seneca Army Depot Activity, Romulus, New York. Parsons Engineering Science, Inc. Ash Landfill, Seneca Army Depot Activity, Romulus, NY, Aug. 2000.

Bio-Polymer Construction and Testing of a Zero-Valent Iron PRB at the Somersworth Landfill Superfund Site. T.A. Krug, K. Berry-Spark, M. Monteleone, C. Bird, C. Elder, R. Focht. Proceeding of the 2001 International Containment & Remediation Technology Conference and Exhibition, Orlando, FL, June 2001.

"Permeable Reactive Barriers for In Situ Treatment of Chlorinated Solvents" (Dover AFB, Area 5). U.S. Environmental Protection Agency. *NATO/CCMS Pilot Study: Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III) 1998 Annual Report*, No. 228. 36-37. EPA542-R-98-002, 1998 (Available at http://www.clu-in.org/partner1.htm).

"Long-Term Performance of an *In Situ* 'Iron Wall' for Remediation of VOCs" (Borden Aquifer). S. F. O'Hannesin, R.W. Gillham. *Ground Water*. 36:1, 164-170, 1998.

Scale-up of Zero-Valent Iron Permeable Treatment Wall Design Parameters (Cape Canaveral Air Station). D.R. Reinhart, J.W. Quinn; C.A. Clausen; M. Chopra; C. Geiger; N. Ruiz; S. Burwinkel. WEFTEC 1998: Remediation of Soil and Groundwater Symposium: Treatment Process and Developments, 1998.

Permeable Reactive Barrier Installation and TCE Source Treatment Using Jetting (DuPont Site, Kinston, NC). Stephen Shoemaker, et. al. Presented at 2001 Solid/Hazardous Waste Conference, Gatlinburg, TN, May 9-11, 2001.

Installation of a Field-Scale Permeable Reactive Wall Using Deep Soil Mixing (Launch Complex 34, Cape Canaveral Air Force Station). D. R. Reinhart, M. B. Chopra, S. Burwinkel, and J. Quinn. 4th Annual Florida Remediation Conference, Orlando, FL, Nov. 10-11, 1998.

Scale-Up Of Zero-Valent Iron Permeable Treatment Wall Design Parameters (Launch Complex 34, Cape Canaveral Air Force Station). D. R. Reinhart , J W. Quinn, C. A. Clausen, M. B. Chopra, C. Geiger, N. Ruiz, S. Burwinkel. Proceedings of the Water Environment Federation Conference, Orlando, FL, Oct. 5-8, 1998.

Emplacement of Zero-Valent Iron for Remediation of Deep Containment Plumes (Massachusetts Military Reservation). D.W. Hubble, R.W. Gillham; J.A. Cherry. 1997 International Containment Technology Conference, St. Petersburg, FL. 872-878. CONF-970208-Proc. DE98001967, 1997.

Permeable Reactive Wall Remediation of Chlorinated Hydrocarbons in Groundwater: NAS Moffett Field, Mountain View, California. Charles Reeter, Arun Gavaskar, Neeraj Gupta, Bruce Sass. After the Rain Has Fallen: 2nd International Water Resources Engineering Conference, 3-7 Memphis, TN, August 1998. American Society of Civil Engineers, Reston, VA. 153-158, 1998.

SAFIRA Abstracts. H. Weiß, H. Rijnaarts, S. Staps, P. Merkel. Abstracts of the workshop of Nov. 17-18, 1999 at Bitterfeld /Germany, UFZ Bericht Nr. 23/2000.

Design and Installation of an In Situ Porous Reactive Wall for Treatment of Cr(VI) and Trichloroethylene in Groundwater (U.S. Coast Guard Support Center, Elizabeth City, NC). T.A. Bennett, D.W. Blowes, R.W. Puls, R.W. Gillham, C.J. Hanton-Fong, C.J. Ptacek, S.F. O'Hannesin, J.L. Vogan. The 213th National Meeting of the American Chemical Society, San Francisco, CA. Preprint Extended Abstracts, Division of Environmental Chemistry. 37:1, 243-245, 1997.

The X-625 Groundwater Treatment Facility: A Field-Scale Test of Trichloroethylene Dechlorination Using Iron Filings for the X-120/X-749 Groundwater Plume (Portsmouth Gaseous Diffusion Plant). L. Liang, O.R. West, N.E. Korte, et al. ORNL/TM--13410. DE98007047, 1997.

"Injection Process Filters Contaminants" ((Handford Site). *Waste Treatment Technology News*, 13:11, Aug. 19, 1998.

"Wall-and-Curtain for Passive Collection/ Treatment of Contaminant Plumes" (Chalk River Laboratories). David R. Lee, David J.A. Smyth, Steve G. Shikaze, Robin Jowett, Dale S. Hartwig, Claire Milloy. *Designing and Applying Treatment Technologies: Remediation of Chlorinated and Recalcitrant Compounds*. Battelle Press, Columbus, OH. 77-84, 1998.

"Monticello Permeable Reactive Barrier Project." U.S. Environmental Protection Agency. *Groundwater Currents*, Issue 36, June 200.

"Permeable Reactive Barrier Cleans Superfund Site" (Monticello). H. Kreuzer. *Pollution Engineering*, pp 12-14, June 2000.

Treatment of Acidic, Mine-Associated Discharge to a Lake Using a Permeable Reactive Barrier (Nickel Rim Mine). J.G. Bain, D.W. Blowes, S.G. Benner. 1998 American Geophysical Union Spring Meeting, Boston, MA, 1998.

Final Solar Ponds Plume Decision Document (Rocky Flats Environmental Technology Site). Rocky Mountain Remediation Services, LLC (RMRS). RF/RMRS-98-286.UN, 1999.

Spectroscopic Studies To Determine Uranium Speciation in ZVI Permeable Reactive Barrier Materials from the Oak Ridge Reservation, Y-12 Plant Site and Durango, CO PeRT Wall *C*. L.J. Matheson, W.C. Goldberg. Supplement to EOS, Transactions, Fall Meeting, American Geophysical Union, Washington, D.C., 1999.

The East Garrington Trench and Gate System: It Works. M. Bowles, L.R. Bentley, J. Barker, D. Thomas, D. Granger, H. Jacobs, S. Rimbey, B. Hoyne. The 6th Annual Conference on Groundwater and Soil Remediation, Montreal, Ont. Canada, June 1997.

"Reactive Barriers for Uranium Removal" (Fry Canyon Site). Ed Feltcorn, Randy Breeden. *Ground Water Currents*, No. 26, December 1997. (Available through http://clu-in.org)

Electronic Resources

Remediaton Technologies Development Forum (RTDF), ***http://www.rtdf.org/***

Strategic Environmental Research and Development Program (SERDP), ***http://www.serdp.org/***

Environmental Security Technology Certification Program (ESTCP), ***http://www.estcp.org/***

U.S. EPA/Kerr Lab - USCG Site, Elizabeth City, North Carolina, ***http://www.epa.gov/ada/research/eliz.html***

U.S. DOE Durango, Colorado Site, ***http://www.doegjpo.com/perm-barr/projects/durango.htm***

AATDF Canadian Forces Base Borden (Canada) and NAS Alameda (CA) sites, ***http://www.ruf.rice.edu/~aatdf/pages/passive.htm***

USGS Fry Canyon (UT) Site, ***http://wwwdutslc.wr.usgs.gov/fry/fry.html***

Interstate Technology and Regulatory Cooperation (ITRC) Working Group Reports, ***http://www.itrcweb.org/common/content.asp?en=TA549175&sea=Yes&set=Both&sca=Yes&sct=Long***

EnviroMetal Technologies Inc. (Ont., Canada) Field Reports, ***http://www.eti.ca/***

United Kingdom Permeable Reactive Barrier Network (PRB-Net), ***http://www.prb-net.org/***

RUBIN (Reinigungswände und -barrieren im Netzwerkverbund), ***http://www.rubin-online.de/***

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FINAL REPORT—PERMEABLE TREATMENT WALL EFFECTIVENESS MONITORING, NEVADA STEWART MINE SITE

MINE WASTE TECHNOLOGY PROGRAM ACTIVITY III, PROJECT 39

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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.

Sally Gutierrez, Director
National Risk Management Research Laboratory

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Abstract

This report summarizes the results of Mine Waste Technology Program (MWTP) Activity III, Project 39, *Permeable Treatment Wall Effectiveness Monitoring Project*, implemented and funded by the U.S. Environmental Protection Agency (EPA) and jointly administered by EPA and the U.S. Department of Energy (DOE). This project addressed EPA's technical issue of Mobile Toxic Constituents – Water through a field demonstration of a water treatment process based on the use of Apatite II™ treatment medium at a remote, inactive underground mine.

This project was undertaken to demonstrate the effectiveness of Apatite II™ (cleaned fishbone) to treat metal-laden water flowing from an abandoned mine. The Nevada Stewart Mine (NSM), located in the Coeur d'Alene Basin near Pinehurst, Idaho, was selected as the site for the field demonstration. The NSM is part of the Bunker Hill Mining and Metallurgical Complex, which was placed on the National Priorities List (NPL) for Superfund cleanup of heavy metals, mainly zinc, lead, and cadmium.

To determine the effectiveness of the apatite material, a permeable treatment wall system [also referred to as the Apatite™ II Treatment System (ATS)] was constructed by MSE Technology Applications, Inc. (MSE) using funds provided by DOE. Subsequently, approximately 17 gallons per minute of the NSM adit discharge was directed through the ATS. The gravity fed ATS was designed and constructed using a baffled, up-flow system that contained a 3:1mixture by volume of apatite and gravel. The composition and quality of the influent and effluent water from the system was monitored by MSE using funding provided by the MWTP on a monthly basis for a 2-year period.

After evaluating the results from the ATS, it was concluded that the system effectively attenuated zinc, iron, manganese, lead, and cadmium as substantiated by the decrease in aqueous phase concentrations between the influent and effluent waters, and increases in those constituents within the solid phase media contained in the system's three treatment tanks. The results from the ATS showed that a combination of mechanisms removed attenuated the metals from the NSM adit discharge. The only removal mechanism verified in the ATS was sulfide mineral precipitation. Other likely or possible removal mechanisms include phosphate mineral precipitation, adsorption, and cation substitution. Results from the microscopy, geochemical modeling, and data evaluation revealed that sulfide mineral precipitation was the main removal mechanism for zinc, forming a zinc sulfide.

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Acronyms and Abbreviations

Ag	silver
Al	aluminum
As	arsenic
ATS	Apatite II™ Treatment System
Au	gold
Be	beryllium
BEIPC	Basin Environmental Improvement Project Commission
Ca	calcium
Cd	cadmium
CdS	cadmium sulfide
CFI	Center for Innovation
CLP	Contract Laboratory Program
Co	cobalt
Cr	chromium
CRDL	contract required detection limit
Cu	copper
DO	dissolved oxygen
DOE	U.S. Department of Energy
DS	downstream
EDX	energy dispersive X-ray
EPA	U.S. Environmental Protection Agency
Fe	iron
FeS	iron sulfide
Golder	Golder Associates Inc.
gpm	gallons per minute
Hg	mercury
IAG	Interagency Agreement
ICP	inductively coupled plasma
ICP-ES	inductively coupled plasma emission spectrometer
IDEQ	Idaho Department of Environmental Quality
IDL	instrument detection limit
K	potassium
lb	pound
lb/mo	pounds per month
LC	lethal concentration
MDL	method detection limit
Mg	magnesium
µg/L	micrograms per liter
mg/L	milligrams per liter
MHRW	moderately hard reconstituted water
mL/min	milliliter/minute
Mn	manganese
MPN	most probable number
MSD	moving standard deviation
MSE	MSE Technology Applications, Inc.

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Acronyms and Abbreviations (Cont'd)

mV	millivolt
MWTP	Mine Waste Technology Program
Na	sodium
Ni	nickel
NOAEL	no observed acute effect level
NPV	net present value
NSM	Nevada Stewart Mine
O&M	operating and maintenance
ORP	oxidation-reduction potential
OU3	Operable Unit Three
P	phosphorus
Pb	lead
PbS	lead sulfide
pcf	per cubic foot
ppb	parts per billion
ppm	parts per million
PRB	permeable reactive barrier
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
ROD	record of decision
RPD	relative percent difference
S	sulfur
Sb	antimony
SC	specific conductivity
Se	selenium
SEM	scanning electron microscopy
Si	silicon
SP1	Sample Port 1
SP2	Sample Port 2
SP3	Sample Port 3
SP4	Sample Port 4
SPA	Sample Port A
SRB	sulfate-reducing bacteria
SVNRT	Silver Valley Natural Resource Trust
Ti	titanium
U	uranium
US	upstream
wt%	weight percent
XRD	X-ray diffraction
Zn	zinc
ZnS	zinc sulfide

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Executive Summary

The Mine Waste Technology Program (MWTP) Activity III, Project 39, *Permeable Treatment Wall Effectiveness Monitoring Project* was implemented by the U.S. Environmental Protection Agency (EPA) and jointly administered by EPA and the U.S. Department of Energy (DOE). Project 39 addresses EPA's technical issue of Mobile Toxic Constituents – Water. This project is a collaborative effort between DOE and EPA's MWTP. The DOE-funded portions of the project included the design and construction of the Apatite II™ Treatment System (ATS) and in-line monitoring system. EPA's MWTP activities addressed establishment of the baseline investigation of the project site, long-term performance monitoring, and decommissioning/closure of the ATS.

The project was conducted at the Nevada Stewart Mine (NSM) site located within the Coeur d'Alene Mining District in Idaho. The NSM is an abandoned lead-zinc mine with an adit discharge of approximately 50 gallons per minute (gpm), primarily contaminated with lead, zinc, and manganese, which drains directly into Highland Creek. The ATS was designed to treat approximately 20 gpm (40%) of the NSM adit discharge. The adit discharge was captured upon exiting the adit and gravity fed through the ATS. Primarily, the ATS consisted of three treatment tanks (labeled 2, 3, and 4) filled with reactive media, which consisted of a 2:1 mixture by weight of gravel to cleaned fishbone (Apatite II™). Monthly performance monitoring of the ATS was conducted between November 2002 and August 2004. Both the treatment system influent and effluent were monitored, as well as upstream and downstream locations relative to the ATS on Highland Creek. For the duration of the project, approximately 13.5 million gallons of water were treated by the ATS.

The project was performed to determine the effectiveness of the ATS in reducing the concentrations of dissolved metals in the mine discharge and to define the attenuation mechanisms (i.e., physical and/or chemical) that reduced the total metal loading of treated waters. To determine the effectiveness of the ATS at reducing the metals loading, the percent reduction was calculated for each metal listed as a target constituent for the duration of the project. The main target constituents present in the NSM discharge included zinc, iron, manganese, calcium, magnesium, lead, and cadmium. Results indicate that the ATS effectively attenuated cadmium, lead, zinc, iron, and manganese, as evidenced by the decrease in aqueous concentrations between inflow and outflow and the increase in solid phase concentrations of these constituents. For the total ATS, the average percent reduction for dissolved zinc, cadmium, iron, and manganese was 55%, 85%, 73%, and 53%, respectively. Dissolution of calcium and magnesium and corresponding increases in concentrations of these constituents occurred over the duration of the project.

Each of the three reactors within the ATS exhibited strong variability in treatment efficiency throughout the project duration, which was dependent upon flow rate, retention time, surface contact, permeability through the medium, and chemistry of the water. Tank 4 treated the water the most effectively, and the average percent reduction of dissolved zinc, cadmium, iron, and manganese for Tank 4 was 94%, 89%, 74%, and 66%, respectively. Tank 4 treated the lowest flow, provided the longest retention time, and had the most reducing environment inside the tank. The increases in concentration of calcium and magnesium were also the greatest for this tank.

A second method of calculating the efficiency of the ATS was to determine the reduction in metals loading entering Highland Creek during the project period. The average monthly zinc loading, for example, was reduced from 37 pounds per month (lb/mo) prior to treatment to 21 lb/mo after ATS installation.

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Extensive research activities were conducted during this project to identify the metals removal mechanisms within the ATS. The attenuation mechanisms identified included precipitation, adsorption, and cation substitution. Specific metals within the influent water were attenuated in different manners. Both the geochemical modeling by Golder Associates, Inc., and mineralogical analysis by Montana Tech confirmed that sulfide precipitation of zinc was probably the dominant mechanism for zinc attenuation within the treatment tanks. This process resulted from reducing conditions being created through the consumption of organic portions of the substrate and the accompanying reduction of sulfate to produce insoluble sulfide by sulfate-reducing bacteria. Attenuation of cadmium and lead due to precipitation was inconclusive; however, speciation modeling showed supersaturation with respect to both cadmium and lead sulfide. The relatively low solid phase concentrations of these metals in the treatment tanks prevented identification of any cadmium/lead secondary mineral phases.

Speciation modeling identified the production of manganese phosphate as a potential precipitate formed within the ATS. This indicates but does not definitely verify that phosphate mineral precipitation was the potential attenuation mechanism controlling manganese concentrations. Similarly, formation of strengite (Fe-phosphate) was identified as a possible sink for iron. Effluent saturation indices indicate undersaturation with respect to hydroxypyromorphite. Because the influent lead concentrations were very low, substitution of lead for calcium during reprecipitation of hydroxyapatite may be one mechanism responsible for lead attenuation. Adsorption of lead, cadmium, and manganese onto ferrihydrite or the Apatite II™ treatment medium could account for an additional reduction in concentration of these metals.

Water samples from the NSM site in Idaho were shipped to the EPA Laboratory in Cincinnati, Ohio, for toxicity tests. A series of acute aquatic toxicity tests with *P. promelas*, the fathead minnow, and *C. dubia*, a freshwater invertebrate, were conducted with these samples. The purpose of these tests was to establish the level of toxicity for discharge from the mine site and to evaluate the effectiveness of the treatment process currently being used at this site. The results from the tests indicate that the treatment system being used to remediate the waste from this mine site reduced the toxicity of the effluent water over that of the influent water.

After assessing the results from the NSM project, it was determined that metals removal was equivalent to about 5% of the weight of the apatite used. For future utilization of apatite for removal of metals, the treatment tank design should be modified to improve the effectiveness and longevity of an ATS by maximizing residence time, preventing plugging, and including means for permeability enhancement/media replacement strategies.

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1. Introduction

1.1 Project Description

Mine Waste Technology Program (MWTP) Activity III, Project 39, *Permeable Treatment Wall Effectiveness Monitoring Project* was funded by the U.S. Environmental Protection Agency (EPA) and jointly administered by EPA and the U.S. Department of Energy (DOE) through an Interagency Agreement (IAG). MSE Technology Applications, Inc. (MSE) implements the MWTP for EPA and DOE. For this project, MSE monitored and evaluated a fishbone, Apatite II™ Treatment System (ATS) designed and implemented to reduce the metals loading from an adit discharge water. The reactive media in the treatment cells consisted of a mixture of fishbone (Apatite II™) and gravel. The objective of Activity III, Project 39 was to monitor and determine the effectiveness of the fishbone apatite material at reducing metals loading in the discharge flowing from an abandoned mine and determine the metal attenuation mechanisms.

The Nevada Stewart Mine (NSM) site selected for this demonstration project is located in the Coeur d'Alene Mining District approximately 6 miles south of Pinehurst, Idaho. The NSM is an abandoned lead (Pb)-zinc (Zn) mine discharging an estimated 50 gallons per minute (gpm) from the collapsed mine adit and underground workings. The primary contaminants in the NSM adit discharge are cadmium (Cd), Pb, iron (Fe), manganese (Mn), and Zn. However, the characterization data indicated that Pb and Cd concentrations were very low during this project, near laboratory detection limits.

The two major phases of the *Permeable Treatment Wall Effectiveness Monitoring Project* were: 1) implementation of the ATS; and 2) long-term monitoring of the ATS. Construction of the ATS was funded by DOE in September 2002 and implementation of long-term monitoring, testing, and evaluation of the ATS system was funded by EPA's MWTP for a 2-year period.

This final report contains the following information:

- Section 1—Description of the demonstration site, scope of work, criteria for success, project schedule, and history of demonstration activities.
- Section 2—Description of DOE's ATS installation, an overview of how Apatite II™ works, the general approach used for installation of the ATS, project design and assumptions, and implementation of the technology.
- Section 3—Description of the 2-year monitoring and testing program implemented under EPA's MWTP that was used to acquire data for evaluation of the ATS.
- Section 4—Review and interpretation of the results for each stage of the project.
- Section 5—Statistical analysis and evaluation of the 2-year monitoring results.
- Section 6—Cost analysis of the ATS on a per-gallon-treated basis.
- Section 7—Summary of quality assurance including activities evaluation and validation of field and laboratory data to determine if the project objectives were achieved.
- Section 8—Project conclusions and recommendations for future projects of this type.
- Section 9—List of references.
- Appendices—Additional data and results.

1.2 Project Objectives and Scope of Work

The overall objective of the monitoring program for the ATS demonstration was to evaluate the ability and efficiency of the system to reduce metals loading of a mining-impacted water. The NSM adit discharge was continuously monitored before and after the ATS was installed to determine if the water quality improved and to

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determine the attenuation mechanisms (i.e., chemical, biological, or physical) that effectively reduced the metals concentrations.

1.2.1 Technology Criteria

The project objectives to determine the effectiveness of the ATS were defined in the MWTP, Activity III, Project 39, Quality Assurance Project Plan (QAPP) (Ref. 1). The effectiveness of the technology was determined by calculating the percent reduction of dissolved metals loading in the treated water compared to the influent water. The system was monitored for a 2-year period. This allowed the ATS system to be fully evaluated, even during low metal removal periods to determine if the metal removal varied seasonally or with permeability enhancements.

1.3 Historic and Background Information

This section provides pertinent information regarding the NSM site selection, as well as the selection of fishbone apatite (hydroxyapatite) as a metals removal medium. The background information is presented as:

- the history of the NSM site and surrounding area;
- regulatory history of the local area;
- previous projects using the Apatite II™ medium for remediation purposes; and
- basic metals removal mechanisms when using Apatite II™ (hydroxyapatite).

1.3.1 NSM Site History

Water from the Coeur d'Alene Mining District, which produced over 150 million tons of Pb, Zn, and silver (Ag) ore since 1885, flows into the South Fork of the Coeur d'Alene River. The South Fork of the Coeur d'Alene River water contains high dissolved metal concentrations that severely inhibit the survival of fish, other aquatic biota, and wildlife along much of the 30-kilometer reach draining the district (Ref. 2). Zinc accounts for approximately 97% of the dissolved heavy metal load, followed by Pb and Cd (approximately 1% each), with other metals [copper (Cu), nickel (Ni), cobalt, antimony (Sb), gold, mercury (Hg)] totaling less than 1% (Ref. 2).

The NSM site is located in Shoshone County near the headwaters of Highland Creek approximately 2 miles east of its confluence with the East Fork of Pine Creek (Figure 1-1). The East Fork of Pine Creek flows into the South Fork of the Coeur d'Alene River. The NSM is an abandoned Pb-Zn mine located 6 miles south of Pinehurst, Idaho, in the Coeur d'Alene Mining District. The waste forms on the site consisted of a discharging adit and surface waste piles. Approximately 8,100 cubic yards of floodplain deposited mine wastes were removed from the site to the Central Impoundment Area at the nearby Bunker Hill Site. The streamside wasterock dump piles at the site were recently pulled back from the stream and recontoured to prevent erosion and reduce contaminant loading to Highland Creek. Discharge from the NSM adit drains directly into Highland Creek (Figure 1-2) and has continuous flow of approximately 50 gpm (Ref. 3).

Most receiving waters in the local vicinity of the NSM have recorded pH values close to neutral and low metals and suspended solids concentrations. However, waters discharging from the NSM carry an increased amount of metals that are detrimental to the adjacent receiving stream. Analytical results indicate high levels of dissolved Zn, Fe, and Mn in the NSM adit drainage and high levels of Zn and Fe in the soils. The concentrations for Cd and Pb in the adit drainage were near the laboratory detection limits.

1.3.1.1 Geology

Coeur d'Alene Basin and mining district geology within the Coeur d'Alene Basin is Precambrian Belt Supergroup rocks consisting of quartzite, carbonates, fine-grained argillites, and dolomitic rock (Ref. 4). The Precambrian rocks were deformed and intruded. Deformations and intrusions and resulting mineralization have formed deposits of valuable minerals including sulfides of Pb, Ag, Zn, Sb, Cu, cobalt (Co), and traces of gold (Au) (Ref. 4). The mineralogy of the mines is dominated by sphalerite [zinc sulfide (ZnS)] that was predominately associated with galena [lead sulfide (PbS)]. Cadmium was a trace element predominantly found with the sphalerite

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and produced as a by-product of the smelting process.

1.3.1.2 Physiography

Terrain around and in the vicinity of the NSM is steep and slightly wooded with various vegetation/grasses. Narrow, steep, and unpaved roads provide vehicle access to most areas of the mine surface. Winter access to the site can be difficult due to deep snow and steep terrain, which impedes sampling efforts (Figure 1-3). During the winter months, however, the NSM discharge did not freeze, nor did the flow through the apatite treatment system.

1.3.2 Site Location History

In 1983, the Bunker Hill Mining and Metallurgical Complex, a former mining and smelting area, located within the South Fork of the Coeur d'Alene River drainage basin, was placed on the National Priorities List for Superfund cleanup due to the presence of high levels of Zn, Pb, Cd, arsenic (As), and other heavy metals. The Bunker Hill Mining and Metallurgical Complex was divided into three distinct areas: Operable Unit One (populated areas); Operable Unit Two (nonpopulated areas of the complex); and Operable Unit Three (OU3) (any mining-related contamination on the broader Coeur d'Alene Basin).

The NSM site is located within OU3. In September 2002, the record of decision (ROD) for OU3 was signed and identified the selected remedy for the area. The Basin Environmental Improvement Project Commission (BEIPC) was created to implement the EPA ROD for OU3. Within OU3, the BEIPC identified four areas that represented the greatest risk, either due to potential human exposure or high levels of contamination. The upper and lower regions of Pine Creek were identified as one of those areas. The NSM discharge contributes to the contamination within the upper reaches of Pine Creek, and since it is adjacent to the Highland Creek Road, it is easily accessed allowing high exposure to humans.

The overall remedy includes remedial action for:

- protection of human health in the communities and residential areas, including recreational areas of the basin upstream of Coeur d'Alene Lake (the Upper Basin and Lower Basin);
- protection of the environment in the Upper Basin and Lower Basin; and
- protection of human health and the environment in areas of the Spokane River (Ref. 5).

The remedial actions selected in the ROD were not intended to fully address contamination within the Coeur d'Alene Basin (Ref. 5). Thus, achieving certain water quality standards, such as state and federal water quality standards and maximum contaminant levels for drinking water, were out of the scope of the ROD.

1.3.3 Previous DOE Apatite Studies

This project was a leveraged effort between DOE and EPA MWTP. The National Energy Technology Laboratory administered the DOE funding for this project to MSE through Technical Task Plan FT10WE31, Task B – Technology Transfer and Commercialization. The DOE-funded portion of the project covered the design and construction of the treatment barrier and monitoring system. The MWTP portion of the project addressed the baseline investigation of the project site, long-term performance monitoring according to an EPA-approved QAPP, corrective maintenance procedures, decommissioning of the treatment barrier, and data analysis and reporting.

Prior to implementing this project, DOE funded a groundwater treatability study using Apatite II™ as a passive treatment medium for removing soluble uranium (U), other metals, and radionuclides from contaminated groundwater. A pilot-scale reactor was installed to treat U and Cd contaminated groundwater at the Y-12 Plant, S-3 Ponds at Oak Ridge, Tennessee. The pilot-scale system demonstrated that Apatite II™ could

effectively remove the Cd and U under field conditions (99% removal efficiency) (Ref. 6). In conjunction with the pilot study, several column studies were performed by DOE under a separate project to determine if Apatite II™ could successfully remove ionized metal contaminants from groundwater in the laboratory. These successful Apatite II™ column studies resulted in the initiation of the MWTP project conducted at NSM.

Additionally, an apatite treatment system installed at the Success Mine in Idaho was showing promise for mine discharge treatment.

1.3.4 Background Information on the Application of Apatite™ II

Apatite II™ works to sequester metals by four nonmutually exclusive processes depending upon the metal, the concentration of the metal, and the aqueous chemistry of the system. In the first process, the dissolution of Apatite II™ continuously supplies a small, but sufficient amount of phosphate to solution to exceed the solubility limits of various metal-phosphate phases such as pyromorphite and autunite (Ref. 7). The following reaction illustrates the overall removal process for Pb.

$$Ca_{10}(PO_4)_6(CO_3)_x(OH)_{2-2x} + 10Pb^{2+} + xH^+ + 2x(OH)^- \rightarrow Pb_{10}(PO_4)_6(OH)_2 + xHCO_3^- + 10Ca^{2+}$$

However, under almost all environmental conditions, Pb-pyromorphite and other phosphate based solids will precipitate only in the presence of an apatite seed crystal; as such, these reactions take place on the surface of the apatite (Ref. 8). Without apatite, other Pb-phases will form that have much higher solubilities (Ref. 9). The Apatite II™ grains serve as a source of seed crystal, as well as a source of phosphate (Ref. 10).

The reaction between the apatite and metals is very rapid (Refs. 7, 11, 12, 13, 14, and 15); consequently, the treatment is effective immediately. The macroscopic flow parameters (i.e., grain size, flow rate, and barrier design) are the limiting factors in the field.

The solubility of the original apatite is key to the effectiveness of this mechanism; it must be sufficiently high to be reactive, but sufficiently low to persist in the environment for many years while preventing phosphate loading. In open systems [i.e., permeable reactive barriers (PRBs), soils, or soil columns] the rate of dissolution of the apatite is little affected by the contaminant concentration because the system rarely approaches equilibrium since dissolved constituents are rapidly removed from the system either by flushing or sorption (precipitation or adsorption).

In the second process, Apatite II™ acts as an excellent buffer (buffers to pH 6.5 to 7) for neutralizing acidity through its PO_4^{3-}, OH^-, and substituted CO_3^{2-} groups. Buffering to neutral pH alone is effective at precipitating many metal phases, particularly aluminum (Al) and Fe(+3) (Ref. 16).

The third removal mechanism is surface chemi-adsorption. Apatite II™ is a strong metal adsorbent, particularly of the transition metals, through its uncompensated phosphate and hydroxyl surface groups. Apatite II™ can adsorb up to 5% of its weight by this process (Refs. 12, 7, and 16). For Zn, Cd, and other transition metals, adsorption by apatite is one of the primary mechanisms for removal under most environmental conditions.

The fourth process is biological stimulation. Apatite II™ supplies both phosphate and readily-bioavailable organics at low concentrations for stimulating microbial communities. As an example, in the presence of sulfate and Apatite II™, Zn and Cd can be reduced to sulfides if the other chemical parameters are favorable. This process, along with adsorption, is one of the primary removal mechanisms for these two elements.

The bioavailability of ingested metal bearing apatite is also greatly reduced (Ref. 17), thus, reducing the risk from animal and human ingestion of metals-loaded apatite.

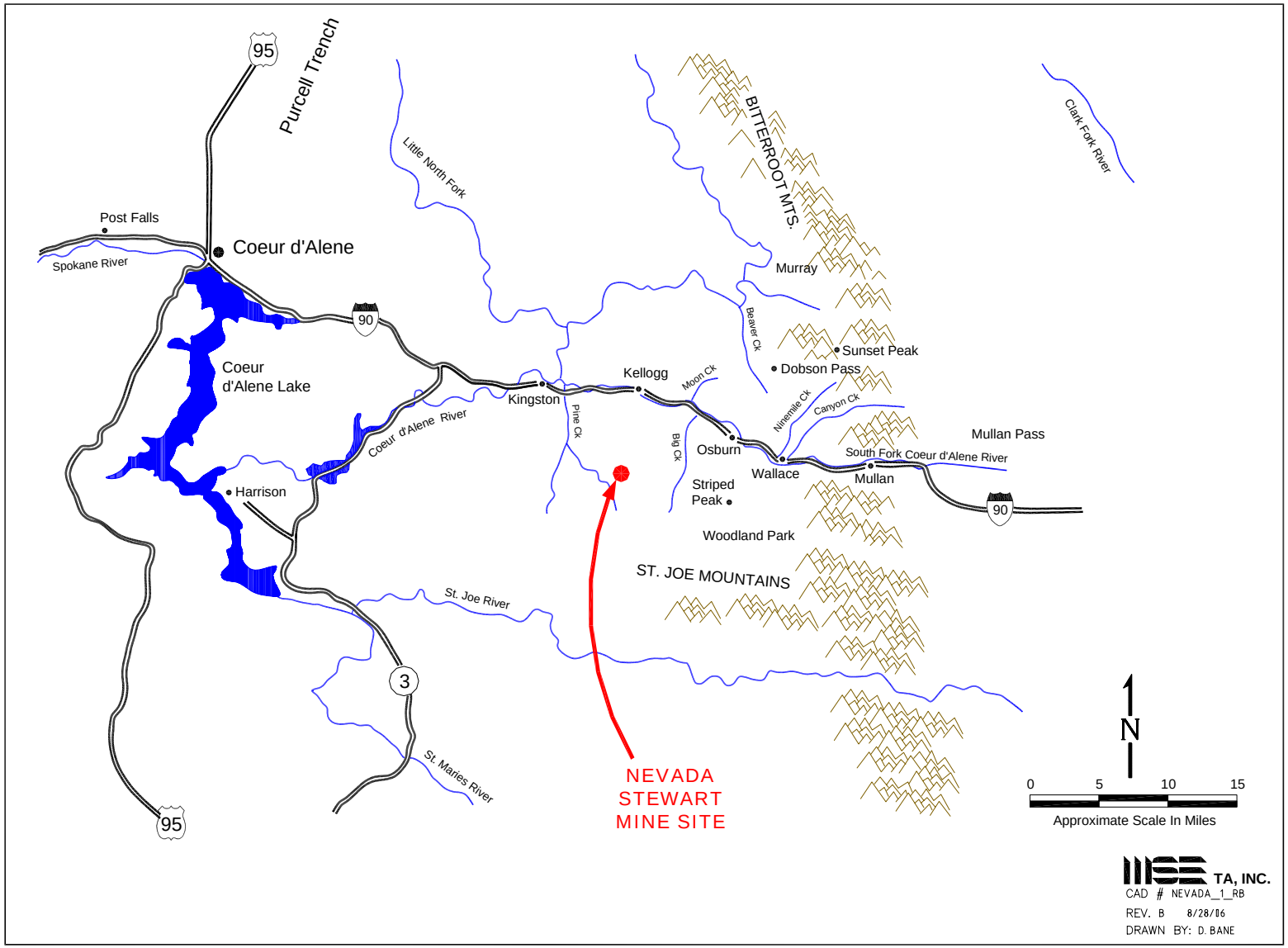

Figure 1-1. Nevada Stewart site map.

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Figure 1-2. NSM site prior to technology implementation. Mine discharge shown flowing over road into Highland Creek.

Figure 1-3. NSM site under winter conditions.

2. Apatite™ II Treatment System Installation

2.1 Purpose of Apatite Treatment System Installation

The purpose for the installation of the ATS at the Nevada Stewart Tunnel site was to reduce the concentration of dissolved Zn in the water that flowed through the treatment system; thus, reducing the overall metals concentration in Highland Creek, a tributary of Pine Creek and the South Fork of the Coeur d'Alene River. EPA Region 10, the Idaho Department of Environmental Quality, the Idaho Bureau of Land Management, and MWTP were all involved in the planning and implementation of the project.

A year prior to the installation of the ATS at the NSM, an ongoing demonstration funded by the Silver Valley Natural Resource Trust utilized Apatite™ II material for removing Cd, Pb, and Zn from groundwater being diverted through a PRB located at the Success Mine and Mill site. This demonstration focused on directing contaminated flow through vaults that contained partially saturated apatite medium. Based on the monitoring completed at the Success Mine site between January 2001 and June 2003, the treatment effectively reduced the concentrations of the contaminants in the groundwater passing through the apatite medium by over 90% (Ref. 18).

Several issues arose during the Success demonstration, including odor, phosphorus (P) release, and bacteria release, which were noted as significant for several months after apatite medium emplacement. After one year in place, the odor, P release, and bacteria release from the medium were within acceptable regulatory limits. Because of the proven ability of Apatite II™ to remove metals from lower pH water (Refs. 16, 18, and 19), additional implementation of this technology was needed to test the effectiveness of the medium in treating other waters. The water at the Nevada Stewart Tunnel site was significantly different from the water at the Success site because it had a circumneutral pH and contained higher Fe and calcium (Ca) concentrations.

2.1.1 Project Description

Given the results from the Success Mine project, DOE installed a fully-contained subsurface retention basin and treatment system designed to capture and treat a specified volume of NSM discharge. Prior to the water flowing into the nearby receiving stream, the volume of influent and effluent system flow, and the water quality of those flows were monitored to provide background information and baseline conditions prior to treatment to determine the performance of the treatment system. The project objective was to provide an economical technology that used apatite as a treatment medium to passively remove Zn from the circumneutral water while minimizing odor problems.

2.2 Technology Description

The technology deployed for this project was Apatite II™ (Ref. 20). The treatment medium was placed into a fully-contained subsurface treatment system. Such tank systems, excluding the treatment medium, are typically installed as subsurface stormwater detention/retention basins where surface impoundments are not desirable either because of aesthetics or land value. By placing the treatment medium into a contained subsurface retention system/tank, several advantages over surface treatment systems were recognized, which included:

- significant odor control;
- protection from freezing;
- protection from vandalism and damage from animals;
- ability to change out or extract the treatment medium, if the attenuation capacity became exhausted;
- ability to accurately monitor inflow/outflow and water quality;

- ability to enhance the permeability of the medium in the tanks; and
- minimal impact on the landscape.

2.3 Project Design Assumptions and Medium Sourcing

For finalization of the ATS design, historical information along with bench-scale column studies were reviewed to determine areas that needed additional research before the ATS was implemented. From previous work, it was known that the NSM discharge water was circumneutral, the permeability of the treatment cells decreases over time, and the temperature of the ATS affects the performance and potentially the permeability. To assist with the design for the NSM ATS, column studies, a literature search, and a review of previously installed systems were performed.

2.3.1 Column Studies

At the Mike Mansfield Advanced Technology Center in Butte, Montana, DOE conducted column studies with water obtained from the NSM site. The objective of the column studies was to ensure the apatite medium would be applicable for treatment of the near-neutral, Zn-contaminated water (Figure 2-1). The apatite medium had not previously been tested in a neutral pH environment; prior laboratory- and field-scale studies/demonstrations had been conducted using contaminated waters with lower pH, which causes greater dissolution of the apatite material (Ref. 20).

For the study, two columns of 10% (by weight) apatite mixed with silica sand were exposed to water from the Nevada Stewart Tunnel for 2 weeks. The flow rate through one column was 5 milliliters per minute (mL/min) and the other was 10 mL/min. After the 2-week test period, Zn was breaking through at the higher flow rate, but was being retained at approximately 60% metals removal efficiency in the lower flow rate system.

Results showed that the Fe was also removed by the low flow rate test system. It was determined that the circumneutral pH had a greater detrimental effect on Zn removal due to decreased dissolution of the apatite, therefore, decreasing "reactivity" with the target ions. A second detrimental effect of the NSM water was caused by Fe deposition, which further decreases the adsorption/precipitation of Zn. After performing the column studies, recommendations for the field design included increasing the residence time by decreasing the flow rate through the system, increasing apatite concentration, or a combination of both.

2.3.2 Scale-Up for Field Design

Data/laboratory results obtained from the column study were used to provide information for the design of the ATS. Calculations were made to scale-up the volume of the treatment medium to allow for adequate residence time by controlling the flow rate through the system. The apatite concentration was also increased from 10 weight percent (wt%) to 33 wt% to provide improved adsorption/precipitation of Zn from that observed in the column study. The field system also had 66 wt% gravel. Design details can be found in MSE's DOE reports (Refs. 20 and 21).

2.3.3 Source of Apatite II™

The Silver Valley Natural Resource Trust (SVNRT) transferred ownership of a quantity of Apatite II™ material (approximately 26 cubic yards) originally obtained from PIMS NW, Inc., for use at the Success Site to the Idaho Department of Environmental Quality (IDEQ) in May 2002. Apatite II™ (U.S. Patent Number 6,217,775) is a form of cleaned fishbone apatite developed by PIMS NW, Inc.

As defined by the column studies, the amount of apatite treatment medium available from SVNRT was a limiting factor in determining the volume of contaminated water to be treated. Calculations were performed, using the information acquired during the column study, to determine the volume of water that could be treated by the ATS design. It was determined that approximately 20 gpm would be diverted and treated on a continuous basis in the ATS at the NSM. An average of 17.9 gpm was treated during system operation.

2.4 Technology Implementation

The specific tasks and specifications required to install the fully contained, subsurface retention basin (Tank 1) and treatment system (Tanks 2, 3, and 4) are described below and illustrated in Figures 2-2, 2-3, and 2-4.

All piping and tanks were emplaced below ground level to protect the ATS from freezing conditions, for odor control, to inhibit public access, and to maintain natural hydraulic flow through the system. The manhole and valve covers to the tanks were buried and insulated, and the tanks were buried at least 1 foot below ground surface. The piping was buried at least 2 feet below the ground surface, with a layer of tarpaper above the piping to provide frost dissipation.

2.4.1 Surface Water Diversion and Sediment Control

The construction of a catch basin for sediment control was completed before other construction at the site to allow for all surface water and NSM drainage to be diverted during the subsequent phases of construction catch basin. The location of the catch basin is depicted in Figure 2-3 and a cross section of the catch basin is shown in Figure 2-4. The diversion system provided a means to measure the mine discharge and flows into the treatment system and catch basin, and allowed sediment/solids to be captured before discharging to Highland Creek. The system also diverted flow under the road removing mine flow over the road and its sediment contribution from vehicles tracking through the flow.

The water diversion system consisted of liner material placed to divert the NSM drainage into a 60-degree, trapezoidal flume (Figure 2-5). The flume directed the adit drainage through two adjustable 6-inch valves. One directed flow through a 6-inch Thel-Mar weir (Figure 2-6) to measure the flow into the retention basin (and subsequently to the treatment system). The other directed flow through a bypass system and into the sediment control/catch basin system before discharging into the stream (Figure 2-2). During construction of the retention basin and treatment systems, all water was directed through the bypass portion of the system.

The sediment control/catch basin system consisted of a 25-foot by 10-foot by 5-foot deep excavation, lined with approximately 6 inches of gravel and large rock (approximately 1 to 2 inches in diameter), as shown in the cross section of the catch basin in Figure 2-7. Both the treated and nontreated water filter through the gravel/rock material and approximately 3 feet of natural stream bank vegetation (grass, trees, and low shrubs) and material before discharging into the stream. Discoloration was noticeable in the bypass.

2.4.2 Subsurface Retention Basin Design

Following the water diversion system construction, material was excavated from the area where the water retention basin and treatment systems were located. Once the site was excavated, a 3-inch sand bed was laid down as a base for all the tanks and piping. The influent from the tunnel drainage was at the highest elevation with depths increasing to the retention tank, header, treatment tanks, and post-treatment and discharge piping. Surface elevation and bottom of the retention basin was measured to ensure consistent level measurement for the tanks.

The retention basin design consisted of a buried 1500-gallon septic tank (5 feet high by 6 feet wide by 13 feet, 2 inches long) with an internal baffle to facilitate sediment settling (see the plan view of Tank 1 in Figure 2-4). Valves controlled the influent flow out through a 10-inch pipe near the top of the retention basin (Tank 1) and was directed to the treatment system via a 10-inch pipe (Figure 2-8).

2.4.3 Treatment System Design

The treatment system consisted of three 3,000-gallon septic tanks (8 feet in diameter by 10 feet long) placed in parallel so that each treatment cell/tank could accommodate a third of the flow (approximately 6 gpm) through the system (Figures 2-3, 2-4, and 2-9). Preceding each tank, an adjustable butterfly valve was used

to control the flow through the apatite medium. Within each tank, two baffles were used to guide the flow through the system; the first one was placed approximately 3 feet from the tank inlet and the second one approximately 3 feet from the first baffle (Figure 2-10 and Figure 2-11). A 3-foot diameter access manhole and riser emerged from each section of the tank up to the ground surface for easy treatment medium emplacement, access, and cleanout.

As designed, flow entered Treatment Tanks 2, 3, and 4 near the tank bottom and flowed up through the treatment medium in the first section, over the first baffle, down through the second section of treatment medium, under the second baffle, then up through the treatment medium in the third section and exited at the end of the tank near the top. Due to this flow regime, the medium was completely saturated, creating an anaerobic environment. Once the water exited the treatment cells, it flowed through sections of a 10-inch pipe equipped with a 10-inch Thel-Mar weir to measure flow. Manholes/risers functioned as sample ports [Sample Port 1 (SP1), Sample Port 2 (SP2), and Sample Port 3 (SP3)] allowing for post treatment water quality samples to be drawn for laboratory analyses.

Upon exiting the sample zone, the treated water flowed into a 10-inch pipe extending under Highland Creek road and into the catch basin before discharging into Highland Creek. A subsurface vent system was placed in the exiting piping system to promote the release of any off-gas production within the pipe. The odor control issue was addressed by passing the off-gas through a vent containing granulated activated carbon. See Figure 2-4 for cross-section of the odor control devices.

A photo of the site just after the ATS was installed is shown in Figure 2-12, a photo of the site after two years is shown in Figure 2-13, and a photo showing the system just after closure is depicted in Figure 2-14.

2.4.4 Treatment Medium Installation

The proper ratio of apatite to gravel was established based on the results of column studies performed for DOE, the system implemented at the Success Mine, and recommendations from the patent holder for the apatite medium—PIMS NW. The apatite provided by the IDEQ needed to be crushed to a smaller size fraction (< 1-¼ inch) to provide additional surface area for treatment processes to occur. To reduce the size fraction of the apatite in the medium, it was rotated in a cement mixer that acted as a grinding mill to process (crush and mix) the apatite medium (Figure 2-15). Once the medium was appropriately sized, it was mixed with the gravel. The material was then funneled into each section of the treatment tank via the manholes/risers. Approximately 24 inches of free board was left at the top of each tank. Additionally, approximately, 3 inches of gravel was placed on top of the medium to prevent flushing of the medium into the next section of the tank (Figure 2-16).

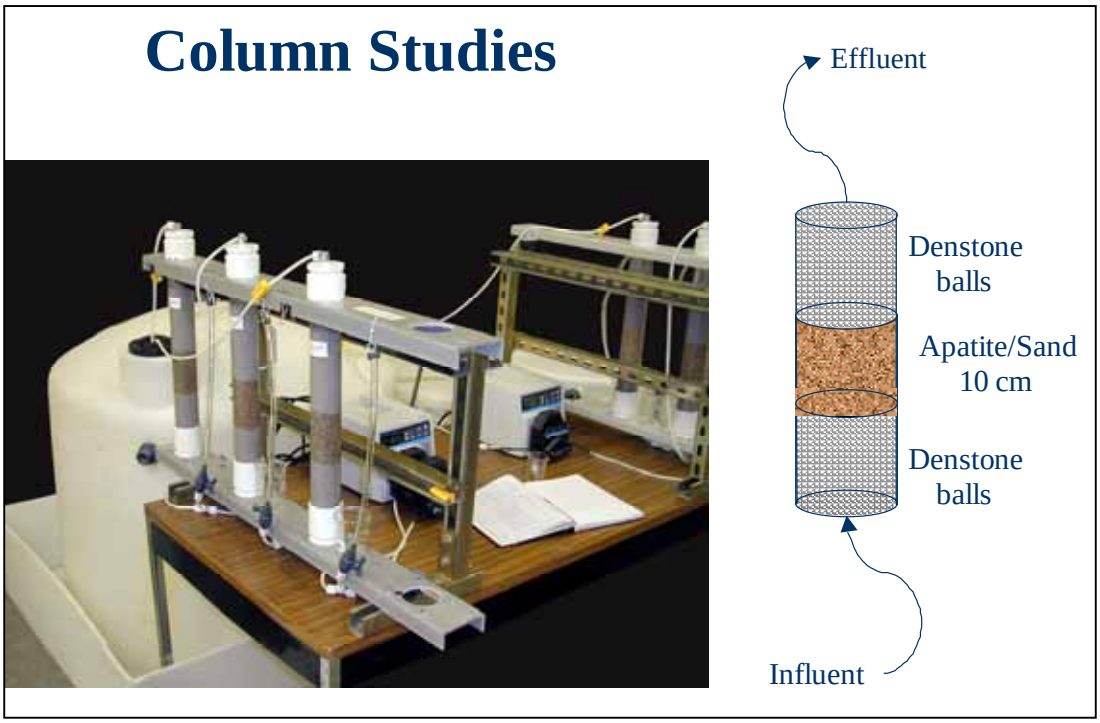

Figure 2-1. Column study.

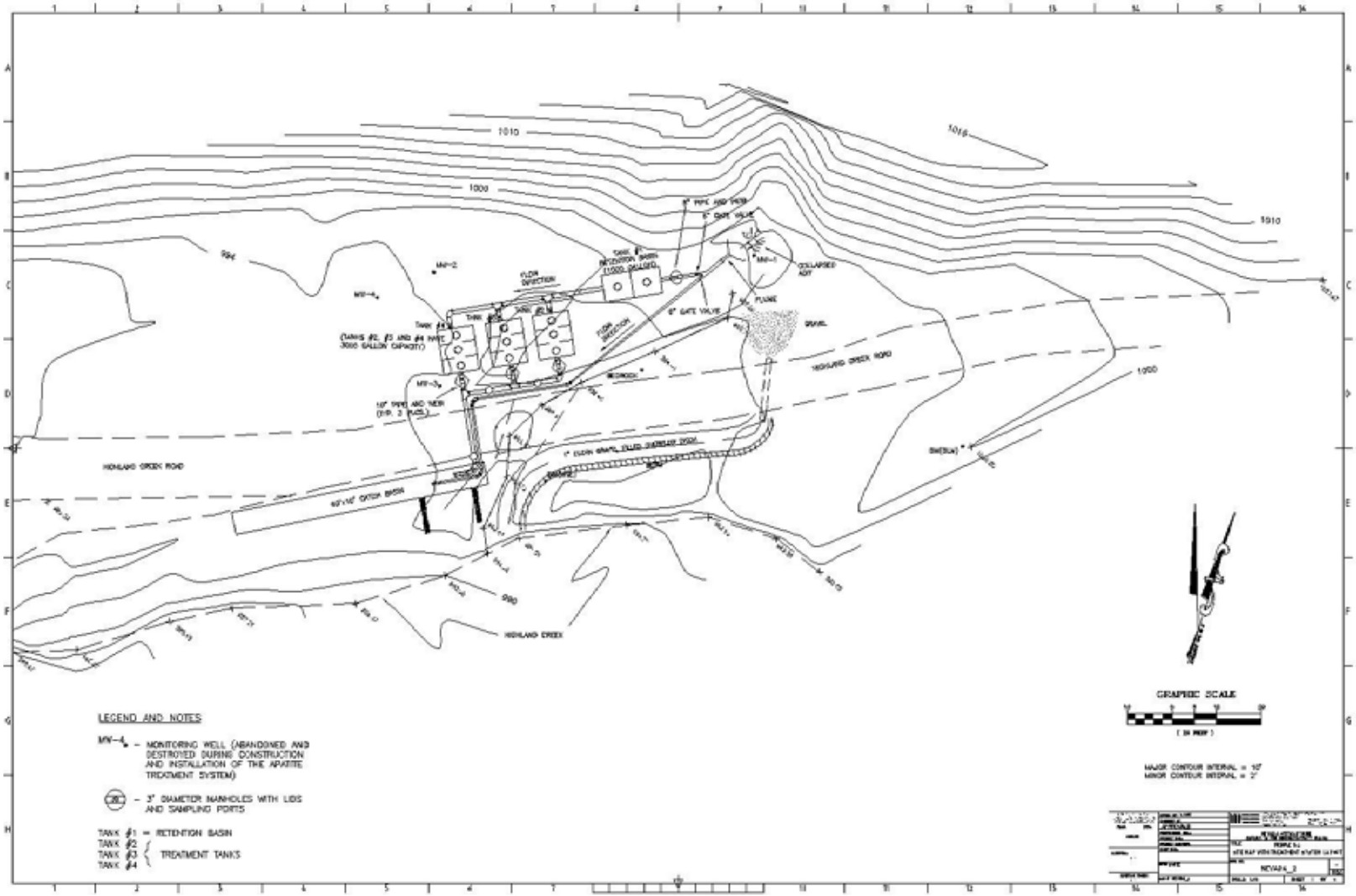

Figure 2-2. Map showing installation of the Apatite Treatment System at the Nevada Stewart Mine.

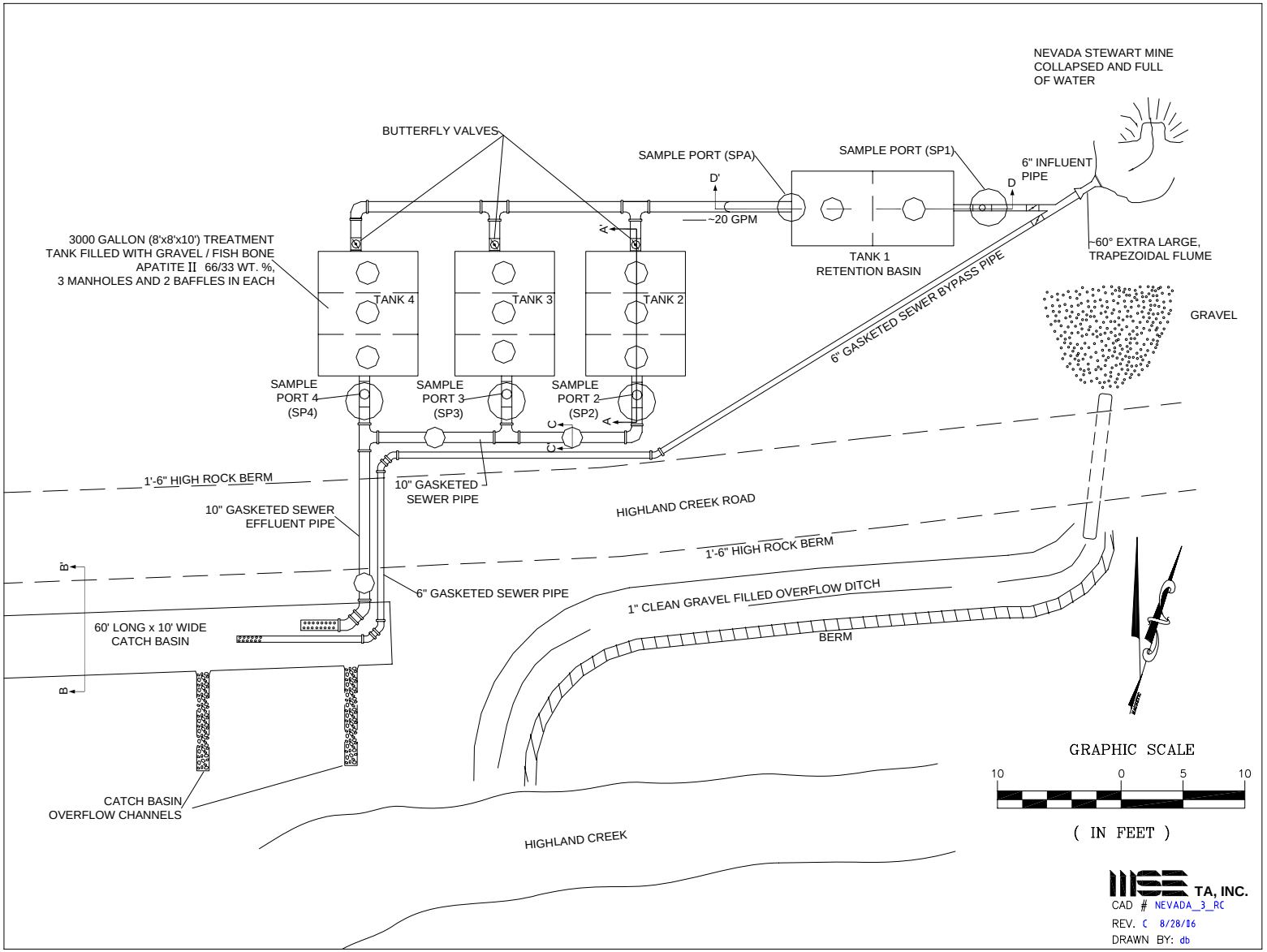

Figure 2-3. Location of sediment control system/catch basin.

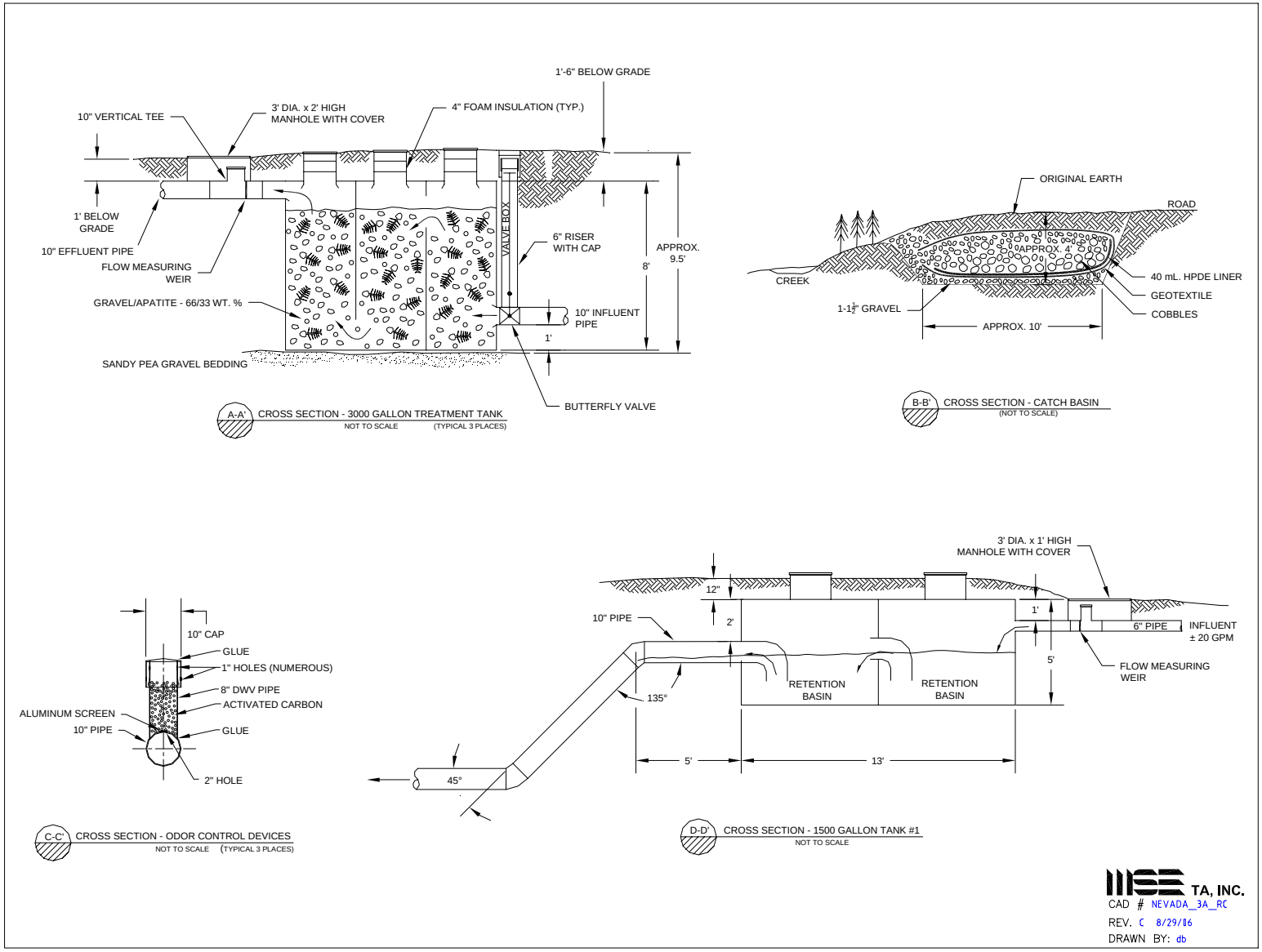

Figure 2-4. Cross-section of catch basin, retention basin, and treatment tank.

Figure 2-5. Sixty-degree trapezoidal flume used to direct NSM adit discharge through the ATS.

Figure 2-6. Thel-Mar weir and bubbler used to measure flow from treatment tanks.

Figure 2-7. ATS catch basin for effluent water.

Figure 2-8. ATS Tank 1 (retention basin) used to trap debris in water.

Figure 2-9. ATS Tank 4 being placed at NSM.

Figure 2-10. NSM ATS construction prior to covering system.

Figure 2-11. ATS system uncovered with risers and sample ports constructed.

Figure 2-12. NSM ATS just after construction looking upstream (November 2002).

Figure 2-13. NSM ATS 2 years after installation looking downstream (September 2004).

Figure 2-14. NSM ATS after closure of system.

Figure 2-15. Installation of whole-bone apatite and gravel mixture into treatment tanks.

Figure 2-16. Whole bone apatite/gravel media before submerging it with water. Note vertical baffle/partition visible in photo.

3. Performance Monitoring and Testing Methods

Several monitoring and testing methods were used to determine the effectiveness of the ATS and determine the attenuation mechanisms capable of removing metals from the NSM discharge. The performance monitoring and testing at the site included:

- monitoring system influent and effluent flow rates by MSE;
- monitoring water quality of the system flows and localized stream flows (resulting in geochemical and statistical analyses performed by Golder and EPA-NRMRL, respectively);
- testing solid phase media [including X-ray diffraction (XRD), scanning electron microscopy (SEM), total solid digestion analysis of the fishbone, and energy dispersive X-ray (EDX) analyses performed by Montana Tech];
- monitoring the influent and effluent flow for toxicity (analysis performed by the EPA-NRMRL) in 2003; and
- monitoring the influent and effluent water for bacteriological activity by the Center for Innovation (CFI).

This section describes the monitoring and testing methods used for evaluating the ATS.

3.1 ATS Flow Monitoring Design and Methods

The treatment system was designed as a watertight, closed treatment system allowing for the influent and effluent flow to be measured and the reduction in historic metal loading to be evaluated. The total discharge from the mine was measured using a 60-degree, extra large trapezoidal flume. Historically, flow measurements and background information were acquired from the Bureau of Land Management and that information indicated that the discharge from the mine adit ranged from approximately 50 to 60 gpm all year (Ref. 3).

The flow to the ATS was split into two flows immediately after the total flow was measured in the flume. The inlet pipe 6-inch valve was set to approximately 17 gpm, to a 6-inch Thel-Mar weir at (SP1) and then into the retention tank and ATS. Any flow exceeding 17 gpm was diverted through the 6-inch bypass valve and pipe and then into the catch basin (Figures 2-2, 2-3, and 2-4).

On the down-gradient effluent side of each of the treatment tanks, the effluent flow was measured using 10-inch Thel-Mar weirs [SP2, SP3, and Sample Port 4 (SP4)] (Ref. 1). The flow was measured once a month unless weather conditions or plugging of the system prohibited sampling during a specific month. Flow rate data in gallons per minute from each sampling event is provided in Figure 4-2 and in Appendix A.

3.2 Water Quality Monitoring

MSE and Golder personnel took water quality samples and flow measurements at SP1, Sample Port A (SPA), SP2, SP3, and SP4. After the mine discharge water had been split, influent water quality samples were taken at AP1 and SPA (located at the inflow and outflow of Tank 1, respectively) to check the effect of the retention tank. Effluent water quality samples were taken as the flow exited Tank 2 (SP2); Tank 3 (SP3); and Tank 4 (SP4) (Figures 2-9, 2-10, and 2-11). Water quality data from the sampling events is in Appendix A.

Monthly water samples and field parameters were taken at the site. Samples were analyzed at HKM Laboratory for specific groups of constituents. A list of the analyzed constituents is in Table 3-1.

3.2.1 Toxicity Characterization

Water samples from the NSM site were shipped to the EPA Laboratory in Cincinnati, Ohio, where a series of acute aquatic toxicity tests with *Pimephales promelas (P. promelas)*, the fathead minnow, and *Ceriodaphnia dubia (C. dubia)*, a freshwater invertebrate, were conducted. The

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purpose of these tests was to establish the level of toxicity for the discharge from the mine site and to evaluate the effectiveness of the treatment process utilized at the site (Appendix B). MSE and Golder took toxicity samples annually, which EPA evaluated at the AAALAC Certified Aquatic Research Facility in Cincinnati, Ohio.

3.2.1.1 Methods

Samples were collected in 1-gallon containers. At least 4 liters of sample were collected from the mine discharge (SP-1), the three tank outlets in the treatment process discharge (SP-2, SP-3, SP-4) and samples upstream and downstream of treatment system. Sample containers were completely filled so no air space was left after they were capped. Samples were placed in a cooler with ice and shipped overnight to the EPA facility in Cincinnati. All coolers were received in good condition with all seals intact, and all samples were in acceptable condition. A total of four water samples were received annually, and the following standard testing conditions were followed for each set of samples (Tables 3-2 and 3-3).

3.3 Solid Phase Characterization

Montana Tech performed an in-depth literature search, XRD, SEM, and EDX analysis to determine and identify the solid materials present in the treatment media and gather information for defining the attenuation mechanisms functioning to remove dissolved metals from solution within the treatment tanks.

One of the goals of this project was to determine the mechanisms responsible for the attenuation of dissolved metals from mining impacted water using fishbone apatite.

An extensive literature search was conducted using several databases available through the Montana Tech Library. A complete listing of all documents found during the literature search is located in the Reference section of Montana Tech's final report provided in Appendix C.

Solid samples of treatment media were collected at selected depths within each treatment tank twice during the project. These samples were used to evaluate whether there was concentration stratification formed within the treatment tanks and at what depth certain metals are removed from solution. Montana Tech took the first solid samples in July 2003, and MSE collected the second set at the closure of the project in September 2004. Core samples were collected at varying depths (surface, 8, 16, 24, and 32 inches) from Tanks 2, 3, and 4 using a 2-inch diameter manual core sampler. The samples were taken from the middle section of the ATS, where flow was forced vertically downward between the baffles. The samples were stored in 1-quart Ziploc bags, labeled, and refrigerated until use. The solid samples were digested and prepared according to EPA Test Method 3050B, Method Two, *Preparation of Sediments, Sludges, and Soil Samples for the Analysis of Samples by Inductively Coupled Plasma Mass Spectrometry (ICP)*. Samples were then analyzed for total metals at SVL Analytical in Kellogg, Idaho for the constituents Ca, Cd, Fe, magnesium (Mg), Mn, Pb, and Zn. The solid media sampled and digested was biased toward fishbone, meaning that the 1- to 1½-inch gravel was not analyzed or digested. Please refer to Section 4.5 for total metals results.

The bone samples collected were also analyzed using XRD and SEM/EDX. Appendix C contains the final report from Montana Tech that discusses the methods and results of the solid media analysis from the ATS.

3.4 Bacteriological Characterization

In September 2004, during the closure of the project, sulfate-reducing bacteria (SRB) samples were taken and evaluated by CFI. These solid samples were taken to determine the level of SRB activity in each of the treatment tanks at the end of the demonstration project. The SRB results by the most probable number method were used to assist with the determination of the attenuation mechanisms working within each of the treatment tanks. Coliform analysis was also conducted every month at SP1, SP4, and upstream and downstream locations in the creek.

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Table 3-1. Baseline and Target Constituents Monitored at the NSM ATS

Constituent	Ports 1 to 4		Port A	Upstream/Down-Stream
	Baseline	Target	Target	Stream Target
Field Parameters				
pH	X	X	X	X
Temperature	X	X	X	X
Conductivity	X	X	X	X
Oxidation-Reduction Potential (ORP)	X	X	X	X
Dissolved Oxygen (DO)	X	X	X	X
Flow	X	X	X	X
General Parameters/Major Ions				
Alkalinity	X	X		
Acidity	X	X		
Ca	X	X	X	
Mg	X	X		
Sodium (Na)	X			
Potassium (K)	X			
Sulfate	X	X		
Sulfide	X	X		
Chloride	X			
Fluoride	X			
Dissolved and Total Metals				
Silicon (Si)	X			
Al	X			
Fe	X	X	X	
Hg	X			
Selenium (Se)	X			
Ag	X			
Thallium	X			
Cd	X	X		X
Cu	X			
Mn	X	X	X	
Pb	X	X		X
Zn	X	X	X	X
As	X			
Sb	X			
Ni	X			
Beryllium (Be)	X			
Chromium (Cr)	X			
Nutrients				
Total Ammonia	X	X		X
Nitrate	X	X		X
Nitrite	X	X		X
Kjeldahl Nitrogen	X	X		X
Dissolved Orthophosphate	X	X		X
Total P	X	X		X
Dissolved Total P	X	X		X
Bacteriological				
Coliform Bacteria[a]	X	X		X

[a]Coliform bacteria monitored at SP1 and SP4, Upstream and Downstream.

Table 3-2. Standard Test Conditions for *C. dubia* Acute Toxicity Tests with Superfund and/or Mine Waste Samples

Test Criteria	Specifications
Test Type	Static-renewal
Test Duration	48 hours
Temperature	20 °C ± 1 °C
Photoperiod	16 hours light/8 hours dark
Test Chamber Size	30 milliliters (mL) (plastic cups)
Test Solution Volume	15 mL
Renewal of Test Solution	Daily
Age of Test Organisms	Less than 24-hours old
Number of Organisms/Per Test Chamber	5
Number of Replicate Chambers/Concentration	4
Number of Organisms/Concentration	20
Feeding	None, fed while holding prior to test setup
Dilution Water	Moderately Hard Reconstituted Water (MHRW)
Endpoint	Mortality, LC50
Test Acceptability	≥ 90% survival in the controls

Table 3-3. Standard Test Conditions for *P. promelas* Acute Toxicity Tests with Superfund and/or Mine Waste Samples

Test Criteria	Specifications
Test Type	Static-renewal
Test Duration	48 hours
Temperature	20 °C ± 1 °C
Photoperiod	16 hours light/8 hours dark
Test Chamber Size	175 mL (plastic cups)
Test Solution Volume	150 mL
Renewal of Test Solution	Daily
Age of Test Organisms	5 days ± 24-hour age range
Number of Organisms/Per Test Chamber	10
Number of Replicate-Chambers/Concentration	2
Number of Organisms/Concentration	20
Feeding	Feed newly hatched brine shrimp prior to testing; do not feed during the test
Dilution Water	MHRW
Endpoint	Mortality, LC50
Test Acceptability	≥ 90% survival in the controls

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4. ATS Performance Monitoring Results

4.1 Flow Volume Results

The ATS was designed as a watertight (closed) treatment system that allowed the effluent and influent flow rates to be measured. A conservative estimate of the total volume of flow treated by the ATS was approximately 13.4 million gallons. The flow for the months of December 2002 through February 2003, when the ATS was plugged, along with the month of January 2004, when weather prevented access to the site, was not included in this total flow volume estimate. While the system was designed to treat 20 gpm, the average flow rate through the system was approximately 17.9 gpm, and this flow varied on a monthly basis (Table 4-1). Treatment Tank 3 treated 48.6% of the flow going through the system (an average flow rate through media was 8.7 gpm); Tank 2 treated 33% of the system flow (an average flow of 5.9 gpm); and Tank 4 treated the least amount of flow, approximately 18% (an average flow rate of 3.3 gpm) (Table 4-1).

Flow through the system was variable due to seasonal fluctuations and the changes in permeability within certain tanks due to settling, increased precipitation of metals, and air sparging of the system that was done to improve the permeability and create new flow pathways through the media. An air compressor with a long lance attachment that could be inserted into the media beds was used to agitate the media. The flow responses to the permeability enhancements conducted in the ATS are presented in Figure 4-1. In this figure, the influent flow reflects seasonal peaks, which occurred during April and May of both project years. May 2003 had the highest volumetric flow through the system at 1.3 million gallons (Figure 4-2). After May 2003, the tanks started to plug for the second time, and air was injected to enhance and restore permeability in the ATS. After May 2003, Tank 2 (SP2) recorded the highest flow values for a period of 3 months; after that period, Tank 3 again treated the majority of the system flow, with some minor fluctuations.

The ATS was plugged from December 2002 to February 2003, and samples were not collected in either December 2002 or January 2003. In February 2003, samples were collected, but those results reflect the conditions of a plugged system, not a properly functioning system. Also, samples were not collected in January 2004 due to adverse weather conditions. An additional sampling event was scheduled and conducted in April 2004 (i.e., samples were taken on April 1 and 29, 2004).

4.2 Water Quality Monitoring Results

Monthly sampling was performed at the Nevada Stewart ATS from November 2002 through August 2004. The main influent sampling location sample port (SP1) and the effluent sample ports (SP2, SP3, and SP4) were sampled monthly (Figure 2-3). Sample Port A was sampled annually to determine the amount of metals removed in Tank 1, the retention basin. The water quality samples were analyzed by HKM Laboratory and personnel acquired the field parameters such as pH, ORP, specific conductivity (SC), DO, and temperature. The complete water quality data set for the project is presented in Appendix A.

Since the permeability of the system declined throughout the project due to media settling and metals precipitation, the permeability in the treatment tanks was improved using air-sparging/injection techniques a number of times. Air was injected into the media through the manholes to lift the media, resulting in the creation of alternative and larger flow pathways. The permeability of the ATS was enhanced after sampling was conducted in February 2003, May 2003, October 2003, and April 2004.

Performance monitoring results and observations are presented in this section in the following order:

- pH and Alkalinity;
- Temperature and SC;

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- Redox Conditions (ORP, DO, ammonia, and sulfide);
- Major Ions (Ca, Mg, and sulfate);
- Metals (Zn, Cd, Pb, Fe, and Mn);
- Nutrients (P and nitrogen); and
- Bacteriological (coliform and SRBs).

4.2.1 pH and Alkalinity

Over the duration of the project, there was a seasonal cycle in pH observed for the influent water (Figure 4-3). The ATS influent pH ranged from 5.3 to 7.0. Influent pH values increased throughout the fall of 2003 remaining stable over the winter months at levels comparable to the winter values observed in 2002 (i.e., pH values from 6.1 to 6.7). This seasonal cycle was repeated in 2004.

For the ATS effluent flows, the average pH ranged from 6.0 to 7.0, except during two instances. The first instance occurred during the period between December 2002 and February 2003, when the ATS system was clogged. Flow throughout the system was restored in February 2003; however, the conditions of the system, as a result of the clogging, were reflected in the pH values recorded from the February 2003 sampling data (Figure 4-3). At that time, the pH at SP4 was alkaline (pH of 8) and the pH of other treatment cells was approximately neutral (pH of 7). The effluent pH values recorded on April 29, 2004 and May 25, 2004, were lower than historically recorded. On April 29, 2004, effluent pH values ranged from 5.3 to 5.5 and were lower than the measured influent pH.

The alkalinity of the effluent water was slightly less than that of the influent waters (Figure 4-4). The most significant difference in alkalinity was observed just after the ATS was installed in November 2002. Sample Port 4 consistently recorded slightly higher alkalinity, up to approximately 30 milligrams per liter (mg/L) more than SP1, SP2 and SP3, with the exception of November 2003 and March to early April 2004, when SP3 samples had higher alkalinity.

4.2.2 Temperature and Specific Conductivity

Minimal variability of the water temperature from the NSM discharge (the influent) and the effluent from the ATS was recognized throughout the project duration; the difference was typically less than 1 °C and the maximum difference was 2.8 °C. The flow from the underground workings had a fairly constant temperature and did not exhibit seasonal fluctuations. However, the temperature fluctuations of Highland Creek, due to seasonal conditions, were dramatic and a graphed representation is provided in Figure 4-5, where US depicts values from the upstream monitoring location and downstream (DS) depicts values from the downstream monitoring location (Figure 2-2).

The SC for the NSM adit discharge, the ATS, and Highland Creek show minimal variability. The main fluctuations recorded were on February 2003 when the system was plugged and on April 29, 2004, and the reason for an outlier cannot be defined (Figure 4-6).

4.2.3 ORP, DO, Ammonia, and Sulfide

The influent from the NSM adit into the ATS was slightly oxidized, as indicated by the presence of DO ranging from 6 to 11 mg/L and by the positive ORP values ranging from 160 to 320 mV (Figures 4-7 and 4-8). Influent ORP values fluctuated seasonally; thus, the ORP values were lower in November and during the springtime runoff/snowmelt periods. The ORP of the effluent waters during the first year of monitoring indicated a change toward reducing conditions, ranging from –90 to 230 mV. From November 2003 to project closure, Tank 2 and 3 maintained higher recorded ORP values (150 mV) than Tank 4, which became increasingly reducing at the closure of the project (ORP < 100 mV). Between November 2003 and April 29, 2004, differences between influent and effluent ORP were minimal (< 10 mV difference). Air sparging did not appear to affect effluent ORP values, an increase in ORP was not consistently observed following sparging events.

Comparisons of the effluent water qualities, indicates variability in the redox conditions between treatment tanks. Although all treatment tank effluent data shows a decline in DO relative to the influent, since May 2003 greater reductions in DO were typically observed in SP2 and SP4 compared to SP3 (Figure 4-7).

The 2004 effluent monitoring results show fairly low sulfide concentrations for all treatment tanks, ranging from below detection limits (< 0.5 to 2 mg/L). Low levels of ammonia (up to 0.2 mg/L) and sulfide (up to 1.6 mg/L) were recorded at SP1 (Figures 4-9 and 4-10 or Appendix D). Over the total monitoring period, a general decline in effluent sulfide concentrations have been observed. Except at SP4 from April 29, 2004 until the project closure, recorded ORP values declined while sulfide, ammonia, and bacteria (coliform) concentrations increased.

Throughout 2003, SP4 consistently recorded the highest sulfide concentrations (Figure 4-10). On the basis of increased sulfide content, SP4 provided data consistent with enhanced SRB activity.

4.2.4 Major Ions

Calcium, Mg, and sulfate were included in the target analyte suite. Calcium concentrations in the influent were relatively stable, ranging from 83 to 103 mg/L. Effluent waters reported slightly higher Ca concentrations, up to 111 mg/L (Figure 4-11).

Monthly monitoring results showed little difference between Mg influent and effluent concentrations, typically less than 1 mg/L (Figure 4-12).

Declining sulfate concentrations were observed between the influent and effluent samples; generally, the declining sulfate concentrations coincided with increasing sulfide concentrations. On a monthly basis, the sample port reporting the highest concentration in sulfide reported the greatest decline in sulfate (Figure 4-13).

4.2.5 Metals

The ATS appears to have effectively attenuated Zn, Mn, Fe, Cd, and Pb (Figure 4-14). However, due to the variability of flows through each treatment tank, the results obtained reflect the effect of the variability with respect to metals concentration, retention time, and attenuation mechanisms functioning in each tank.

Zinc

Over the duration of the ATS monitoring project, the influent dissolved Zn concentrations from samples taken at Tank 1 have gradually increased from approximately 5.5 to 8.0 mg/L (Figure 4-15). Dissolved Zn at Tank 2 ranged between nondetect and 5 mg/L (Figure 4-15). Tank 3 ranged between nondetect and 6 mg/L. Tank 4 ranged between nondetect and 1.5 mg/L. The effluent dissolved Zn concentrations were below 5 mg/L for both Tanks 2 and 4. Between November 2003 and April 2004, Tank 4 effluent Zn concentrations gradually increased, coinciding with the increase in DO, indicating a change to more oxidizing conditions. The Zn concentrations for Tanks 2 and 4 gradually increased over the duration of the project. Tank 4 reduced the Zn concentrations below 0.1 mg/L for over a year and then the maximum Zn concentration recorded was 1.6 mg/L during the April 29, 2004, sampling event. At the closure of the project (August 17, 2004) the Zn concentrations were approximately 0.1 mg/L at Tank 4.

However, Tank 3 exceeded the 5 mg/L after 11 months (i.e., effluent Zn concentration ranged from 1 to 6 mg/L) and after treating 3.5 millions gallons of NSM water (Figure 4-15), provided the least Zn attenuation. The effluent Zn concentrations were reduced when air was entrained into the treatment tanks to improve the permeability of the apatite media.

The Highland Creek Zn concentrations were higher downstream of the ATS. This results from waste material at the site and untreated adit discharge that bypassed the system. Between 50% and 65% of the untreated discharge enters

Highland Creek up-gradient of the downstream sampling location. It should be noted that only 17 gpm of the approximately 40 to 60 gpm flow discharging from the NSM adit was treated by the ATS.

Iron

Dissolved iron concentration in the discharge was relatively low. For applications with higher dissolved iron concentrations, iron precipitates will likely clog the treatment media. On average, the influent concentration for Fe recorded at Tank 1 was approximately 0.6 mg/L. However, concentrations varied between 0.2 and 0.9 mg/L. Lower iron concentrations were recorded for the effluent flows than the influent flows for the full duration of the project (Figure 4-16). Over the duration of the project, there were significant variations between the treatment tanks. At Treatment Tank 2, the Fe concentrations did not exceed 0.2 mg/L for the project duration, and permeability enhancements reduced the Fe concentrations except on May 2003 when flows were uncharacteristically high. Higher Fe concentrations were recorded when the system was partially clogged.

Tank 3 iron concentrations peaked from May to October 2003. During this period, large quantities of water were treated in Tank 3. Air enhancements decreased the concentrations of Fe every time at Tank 3.

Tank 4 iron concentrations exceeded 0.2 mg/L only twice, in June and July 2004. Peak concentrations coincided with the increase in dissolved Fe concentrations in the influent. Permeability enhancements effectively reduced the concentrations of dissolved Fe in the effluent until April 2004, when the Fe concentrations increased at SP4, which correlates to very low ORP values and increased sulfide concentrations.

Manganese

The concentration of dissolved Mn in the influent to the ATS was approximately 0.6 mg/L on average with only minor variations through the project duration (Figure 4-17). The effluent dissolved Mn concentration for Tank 2 ranged between a maximum of 0.42 mg/L and a minimum of 0.071 mg/L.

The effluent dissolved Mn concentrations in Tank 3 ranged from a maximum of 0.5 mg/L during April and May 2003 to a minimum of 0.092 mg/L in June of 2004. It should be noted that Tank 3 treated 0.85 million gpm during April and May 2003 compared to 0.15 million gpm in June 2004. Additionally, permeability enhancements reduced the Mn concentrations significantly in Tank 3, lowering the resultant concentration each time it was performed (Figure 4-17).

Tank 4 dissolved Mn concentrations ranged between a maximum level of 0.384 mg/L to a minimum of 0.155 mg/L. The concentration at Tank 4 increased after air enhancement of the ATS. However, as time progressed, the Mn concentration decreased until another permeability enhancement was initiated.

Cadmium

Observed influent concentrations for Cd were very low at < 1 part per billion (ppb) (Figure 4-18). Dissolved concentrations monitored in the effluent water were generally below the detection limits.

The highest Cd concentrations recorded for this project were those in Highland Creek, both in the upstream and downstream samples. The concentration of Cd in the ATS effluent was at or below the laboratory instrumentation detection limit. The highest Cd concentrations occurred in the winter of 2003, from November 2003 to April 2004, from samples collected in Highland Creek.

Lead

The influent concentrations for Pb were also very low, 0.0005 to 0.0023 mg/L (Figure 4-19). From November 2003, the concentration of Pb in the effluent was at or below the laboratory instrumentation detection limit. The highest Pb concentrations in the treatment effluent were in June and July 2003 just after the ATS air enhancement was performed.

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The highest Pb concentrations recorded for this project were those in Highland Creek, both in the upstream and downstream samples. The Pb concentrations for Highland Creek were always higher than the influent Pb concentrations from the NSM. During the initial months of the project, the Pb concentrations downstream were higher than Pb concentrations upstream. In May 2003, this trend reversed and higher concentrations of Pb were detected upstream and lower concentrations were recorded downstream of the ATS (Figure 4-19).

4.2.6 Nutrients

As expected, an increase in P concentrations was detected in the effluent when compared to the influent (Figure 4-20). However, the total phosphorous in Highland Creek, upstream was near that of the downstream samples. However, on July 2003 and September 2003, the Highland Creek upstream total P values exceeded the downstream values from 0.2 mg/L to as much as 5 mg/L.

The total nitrogen in the effluent was also higher than in the influent (Figure 4-21). The highest nitrogen concentration in the effluent was reported in November 2002 during the initial start-up month for the ATS in Tank 4. Tanks 2 and 4 recorded the highest nitrate/nitrite values, but all were below 1.5 mg/L.

Plots of dissolved orthophosphate and Kjeldahl nitrogen are provided in Figure 4-22 and Figure 4-23. The dissolved orthophosphate concentrations are much higher in Tank 4 than Tanks 2 and 3 for the full duration of the project. Tank 3 was 38 mg/L and SP2 was 8 mg/L. These concentrations decreased after the system was unplugged in February 2003. As the system was restarted, the recorded concentrations were below 2 mg/L (Figure 4-22). Peak concentrations occurred in July 2004 just before closure of the project.

Kjeldahl nitrogen was highest in November 2002 in Tank 2 and Tank 3, when the ATS was brought on-line. Injection of the air into the ATS changed which tank provided the highest monthly source of Kjeldahl nitrogen. Initially, Tank 3 provided the highest source of Kjeldahl nitrogen, but after unplugging the system, Tank 4 recorded higher values, then Tank 2. Changes are concurrent with air injection into the ATS to enhance permeability (Figure 4-23).

4.2.7 Bacteriological

Influent and effluent total coliform concentrations, measured at SP4, are shown in Figure 4-24. See also Figure 13 in Golder's report in Appendix D. Influent total coliform concentrations typically ranged from below detection limits (< 1 per 100 mL) to less than 10 per 100 mL. The July 2004 influent total coliform concentrations were anomalously high at 140 per 100 mL. The total coliform was generally less for the influent than the effluent. Peak effluent total coliform was measured in March 2003 at 500 per 100 mL; June 2003 at 467 per 100 mL; March 2004 at 30 per 100 mL; and July 2004 at 500 per 100 mL. Total coliform values from SP4 exceeded the coliform values from Highland Creek, both upstream and downstream, on the months listed above. Otherwise, the treatment tank coliforms were less than the coliform values recorded for the stream.

The results of the single SRB enumerations are shown in Table 4-2. These results of the microbiological analyses are from samples taken on September 29, 2004. The samples were analyzed for SRB using a most probable number (MPN) assay. Results indicate that SRBs were not active in the influent samples or in the effluent from Treatment Tank 3. However, viable quantities of SRBs were present in the effluent from Treatment Tanks 2 and 4.

4.3 Geochemical Modeling

Geochemical modeling was conducted by Golder. Section 4.4 is taken from the Golder report. Golder also prepared interim reports throughout the study. The complete report provided by Golder is in Appendix D. This model has the ability to simulate mixing of water, precipitation/dissolution of selected solids, redox reaction, atmospheric interaction, and adsorption

of metal onto iron oxides. The MINTEQA2 thermodynamic database was selected for this project because it is considered by many in the geochemical and regulatory communities to be the most accurate geochemical database currently available. The fast reaction kinetics of hydroxyapatite dissolution (Ref. 22) supports the application of an equilibrium model.

4.3.1 Speciation Modeling

Calcium, phosphorus, and nitrogen showed net increases, while iron, manganese, zinc, and aluminum showed net declines (see Table 4-3).

To evaluate possible controlling mineral phases, inflow and outflow water chemistries were speciated and saturation indices evaluated. Concentrations of constituents reported as below detectable limits were assumed equal to the detection limit during the modeling exercise. The potential for mineral precipitation was assessed using the saturation index provided in Appendix D and shown in Table 4-4 for August 2004.

4.4 Solid Phase Sampling Results

During the implementation of the ATS, three 5-gallon samples of treatment tank material (unused fishbone and gravel) were taken as the media was placed into the treatment tanks from the cement mixers (Figures 2.15 and 2.16). One representative sample was taken from each tank. For each bucket, the fishbone and gravel was separated, weighed, and the volumes were calculated.

Results showed that the unused media was 66.7% fishbone by volume, and 30.2% fishbone by weight; and the unit weights of the fishbone and gravel were calculated to be 20.85 pounds per cubic foot (pcf) and 94 pcf, respectively.

For the ATS treatment system, the total weight of the gravel used was 10 tons and the total weight of the Apatite II™ was 5 tons. Equal quantities of gravel and fishbone were distributed through each treatment tank.

4.4.1 Total Digestion of Fishbone from ATS

Fishbone samples from Tanks 2, 3, and 4 were digested and analyzed to determine the total concentrations of contaminants contained on the fishbone.

Digested fishbone samples from each tank were sent to SVL Analytical in Kellogg, Idaho for the analysis of Zn, Cd, Pb, Fe, Mn, Mg, and Ca. The results for the solid phase digestions are presented in Appendix E.

The results obtained from the digest analysis indicate an increase in the concentrations of Zn, Cd, Pb, Fe, and Mn compared to fishbone that was not exposed to the contaminated water (Figures 4-25, 4-26, 4-27, 4-28, and 4-29). See also Figure 21 in Golder's report in Appendix D. Untreated fishbone samples 1, 2, and 3 were obtained from each of the treatment tanks during the installation of the ATS. Comparing these samples to the treated fishbone samples collected from each treatment tank after NSM discharge was treated, the concentrations of Zn increased by an average of 97 times; Mn by 48 times; Fe by 18 times; Pb by 12 times; and Cd by 4 times. Magnesium and Ca were the only elements analyzed that decreased in concentration (Figures 4-30 and 4-31). Also, see Figure 7 from the Golder Report contained in Appendix D.

As can be seen in Figures 4-25, 4-26, 4-27, 4-28, and 4-29, Cd, Pb, Fe, and Mn concentrations were highest at the top or surface of the media placed in the tanks. However, Zn concentrations varied with depth throughout the entire sampled interval.

4.4.2 X-Ray Diffraction

Samples from Tanks 2, 3, and 4, and a sample of the uncontaminated (raw) fishbone were analyzed using XRD to identify any crystalline structures present in the treatment media.

The analysis confirms the composition of the bone as poorly crystalline hydroxyapatite. The samples analyzed from Tanks 2, 3, and 4 had no detectable crystalline structures other than that of the

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hydroxyapatite itself. If any crystalline materials are being produced in the reactor, the mass of the crystalline structure was too small to detect, or the materials are amorphous and could not be detected using XRD. Figure 4-32 is a representation of the graphs produced from the XRD analysis. The graphs from all samples were virtually identical.

4.4.3 Scanning Electron Microscopy/ Energy Dispersive X-Rays

Analysis using SEM/EDX was performed on the raw fishbone as well as the contaminated fishbone from each treatment tank. Analyses were performed at Montana Tech, Butte, Montana, and Image and Chemical Analysis Laboratory, Bozeman, Montana.

4.4.3.1 Unreacted (Raw) Fishbones

A sample of uncontaminated fishbone was analyzed using SEM/EDX. Results from the EDX analysis identified the primary composition of the raw fishbone as oxygen, carbon, Ca, and P, which are the primary elements found in hydroxyapatite. The results are shown in Figure 4-33.

4.4.3.2 Treatment Tank 2

The results from several of the bone samples in Treatment Tank 2 have similar trends. Zinc was the focus during this project due to the concentrations found in the influent water and on the reacted fishbones. Zinc accounts for approximately 6% of the total sample mass within the scanned area. The EDX analysis also shows a weight percent increase in sulfur. This trend was common in all samples analyzed. The remaining mass can be attributed to Ca, Al, P, silica, and several other metals. Figure 4-34 is a spectrum of the scan area on the bone from Treatment Tank 2.

Specific “bright spots” observed using the EDX backscatter option on the SEM were analyzed from a fishbone sample from Tank 2. The results from the EDX analysis show that the scan of the selected spot is made up primarily of oxygen, Zn, and sulfur. The Zn accounted for approximately 18% of the total weight within the scan area, while sulfur accounts for roughly 10%. Figure 4-35 is the EDX scan of a bright spot from Tank 2.

4.4.3.3 Treatment Tank 3

The bone samples analyzed from Treatment Tank 3 demonstrated similar results to those from Treatment Tank 2. Zinc is attributing roughly 6% of the total weight within the scan area, while sulfur contributes about 3% after treating a volume of 2.85 million gallons of water as of July 2003. An additional fishbone sample from Tank 3 was analyzed using the backscatter detector. The EDX analysis of a bright spot shows that Zn accounted for approximately 16% of the total weight, similar to the 18% found in Tank 2. Scans and data from Tank 2 can be found in Appendix C.

4.4.3.4 Treatment Tank 4

The bone samples analyzed from Tank 4 are again similar to those analyzed from Tanks 2 and 3 in that the surface of the bone particles was enriched in both Zn and sulfur within the area scanned when compared to the unreacted bone. Treatment Tank 4 had an average Zn weight percent on the bone surface of roughly 17% and a sulfur weight percent of approximately 13% after treating a volume of 1.5 million gallons of water as of July 2003. The resulting average value was based on scanning the entire surface of the fishbone not just one location (Figure 4-36).

Table 4-5 provides the results of the EDX analysis for a fishbone sample taken from Treatment Tank 4.

The backscatter detector was also used to look at a sample of fishbone from Treatment Tank 4. In addition, a comparative analysis was performed between one of the “bright spots” and a section of dark surface. Figure 4-37 is an image showing the two scanned areas. Tables that follow represent the weight percent of various elements found within the bright and dark regions.

Results from Table 4-6 show that the bright spot that was analyzed is 36.5% Zn and 17.4% sulfur. These two elements account for more than half of the total weight percent in the area that was scanned. Results from Table 4-6 show that the dark region that was scanned is approximately 6% Zn, while sulfur is roughly 5% of the total weight.

For confirmation of the presence of ZnS, a fishbone sample taken from Tank 4 was analyzed under high vacuum using the SEM. Figure 4-38 is an image of ZnS crystals that were formed on the surface of a fishbone sample from Tank 4. This image is magnified 9,000 times and has a scale of 300 nanometers.

The spherical structures within the image were identified as ZnS crystals. Previous research performed identified similar shaped ZnS crystals in an anaerobic treatment system. Raw Fishbone date in represents an EDX analysis of Figure 4-38. The Zn accounts for over 36% of the total weight within that scan region, while sulfur contributes over 17% of the total weight.

Since ZnS is being precipitated in the ATS, it can be stated that Cd and Pb may also precipitate as metal sulfides. If concentrations of Zn, Cd, and Pb were equal, the solubility products for each metal could predict this. This is due to the solubility products of each metal. Zinc sulfide is the most soluble, which indicates that cadmium sulfide (CdS) and PbS should precipitate before ZnS. Table 4-7 is a list of the solubility products of Cd, Pb, and Zn.

4.5 Toxicological Sampling Results

Water samples from the NSM site in Idaho were shipped to the EPA Laboratory in Cincinnati, Ohio for toxicity testing in 2003 and 2004. A series of acute aquatic toxicity tests with *P. promelas*, the fathead minnow, and *C. dubia*, a freshwater invertebrate, were conducted with these samples. The purpose of these tests was to establish the level of toxicity for discharge from the mine site and to evaluate the effectiveness of the treatment process currently being used at this site.

Routine initial chemical parameters were determined and toxicity tests were started upon arrival of the samples. The tests with *P. promelas* and *C. dubia* were 48-hour renewed acute tests, conducted at 20 °C. Each sample was analyzed using both species.

All tests were conducted using moderately hard, reconstituted water as the control and dilution water. Appendix B contains summaries of all initial and final chemistries and results for toxicity tests.

All LC50 values were determined using the EPA statistical analysis disk and Trimmed Spearman-Karber Program, Version 1.5, which adjusts for control mortality. The survival no observed acute effect level (NOAEL) was determined using the EPA statistical analysis disk and Dunnett's Program, Version 1.5.

Table 4-8 summarizes the toxicity results for the 2003 and 2004 samples. The results from the tests indicate that the treatment system being used to remediate the waste from this mine site reduced the toxicity of the effluent water over that of the influent water. Refer to Appendix B for the complete toxicity results.

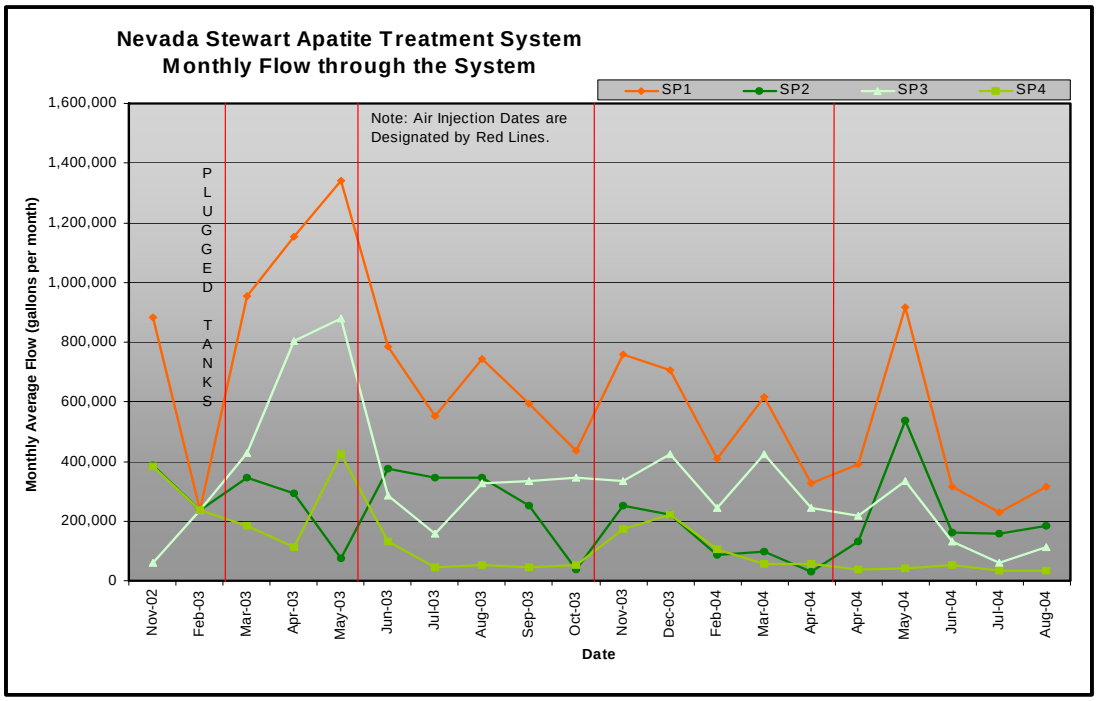

Figure 4-1. NSM ATS flow through system in gallons per minute.

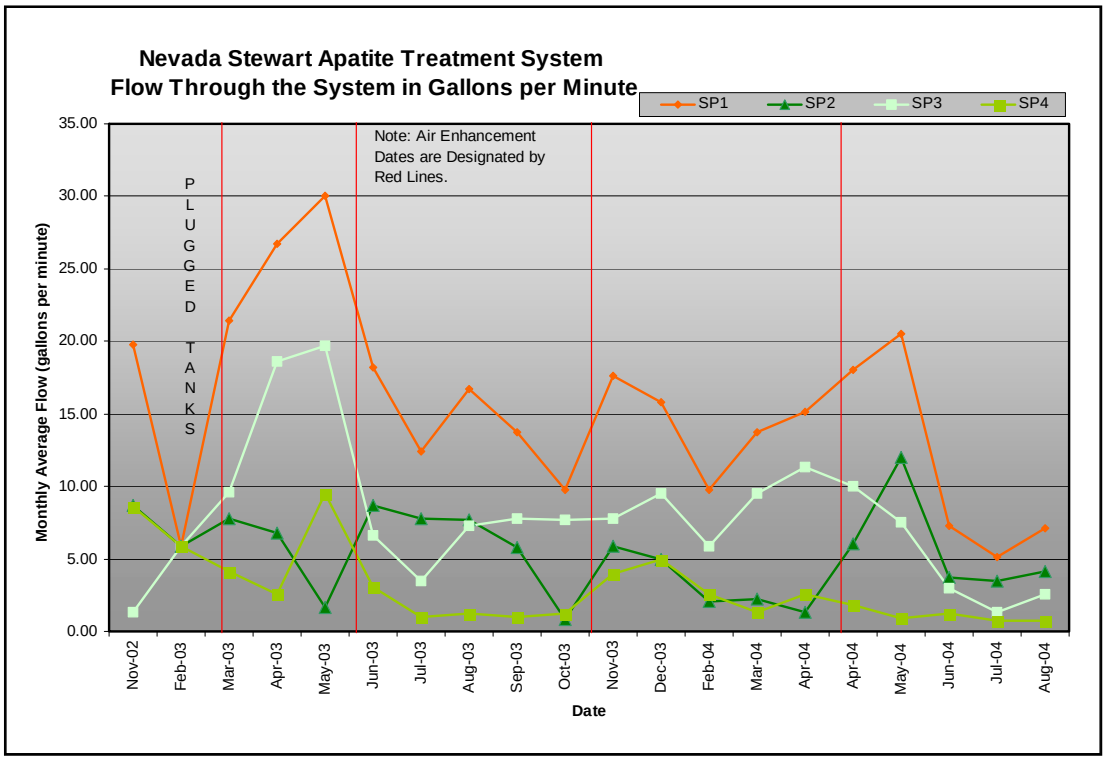

Figure 4-2. NSM ATS monthly flow through system.

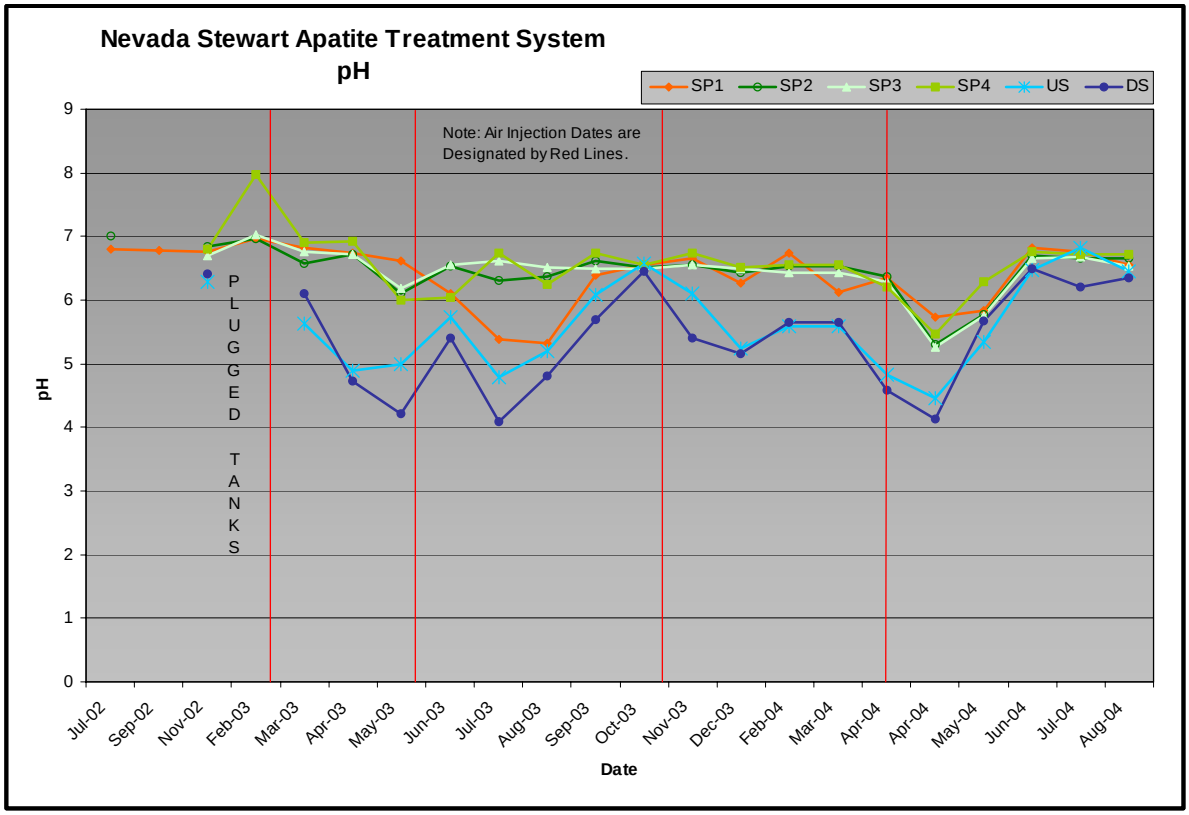

Figure 4-3. NSM ATS pH levels.

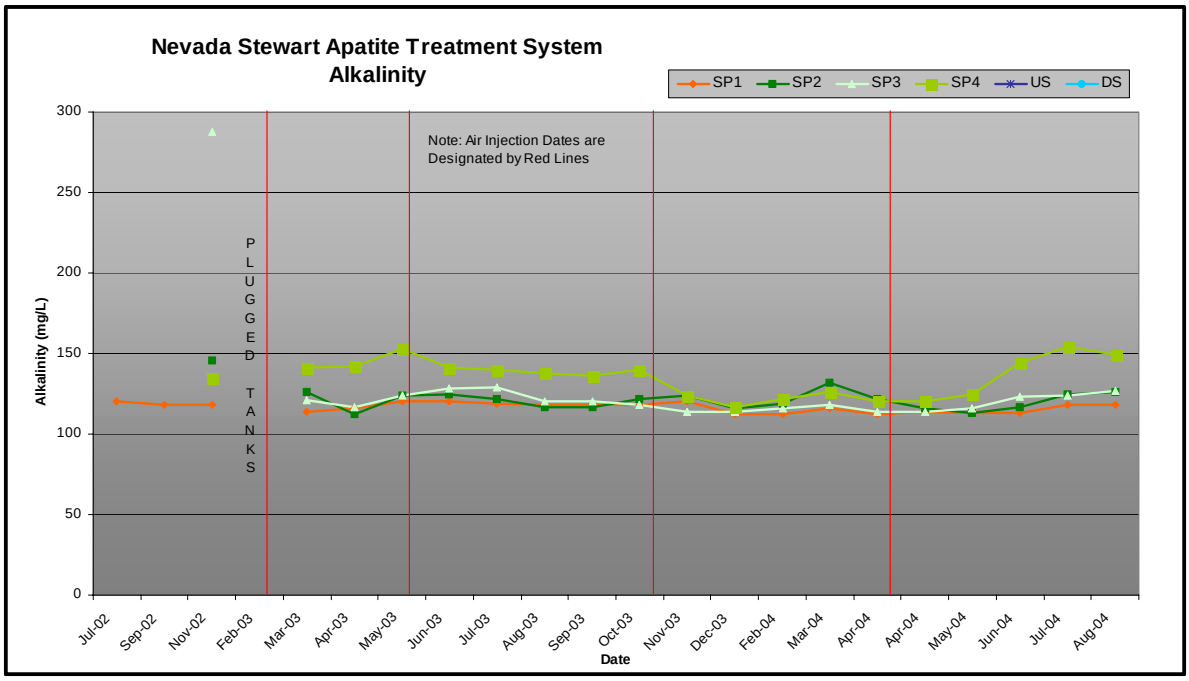

Figure 4-4. NSM ATS alkalinity.

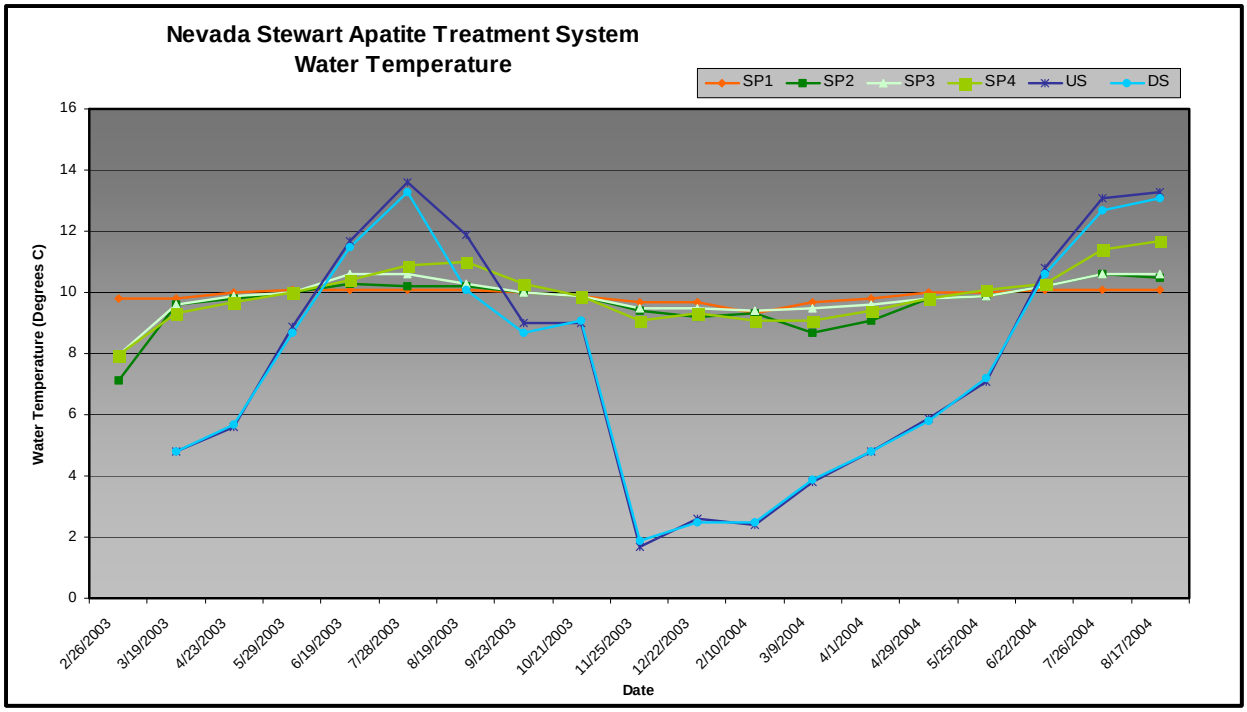

Figure 4-5. NSM ATS water temperature.

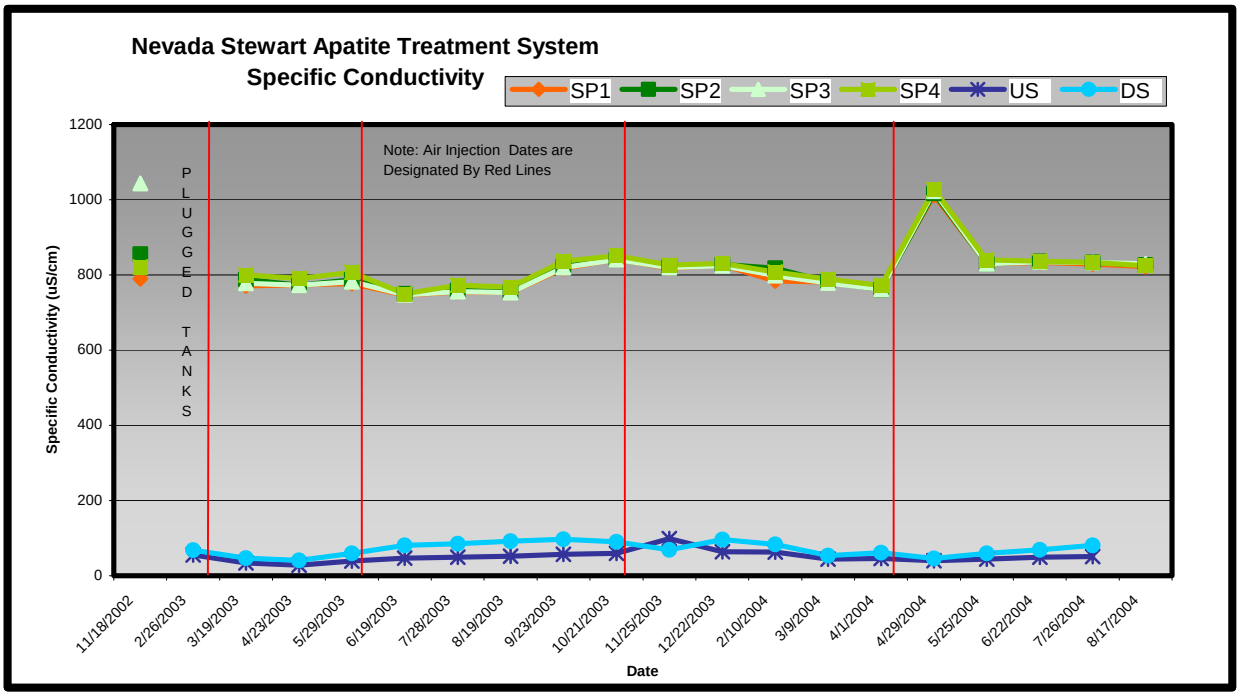

Figure 4-6. NSM ATS specific conductivity.

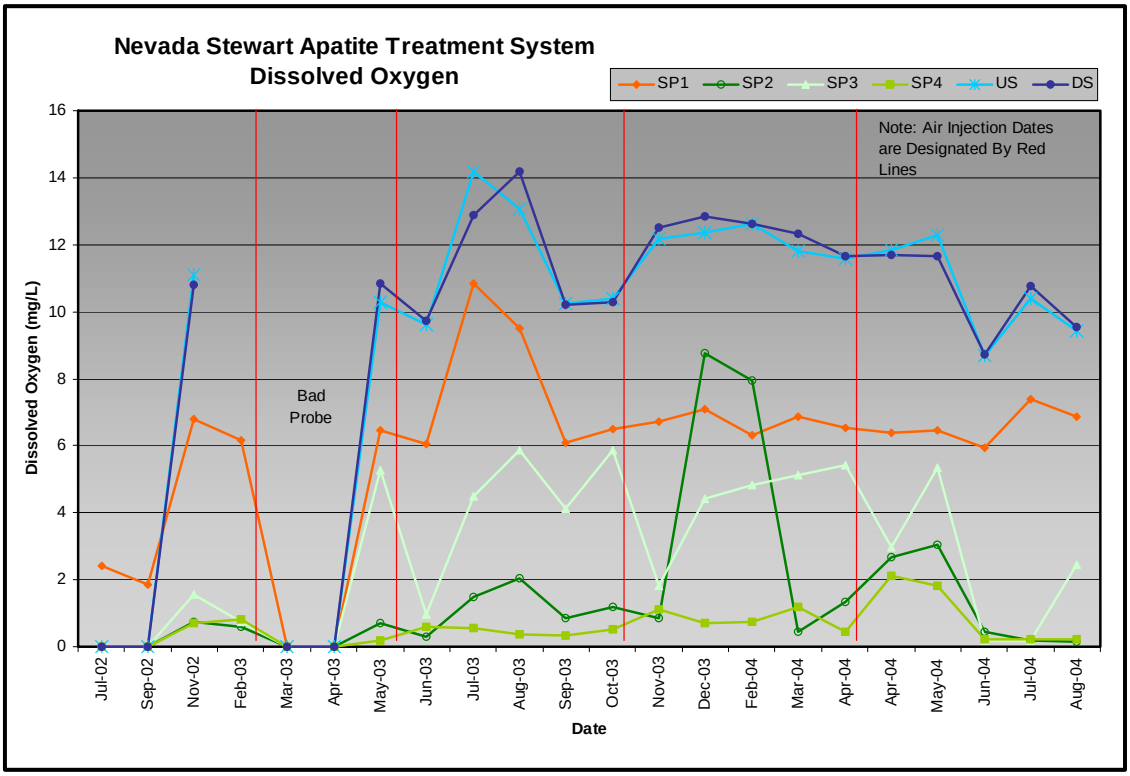

Figure 4-7. NSM ATS dissolved oxygen.

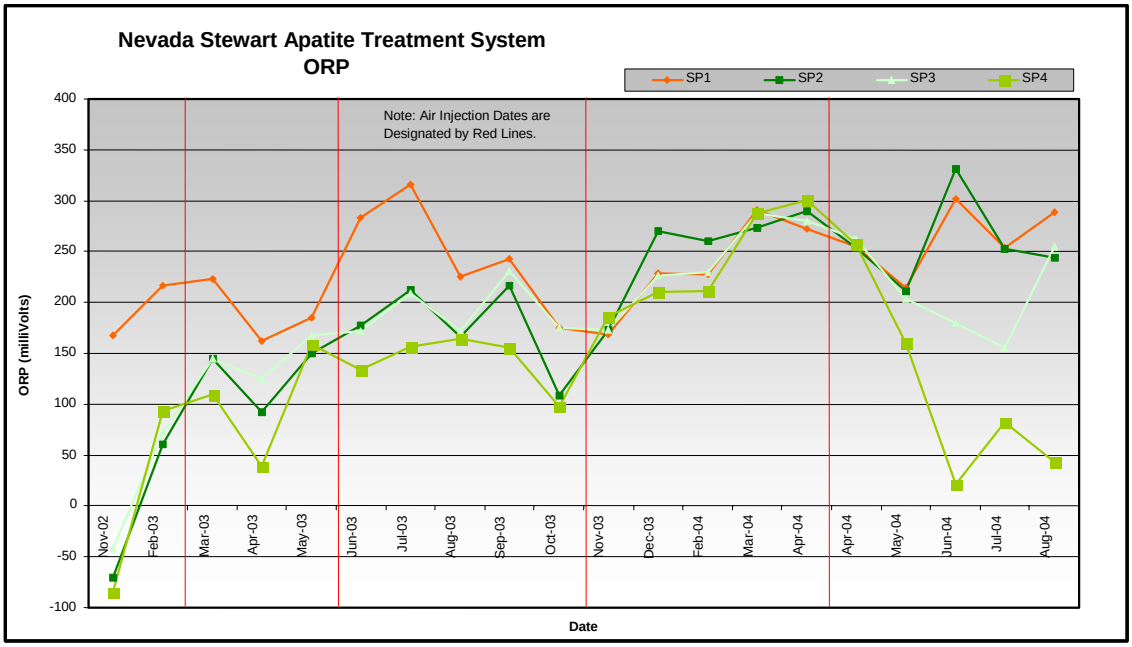

Figure 4-8. NSM ATS ORP.

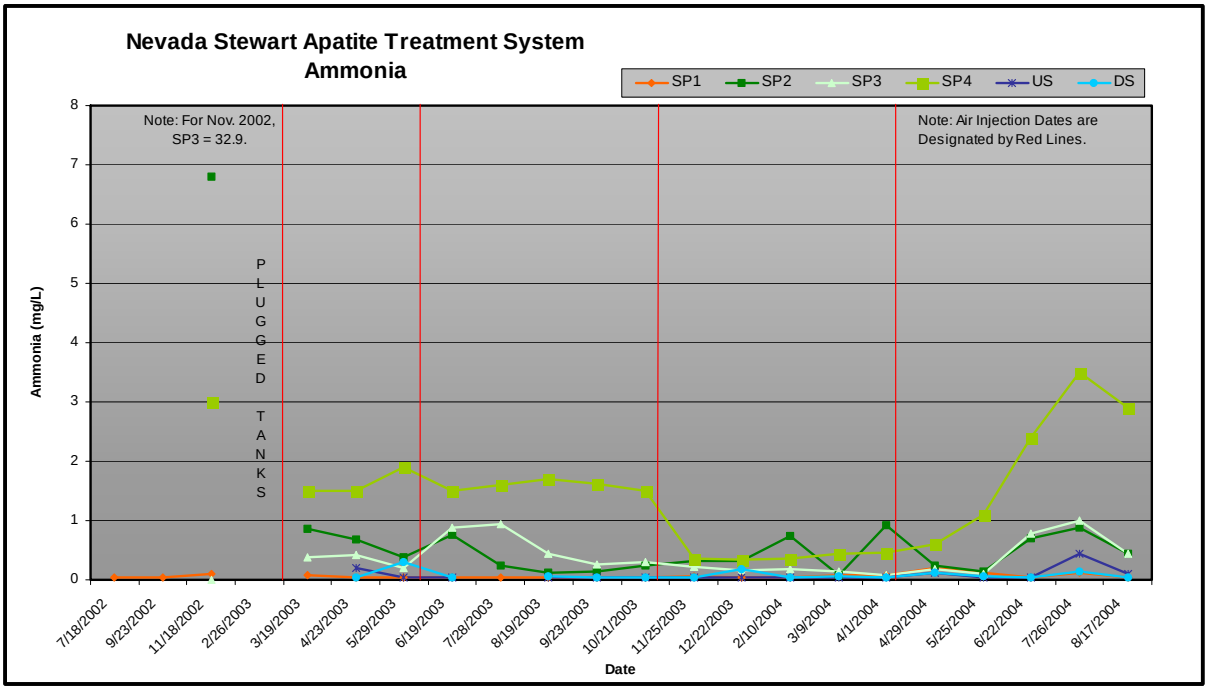

Figure 4-9. NSM ATS ammonia.

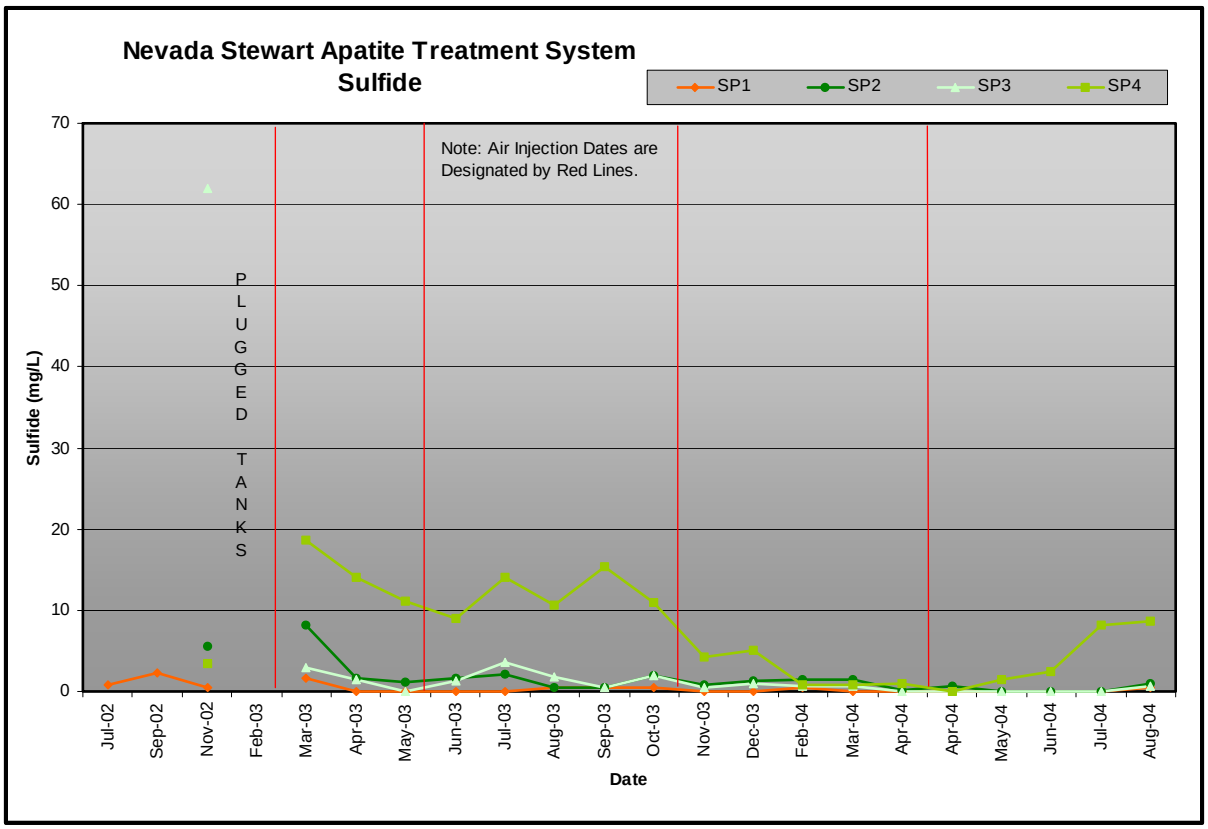

Figure 4-10. NSM ATS sulfide.

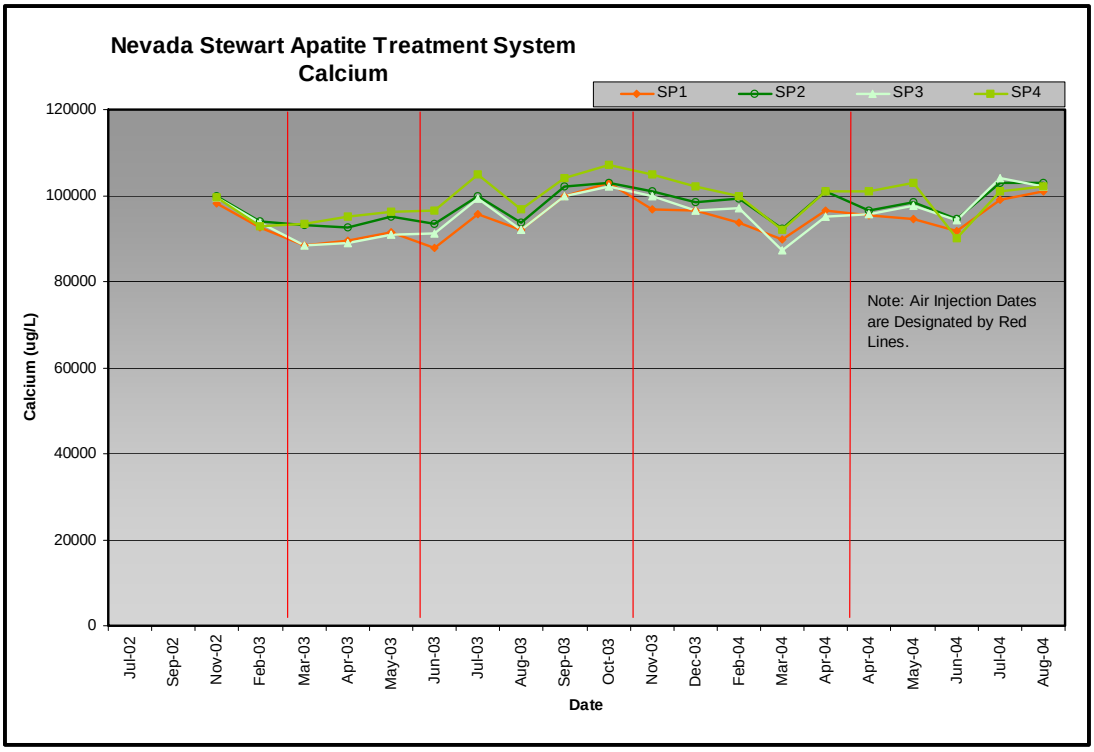

Figure 4-11. NSM ATS Ca.

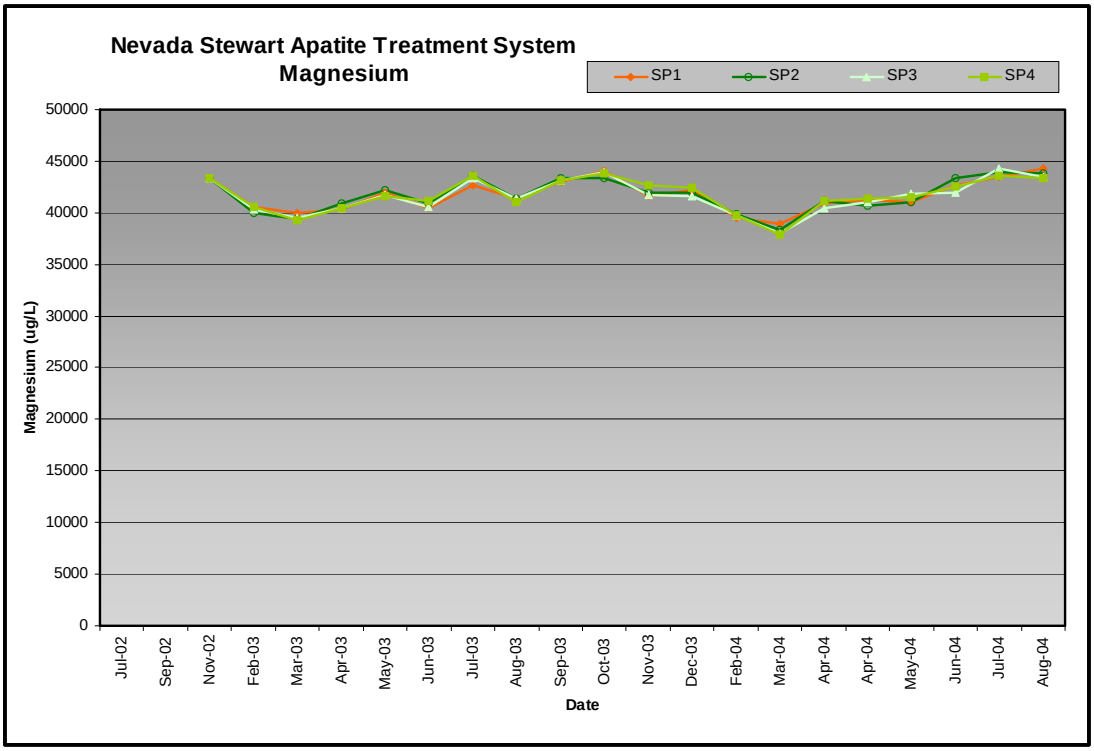

Figure 4-12. NSM ATS Mg.

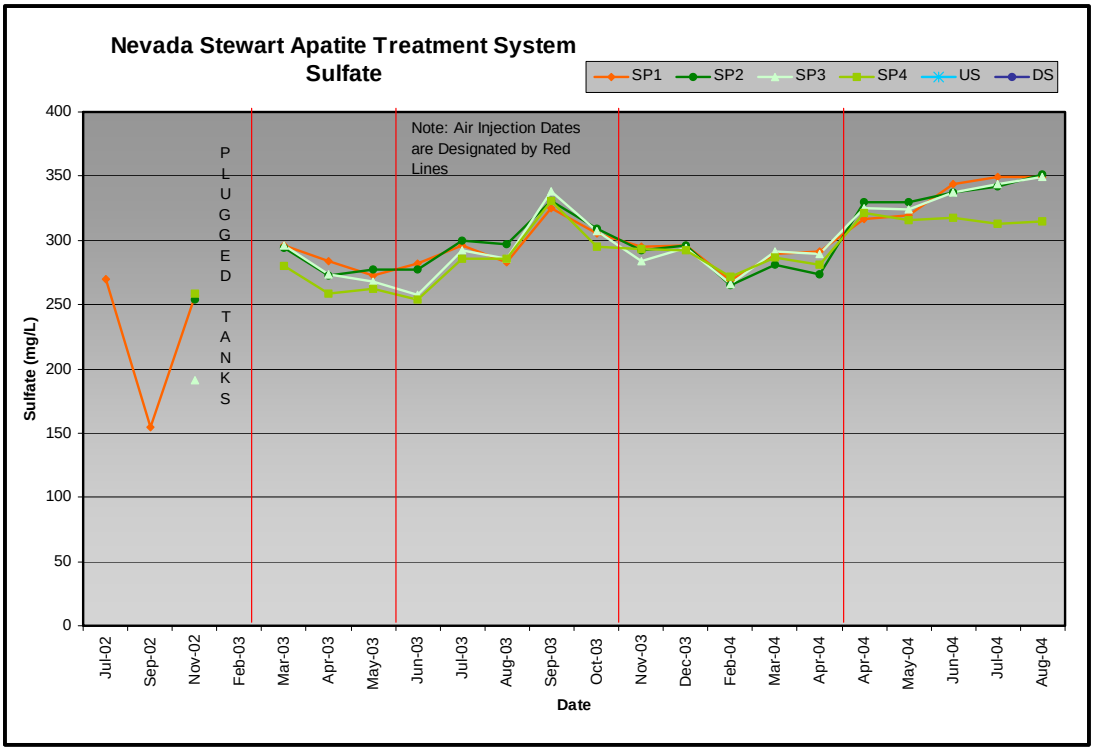

Figure 4-13. NSM ATS sulfate.

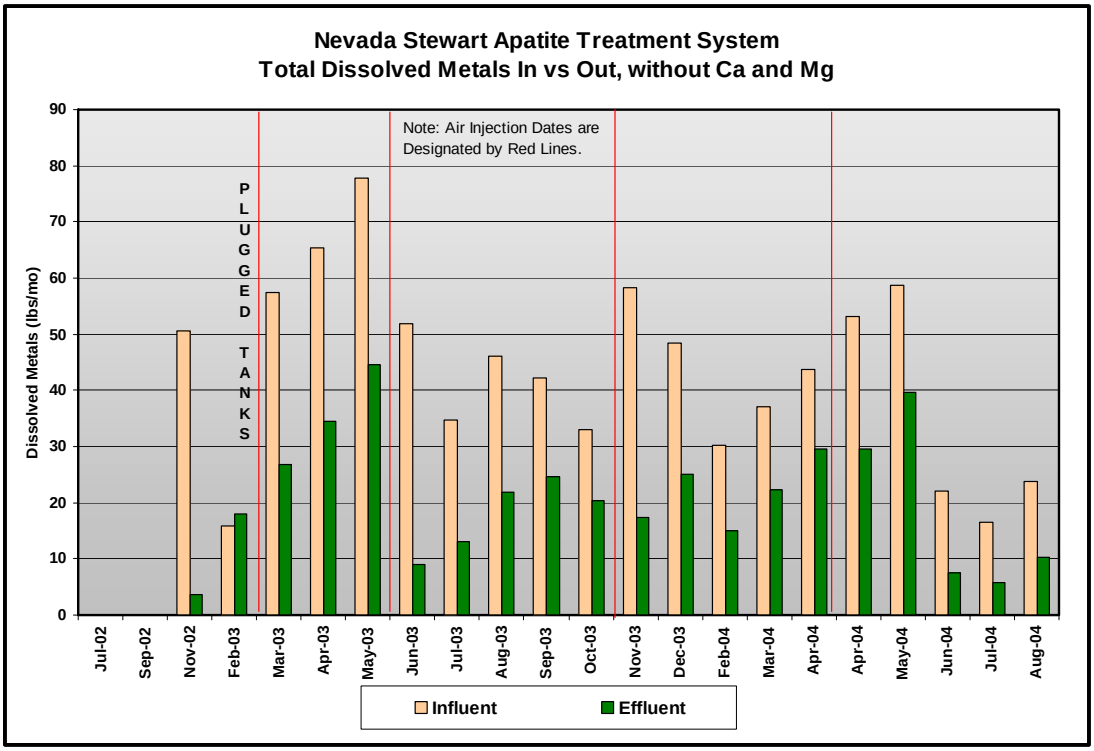

Figure 4-14. NSM ATS total dissolved metals, in versus out, without Ca and Mg.

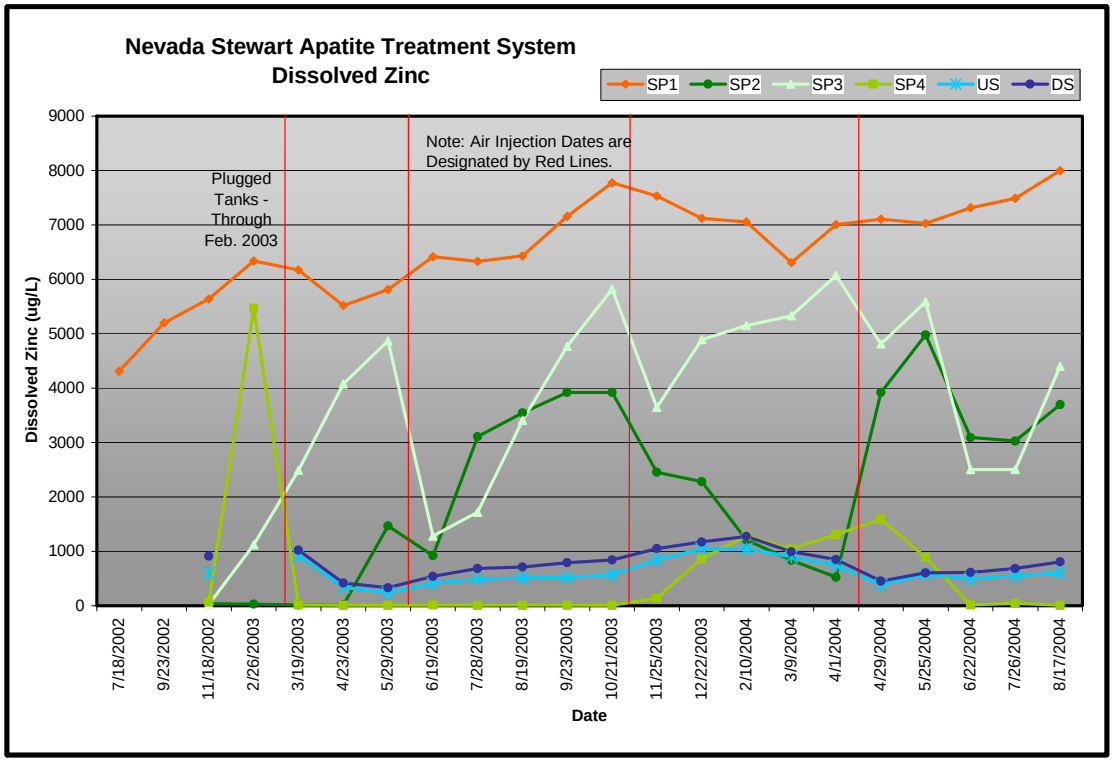

Figure 4-15. NSM ATS dissolved Zn.

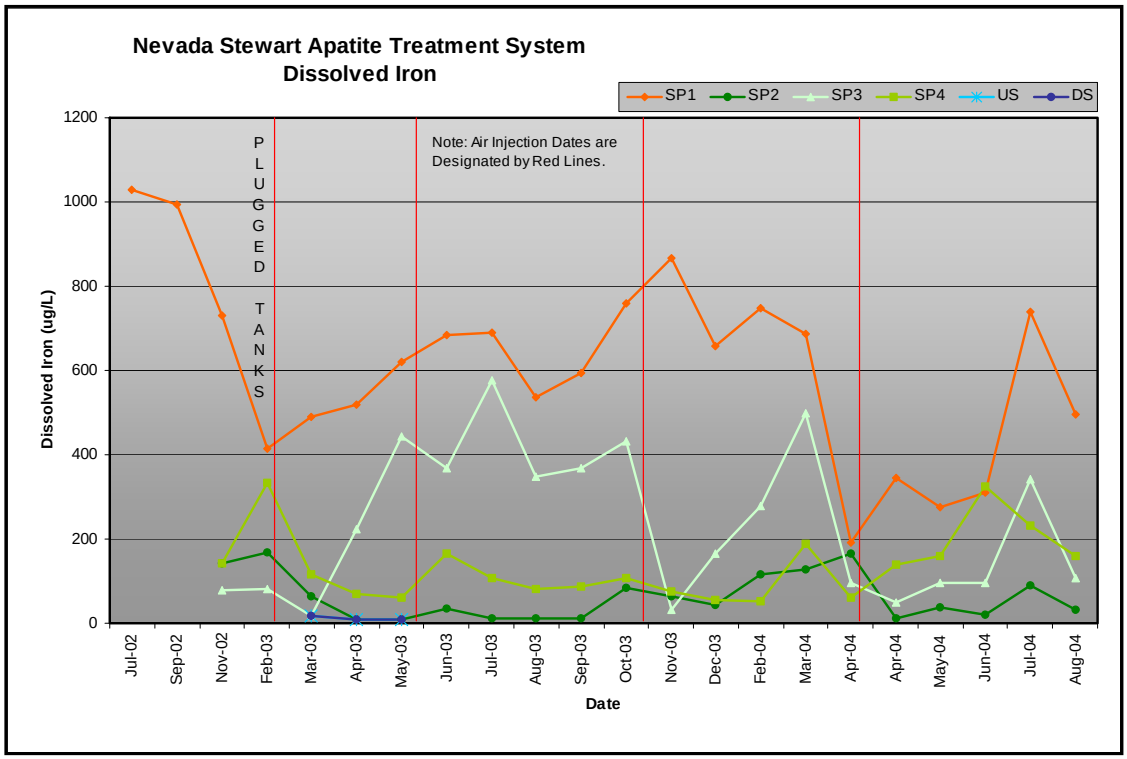

Figure 4-16. NSM ATS dissolved Fe.

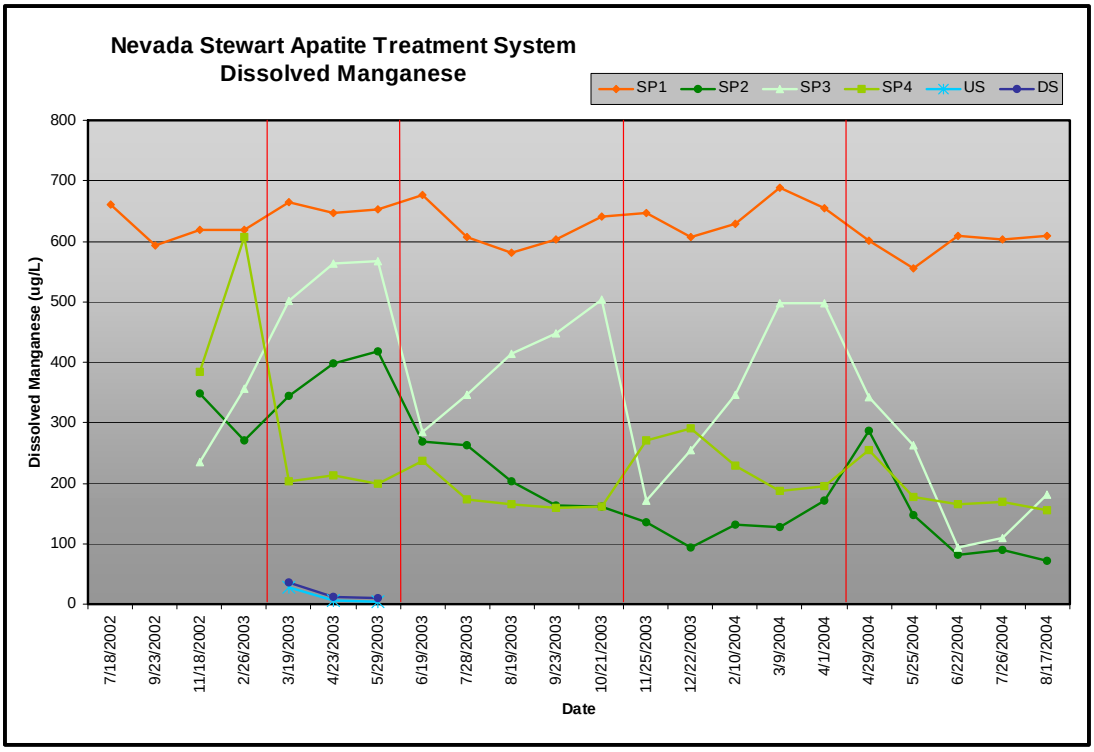

Figure 4-17. NSM ATS dissolved Mn.

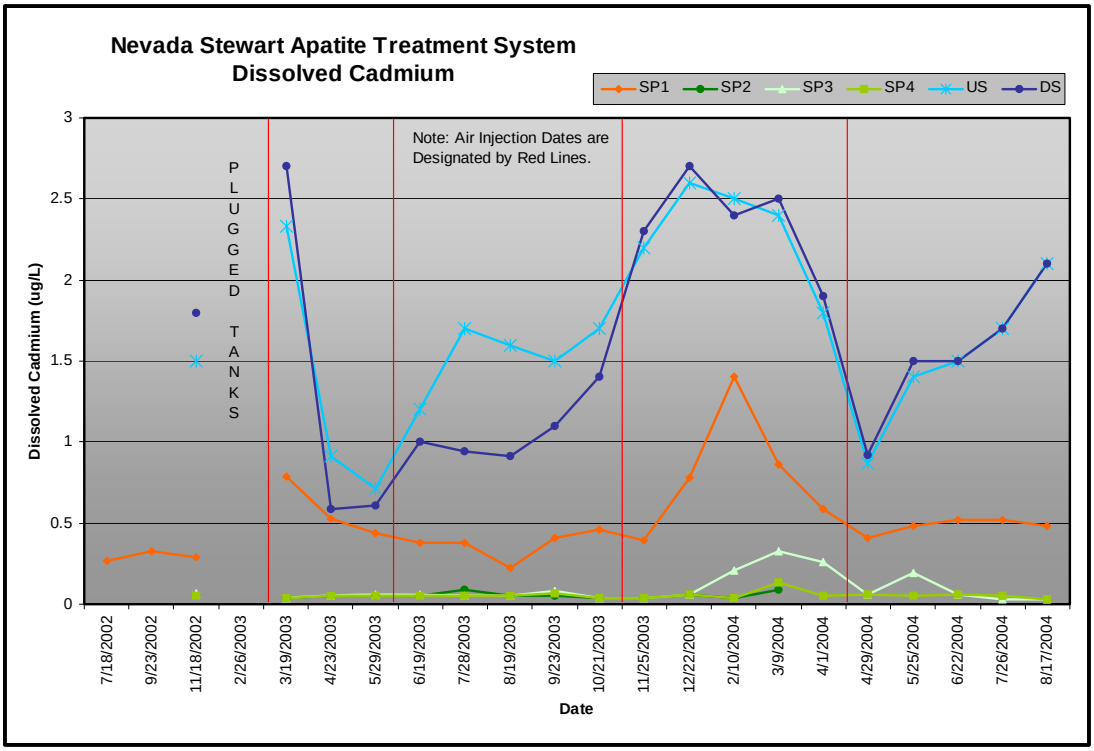

Figure 4-18. NSM ATS dissolved Cd.

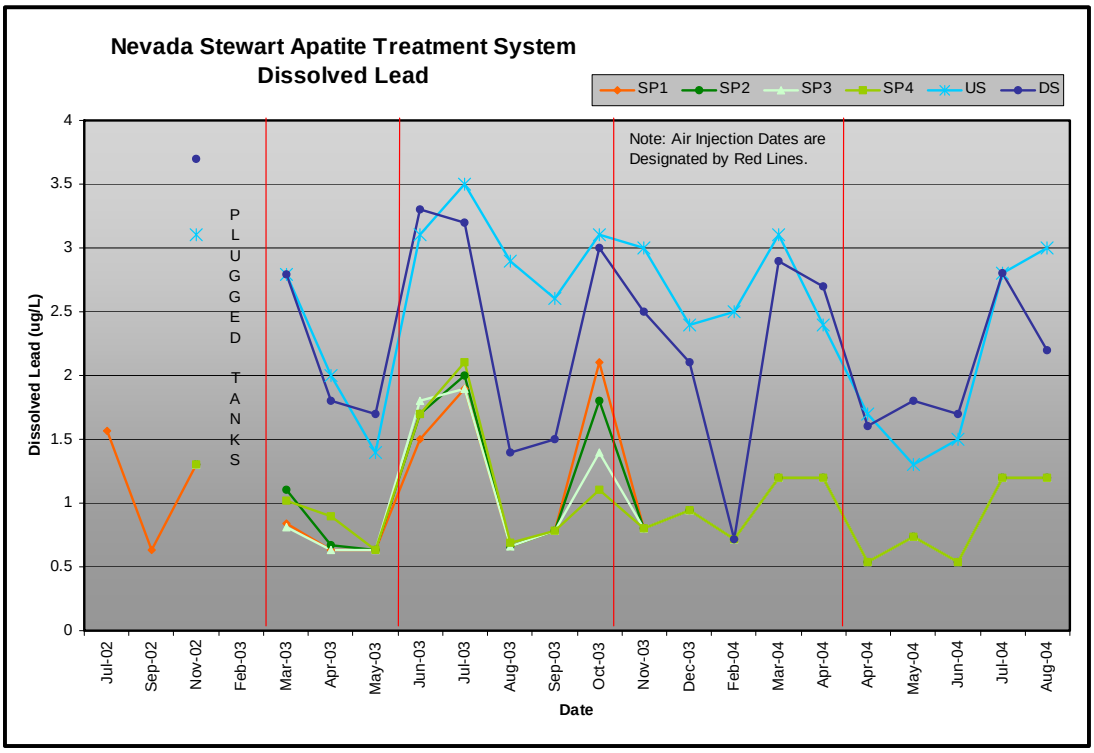

Figure 4-19. NSM ATS dissolved Pb.

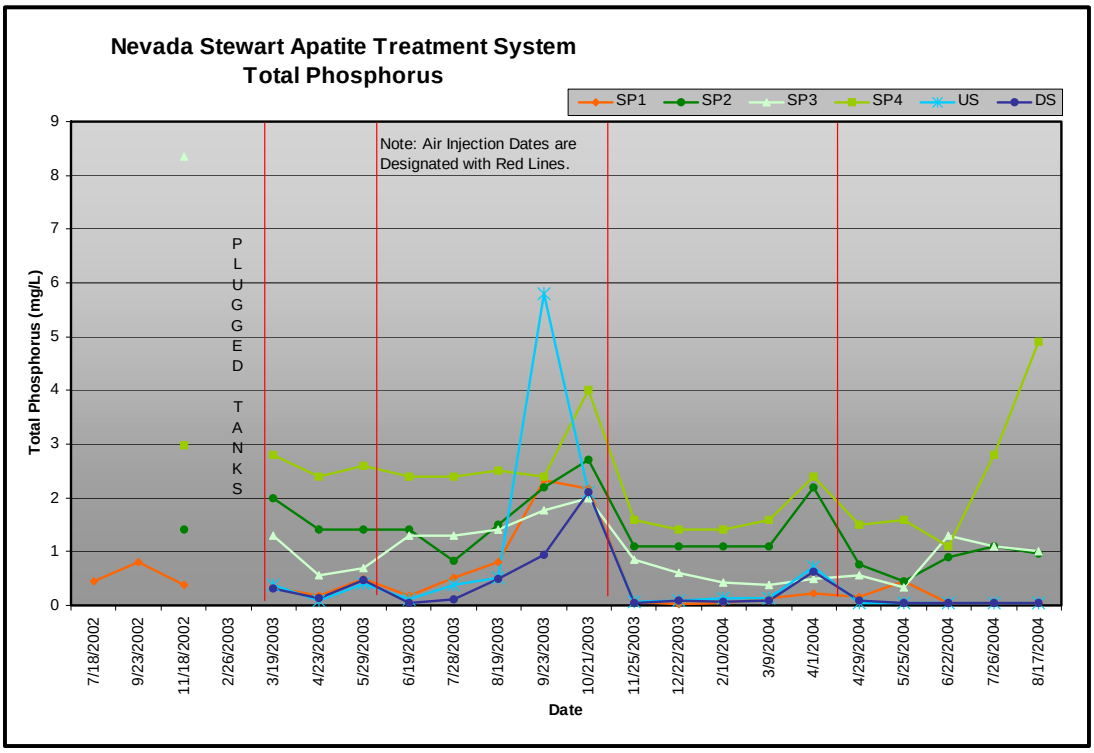

Figure 4-20. NSM ATS total P.

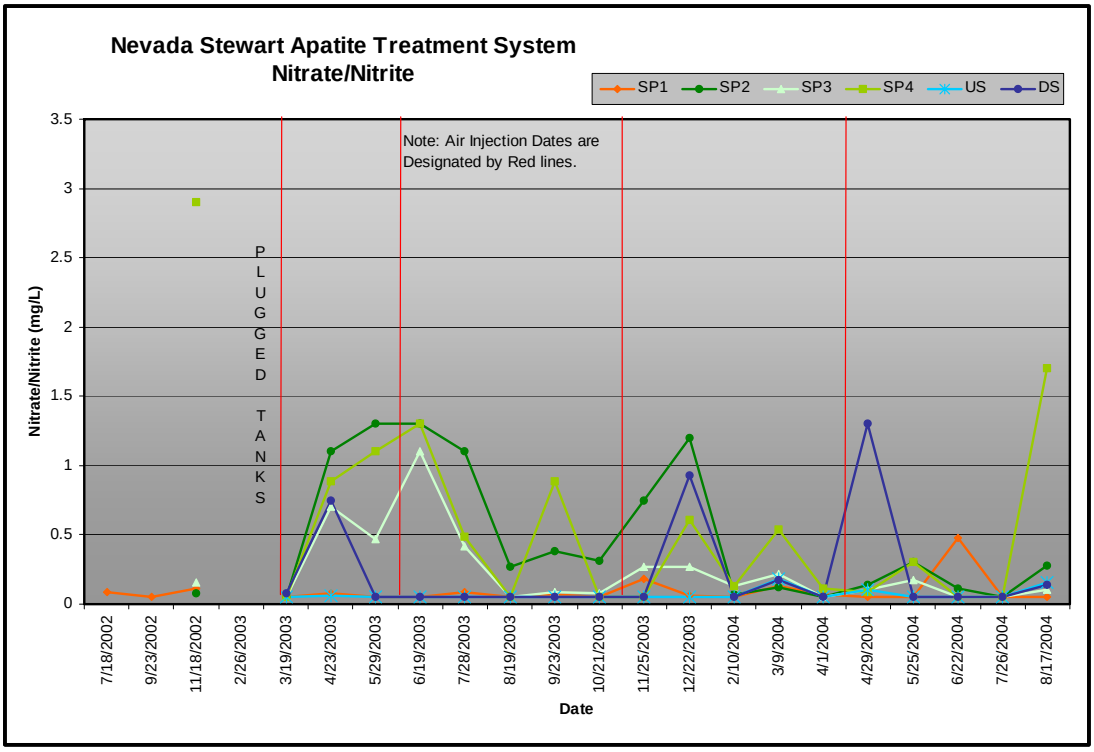

Figure 4-21. NSM ATS nitrate/nitrite.

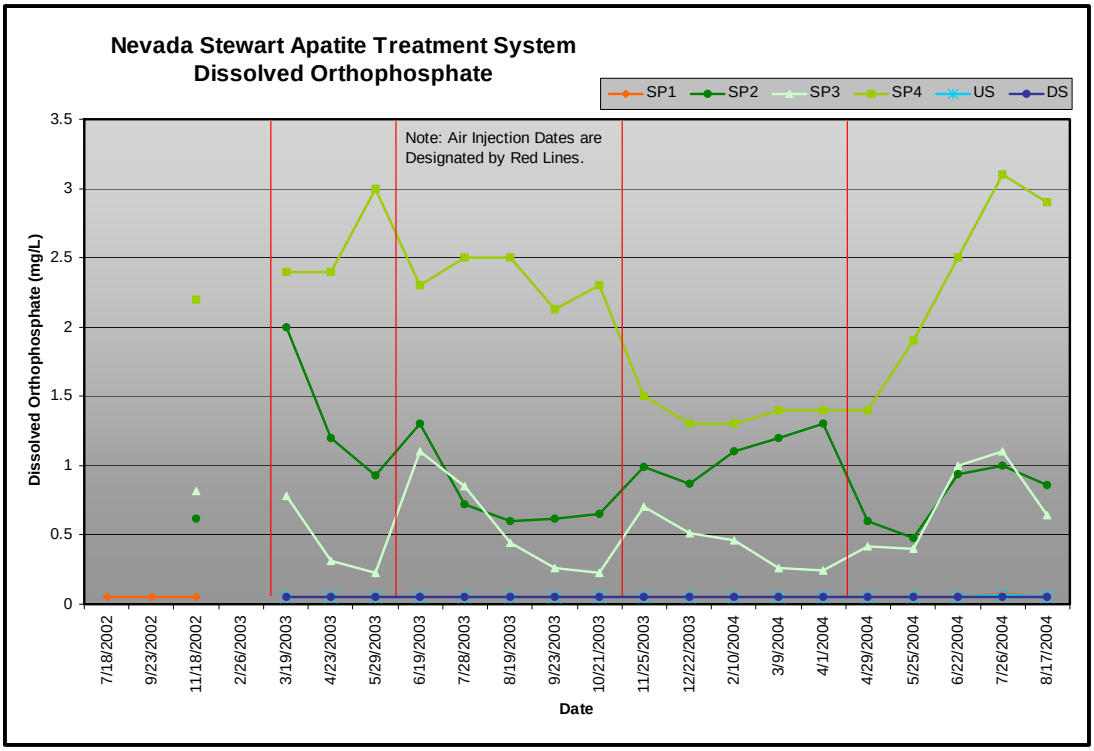

Figure 4-22. NSM ATS dissolved orthophosphate.

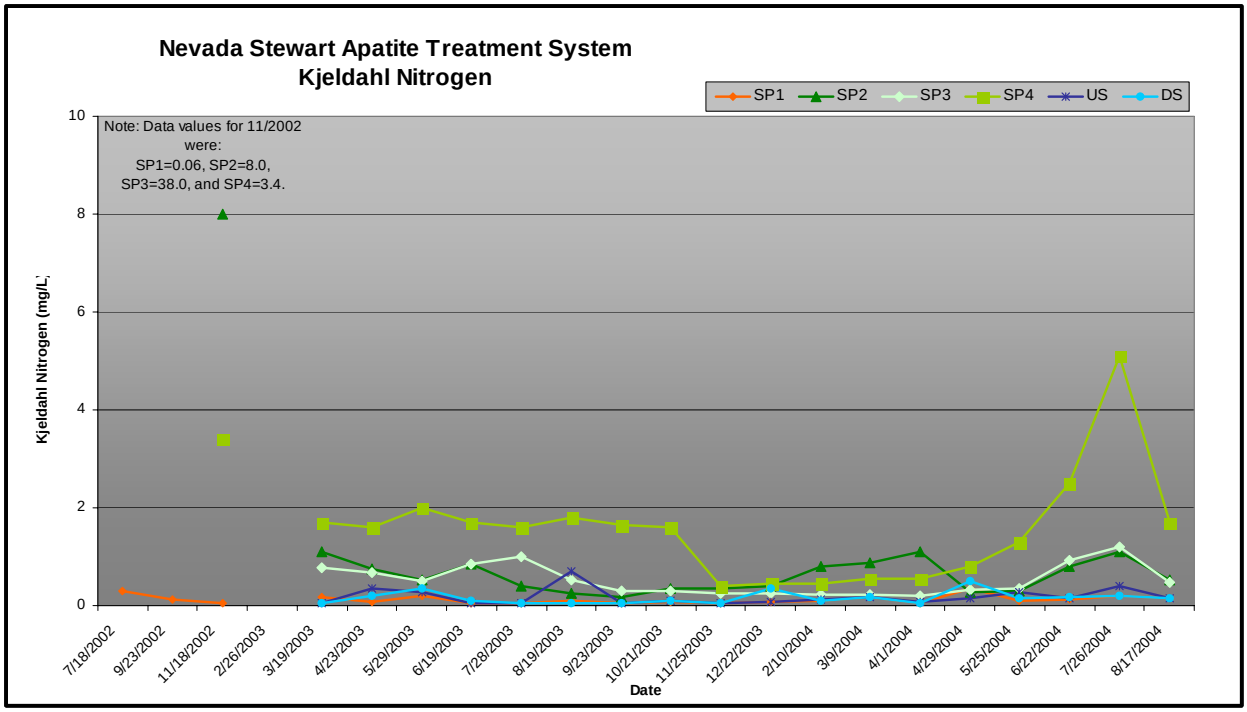

Figure 4-23. NSM ATS Kjeldahl nitrogen.

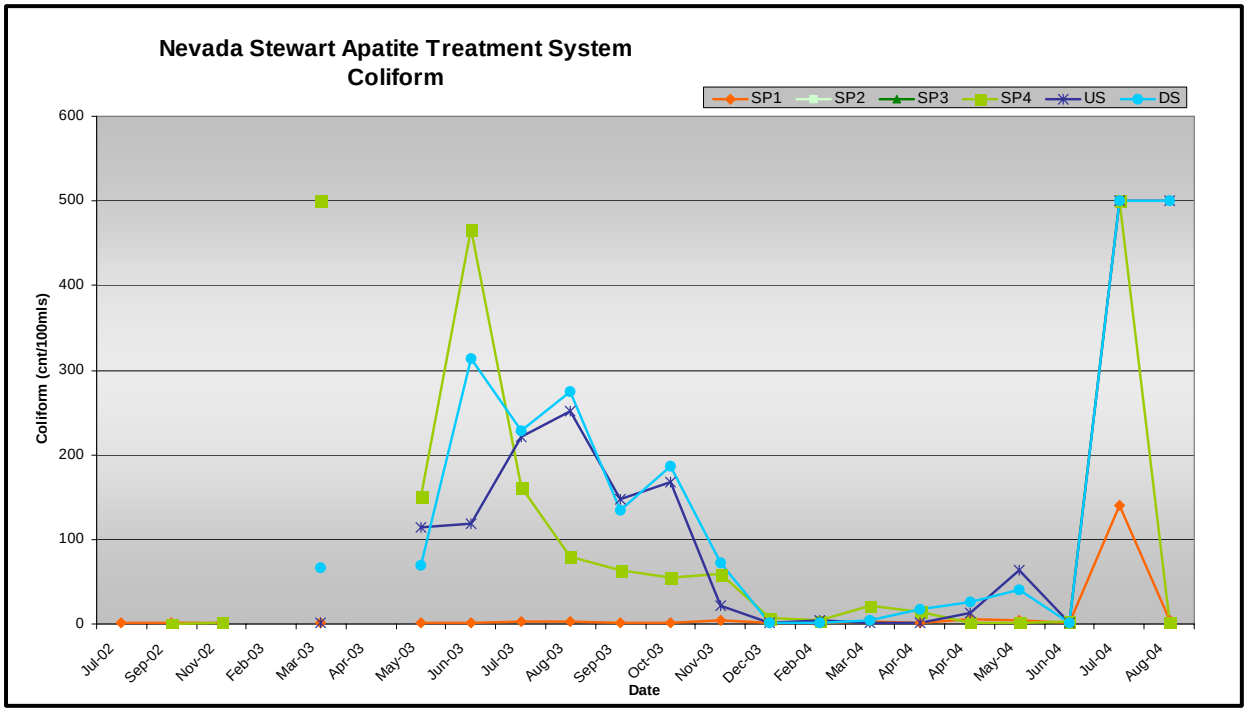

Figure 4-24. NSM ATS coliform.

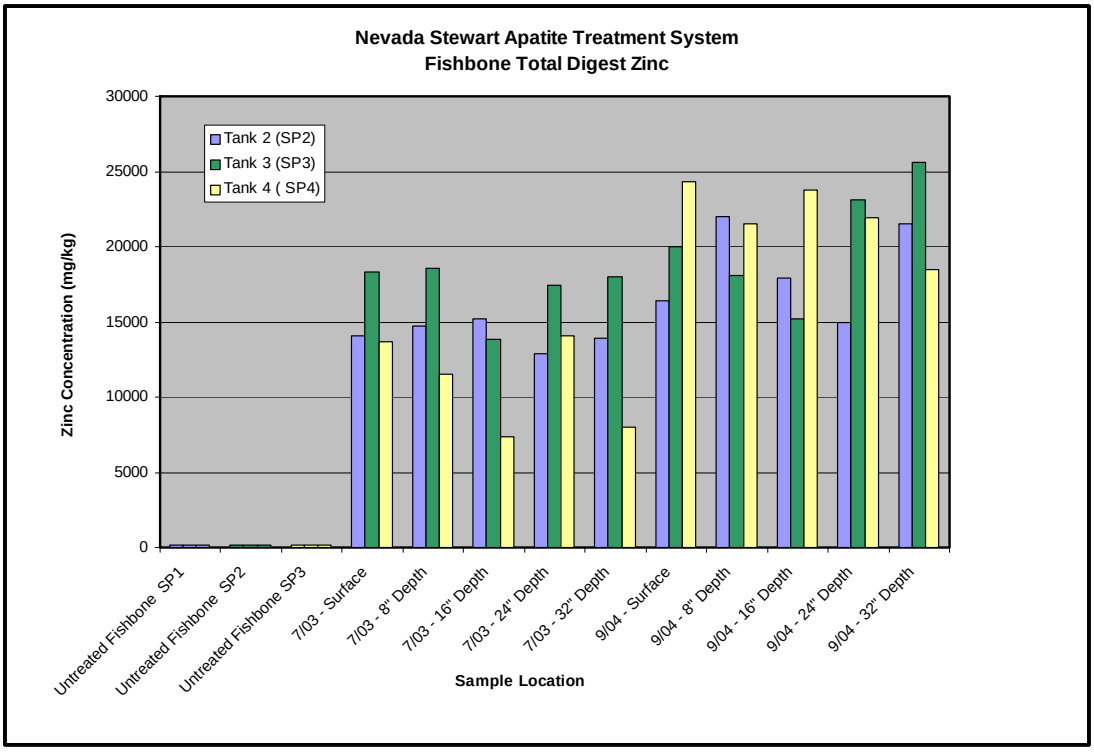

Figure 4-25. NSM ATS total digest Zn.

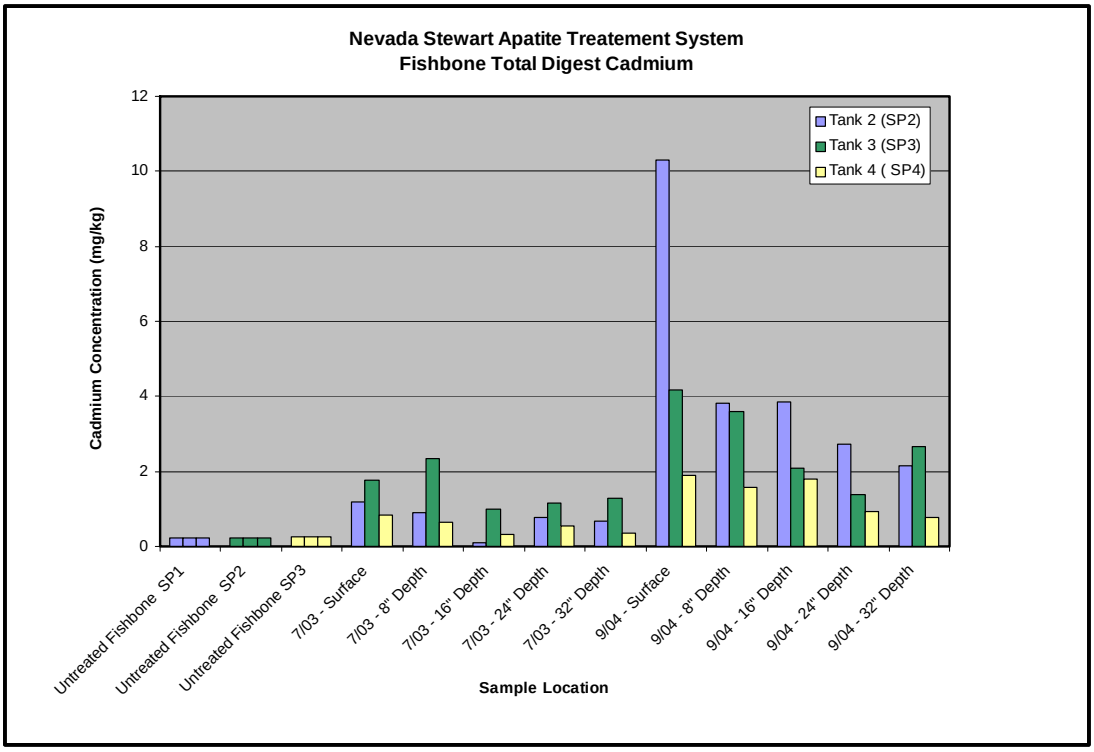

Figure 4-26. NSM ATS total digest Cd.

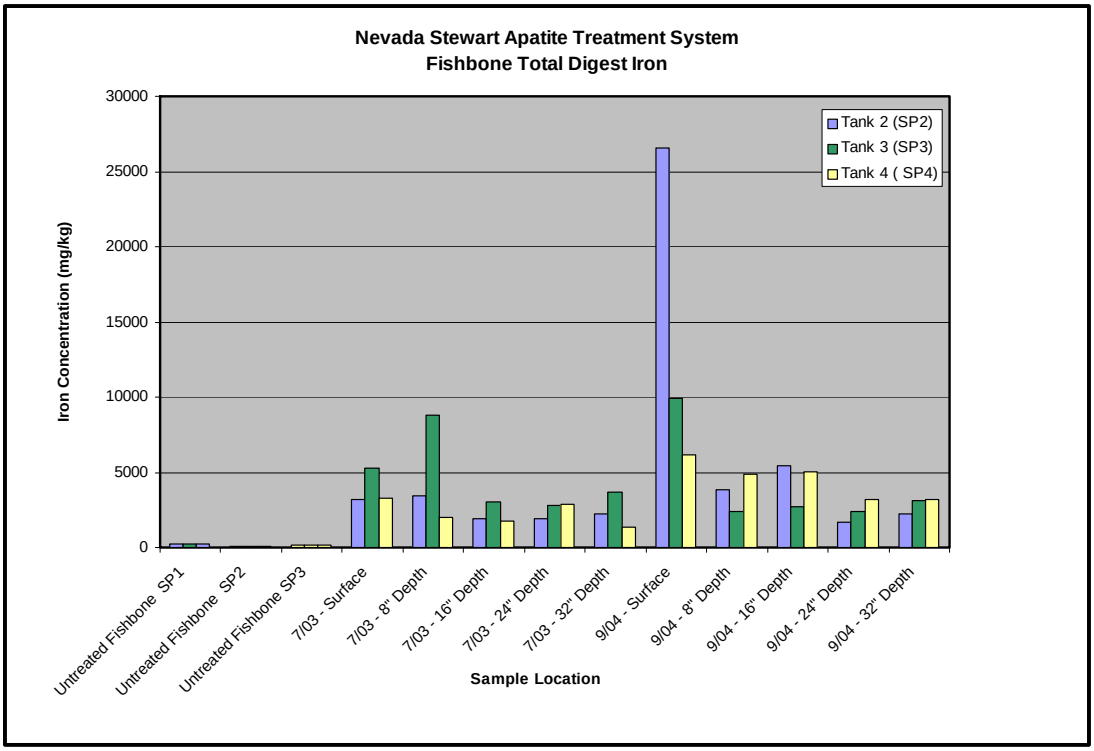

Figure 4-27. NSM ATS total digest Pb.

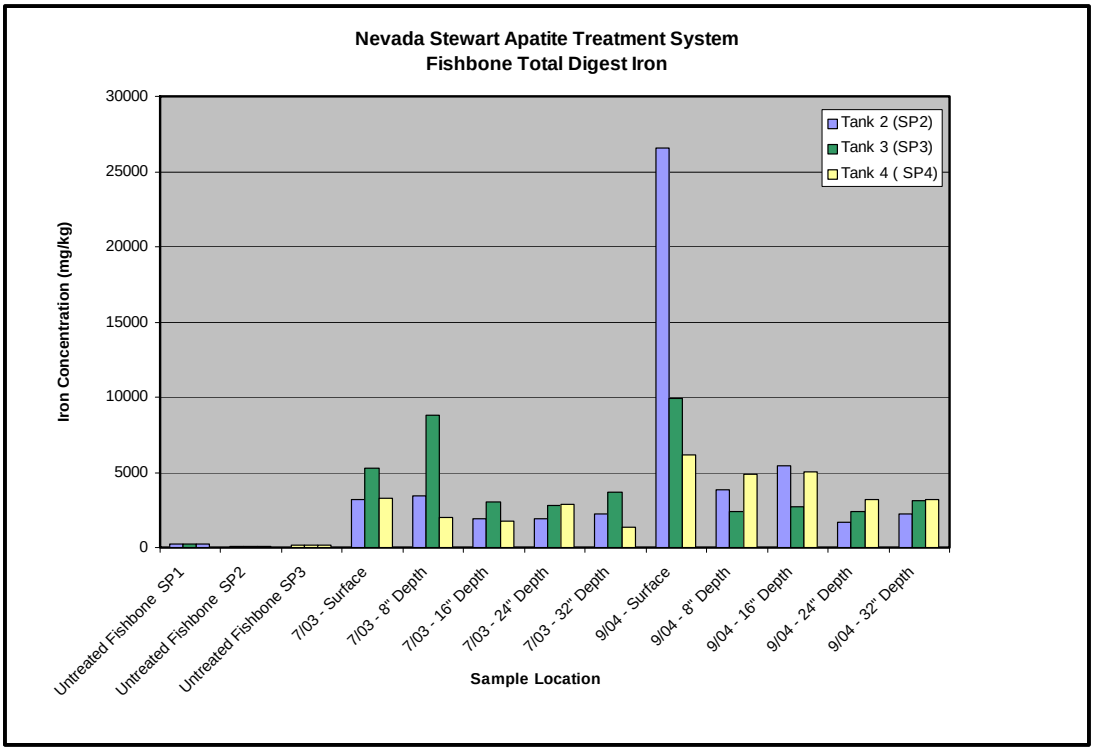

Figure 4-28. NSM ATS total digest Fe.

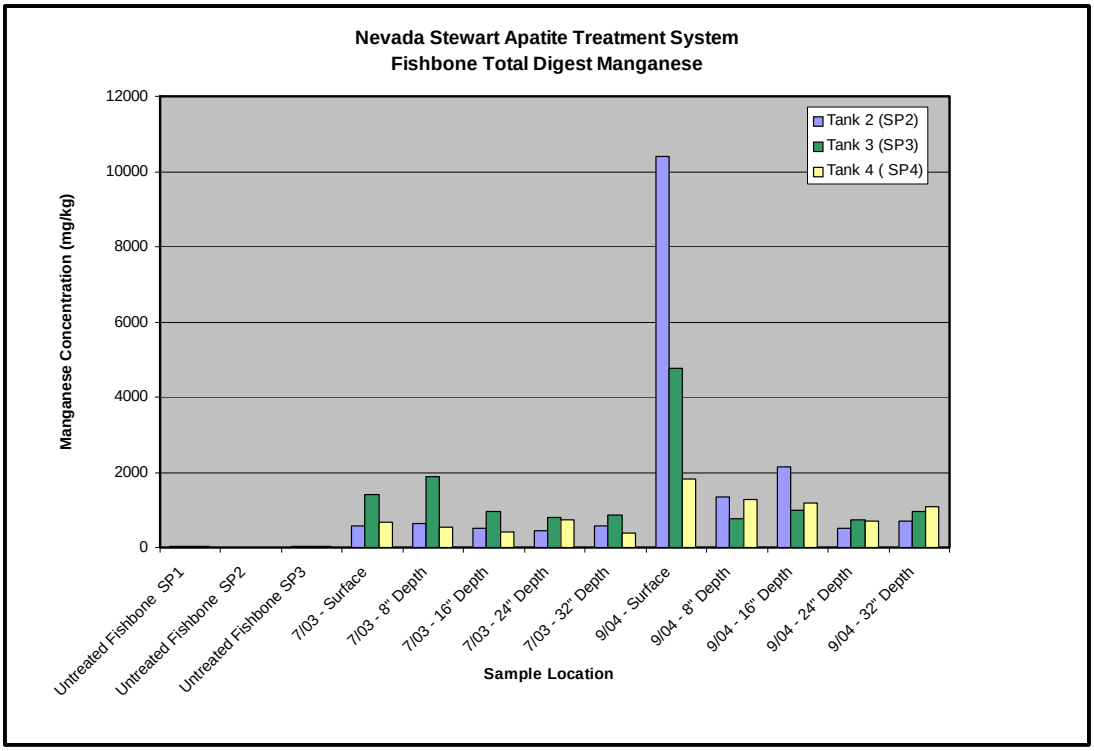

Figure 4-29. NSM ATS total digest Mn.

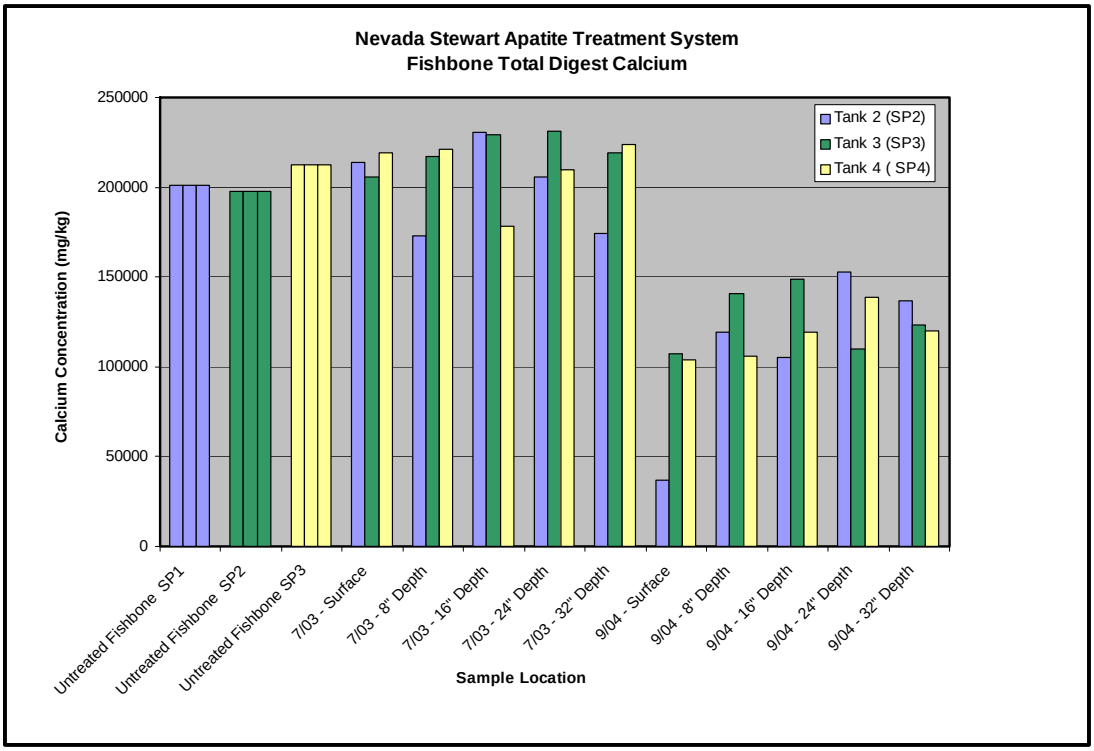

Figure 4-30. NSM ATS total digest Ca.

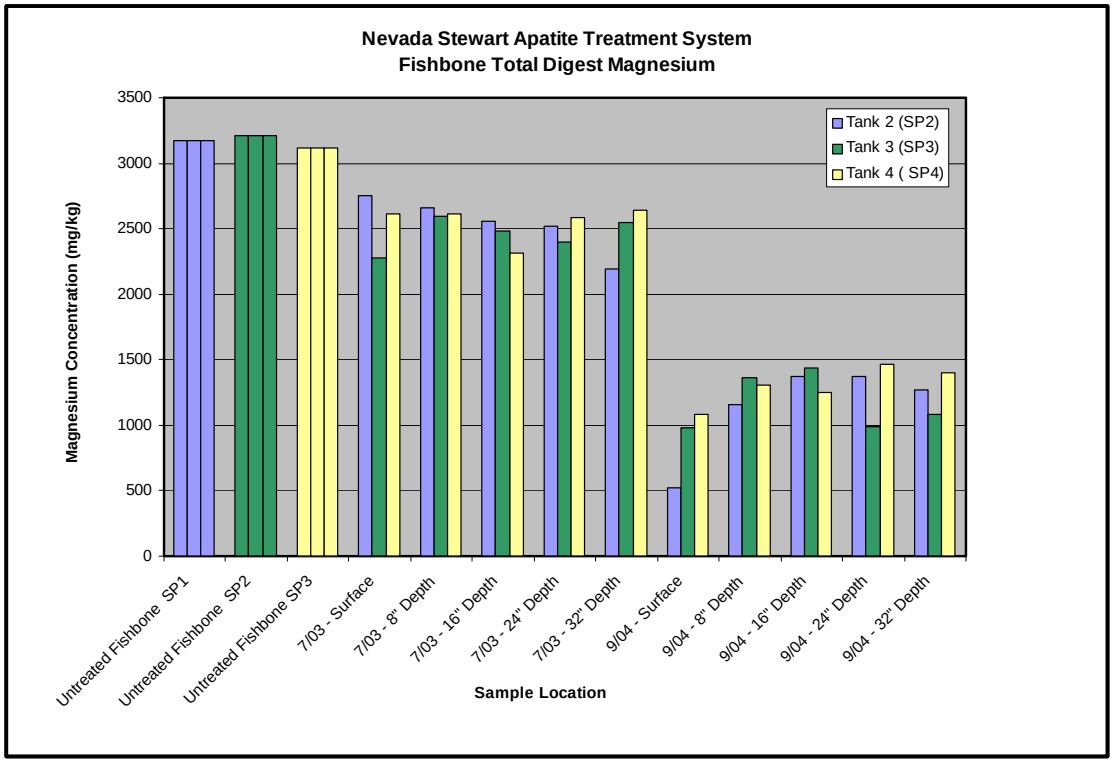

Figure 4-31. NSM ATS total digest Mg.

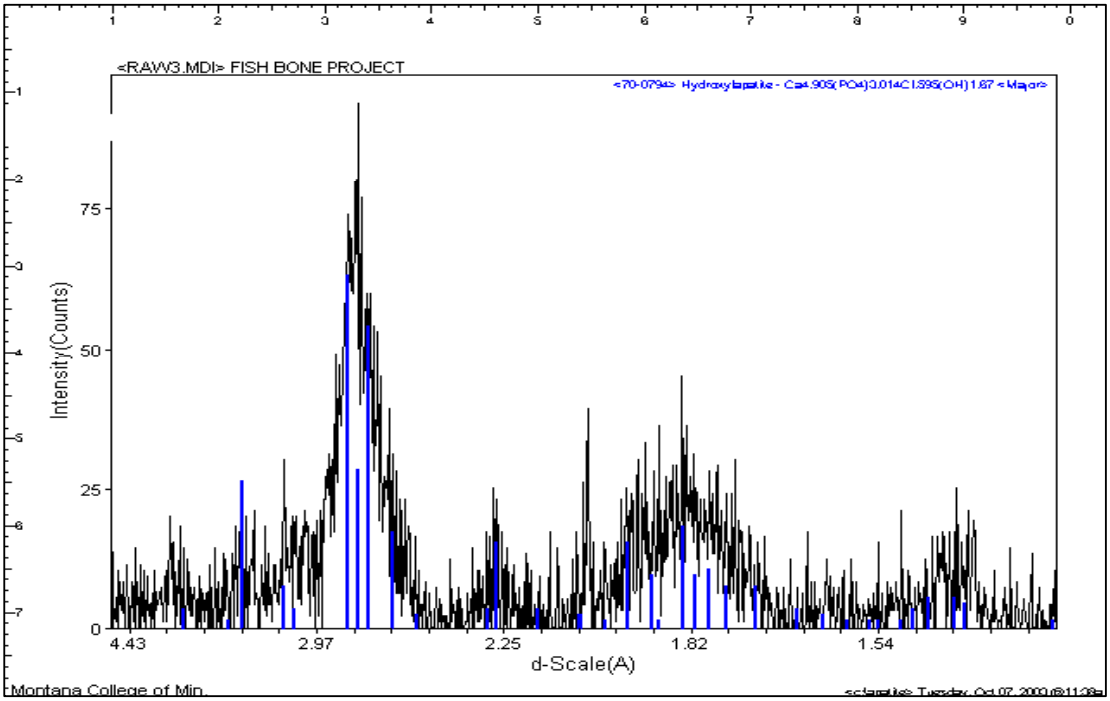

Figure 4-32. XRD graph showing a hydroxyapatite (>70 counts) peak, illustrating the only crystalline structure detected in the raw fishbone sample. This graph was similar to XRD results from Tanks 2, 3, and 4.

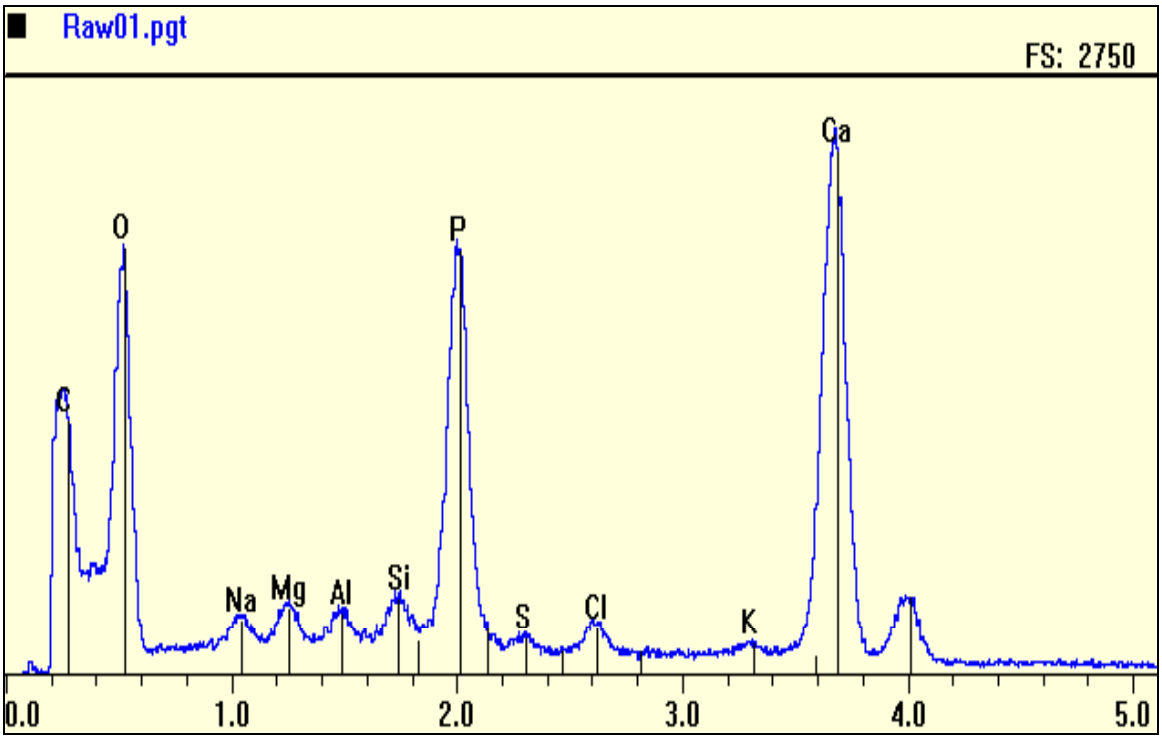

Figure 4-33. Unreacted fishbone EDX scan illustrating the peaks that indicate the primary composition of the fishbone material.

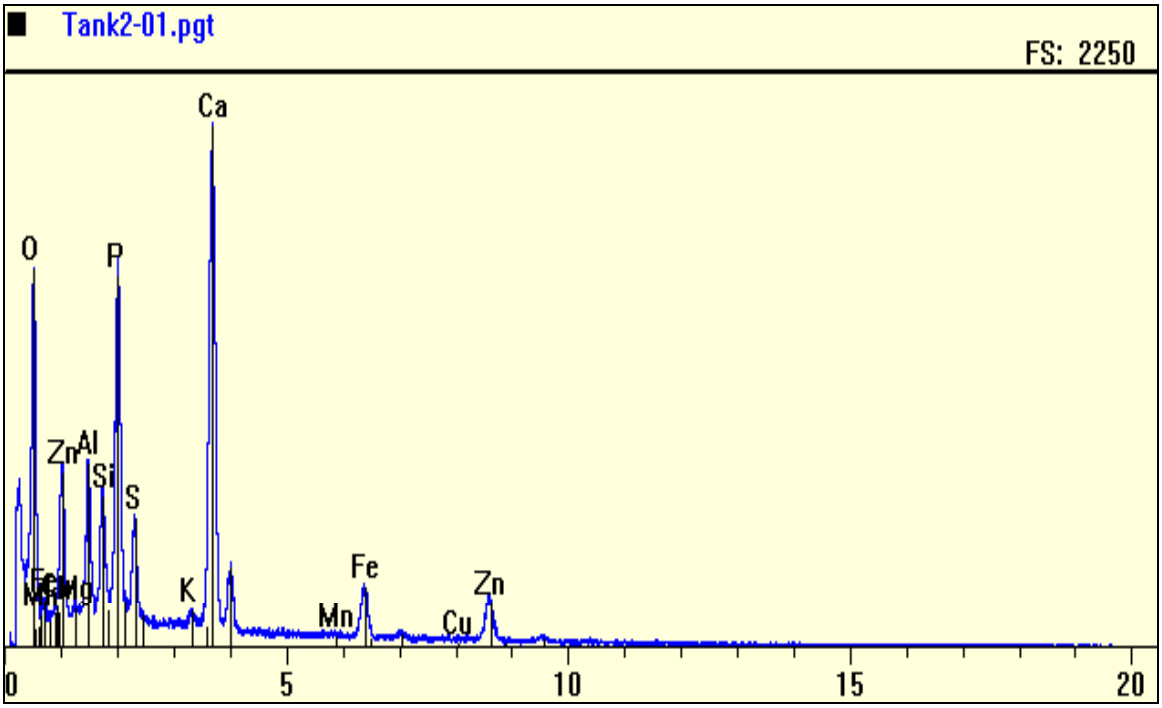

Figure 4-34. Typical EDX scan for Tank 2 (July 2003) sampled after 1 year of treating NSM discharge water. Volume treated by July 2003 was approximately 2 million gallons.

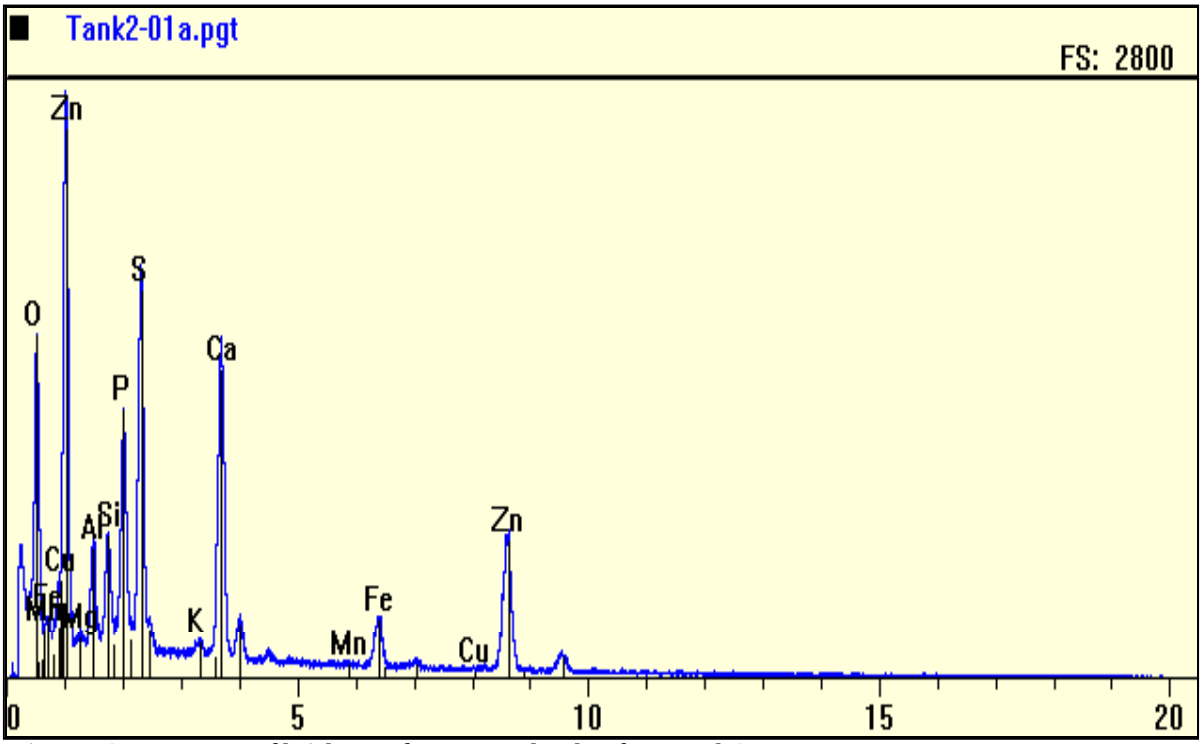

Figure 4-35. EDX scan of bright spot from a sample taken from Tank 2.

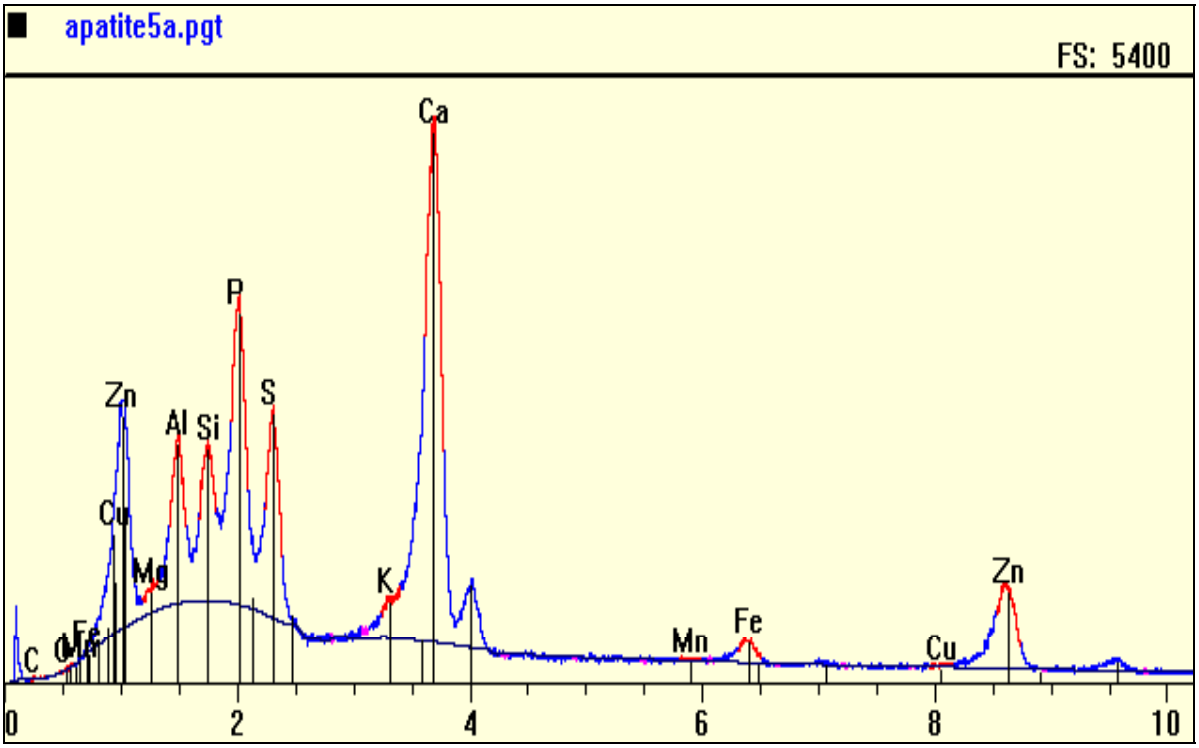

Figure 4-36. EDX scan of entire bone from a sample collected from Tank 4 in July 2003.

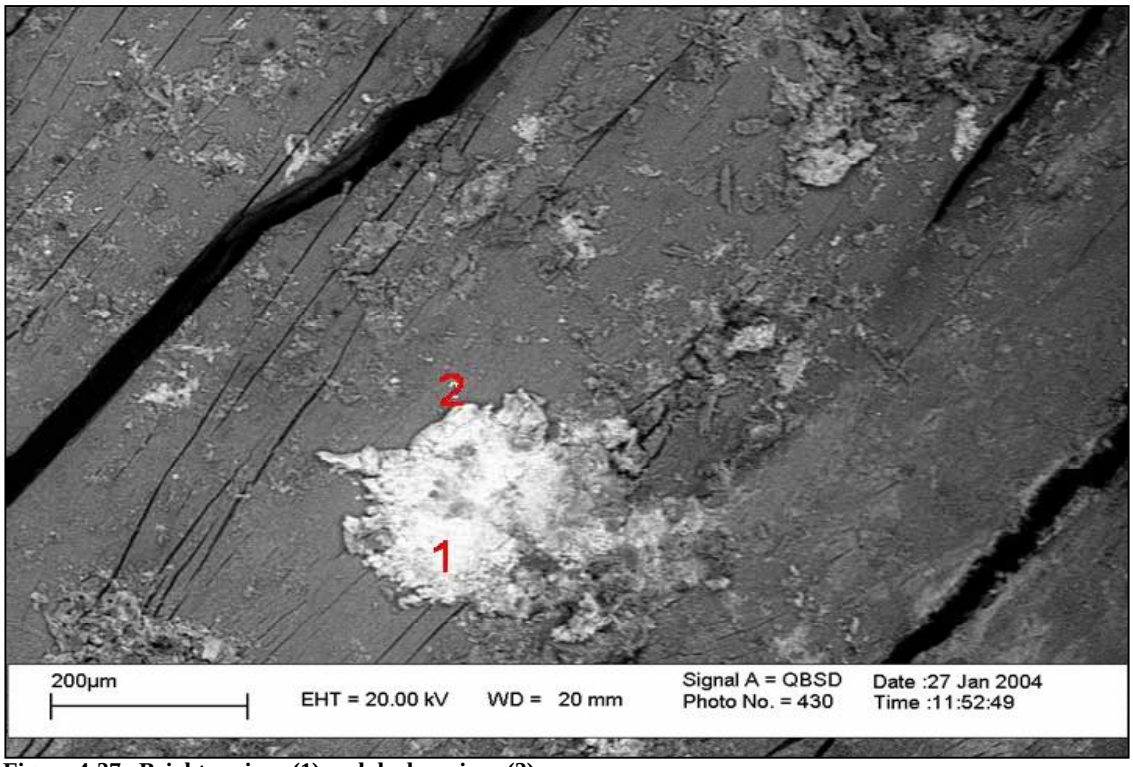

Figure 4-37. Bright regions (1) and dark regions (2).

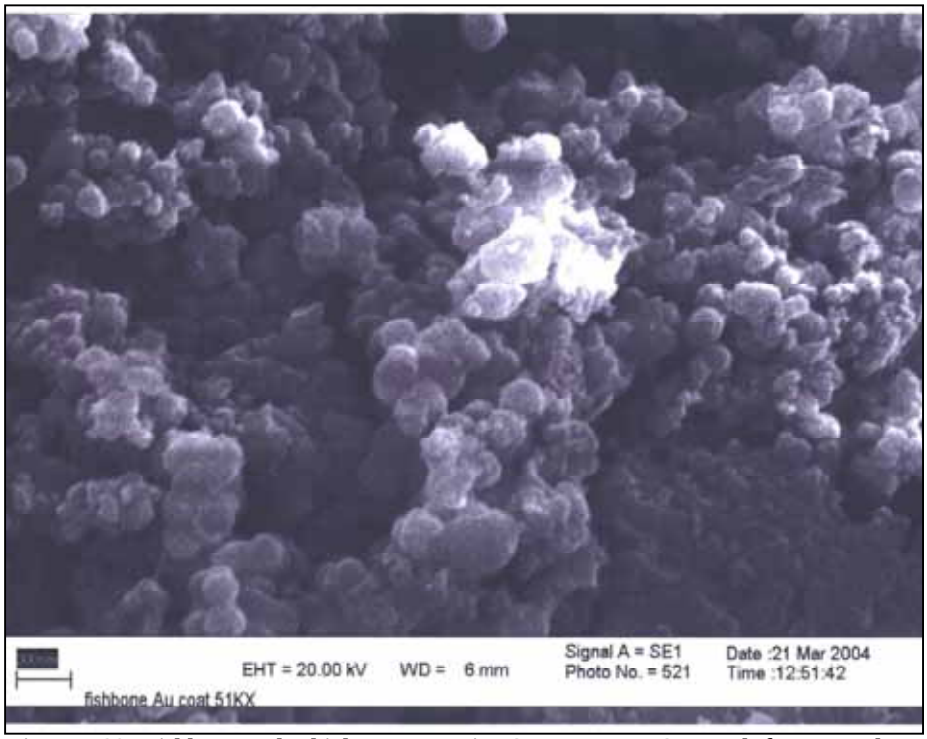

Figure 4-38. Fishbone under high vacuum using SEM to see ZnS crystals from samples collected from Treatment Tank 4 at the NSM ATS.

Table 4-1. NSM ATS Average Volumetric Flow in Gallons Per Minute

Sampling Port Measured	Average Flow Through the System (gpm)	Total Flow Through Each Tank over 2-Year Monitoring Period (million gallons)
SP1 – Influent Flow at Tank 1	17.9	13.4
SP2 – Effluent Flow at Tank 2	5.9	4.5
SP3 – Effluent Flow at Tank 3	8.7	6.4
SP4 – Effluent Flow at Tank 4	3.3	2.5

Table 4-2. NSM SRB Analysis – September 2004

	Tank 1 (SP1) Influent	**Tank 2 (SP2) Effluent**	**Tank 3 (SP3) Effluent**	**Tank 4 (SP4) Effluent**	**Tank 4 (SP4) Effluent Duplicate**
SRB (MPN/mL) – Date: 9/28/2004	<1.8	20	<1.8	78	45
Sulfide (mg/L) – Date: 8/17/2004	0.5	0.95	0.59	8.6	---

Table 4-3. Net Increase and Decline in Concentration as Indicated by Water Quality Monitoring Results

Net Increase in Concentration (Treatment Cell = Source)	**Net Decline in Concentration (Treatment Cell = Sink)**
Ca	Fe
P	Mn
Nitrogen	Zn
	Al[1]

[1] Al was taken only on an annual basis. Other metals were sampled on a monthly basis.

Table 4-4. Saturation Indices for the NSM ATS Influent and Each Separate Effluent Flow for the System (Results are from the Last Sampling Event taken on August 17, 2004, after System had Functioned for a 22-Month Duration)

Saturation Indices for the NSM ATS Influent and Each Effluent*				
Mineral Phase	**Influent Flow**	**Effluent Flow**		
	SP1	**SP2**	**SP3**	**SP4**
Ferrihydrite	1.1	-0.6	-0.1	-3.6
Mackinawite	-2.8	-3.5	-3.2	0.1
Pyrite	21.1	19.2	19.6	19.3
$MnHPO_4$	1.3	1.4	1.6	2.5
Hydroxyapatite	-0.7	2.9	1.9	5.4
Sphalerite	6.3	6.3	6.2	1.0
Wurtzite	4.3	4.3	4.1	1.0

***** The geochemical results presented are from sampling event on August 17, 2004, and not the other dates for the project.

Table 4-5. Weight Percent Data from EDX Scan for Sample Collected from Tank 4 in July 2003

Element	Wt%	Atomic Weight Percent (At%)
C	0.00	0.00
O	0.00	0.00
Mg	1.75	2.62
Al	7.67	10.35
Si	6.44	8.34
P	22.51	26.44
S	12.75	14.46
K	2.90	2.70
Ca	26.41	23.98
Mn	0.21	0.14
Fe	2.10	1.36
Cu	0.37	0.21
Zn	16.90	9.40
Total	**100.00**	**100.00**

Table 4-6. Weight Percent Data from Bright Region and Dark Region Located on Fishbone Material from Treatment Tank 4 Compared to Data from Sample of Untreated (Raw) Fishbone Material

Element	Bright Region		Dark Region		Raw Fishbone[a]	
	Wt%	At%	Wt%	At%	Wt%	At%
O	25.68	49.16	62.31	79.65	72.84	85.06
Mg	0.21	0.26	0.00	0.00	1.11	0.86
Al	4.42	5.02	2.53	1.92	2.13	1.48
Si	0.88	0.96	0.54	0.39	1.43	0.95
P	3.78	3.73	7.84	5.18	9.00	5.43
S	17.38	16.60	4.79	3.05	0.18	0.11
K	0.00	0.00	0.00	0.00	0.62	0.30
Ca	6.06	4.63	14.55	7.42	12.11	5.64
Mn	0.34	0.19	0.20	0.07	0.00	0.00
Fe	0.80	0.44	0.67	0.25	0.34	0.11
Cu	3.93	1.90	0.63	0.20	0.12	0.03
Zn	36.52	17.11	5.96	1.87	0.11	0.03
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.0**	**100.0**

[a] EDX analysis of Figure 4-33.

Table 4-7. Solubility Products

Metal Sulfide	Formation	Log K
CdS (Greenockite)	$CdS + H^+ \leftrightarrow Cd^{2+} + HS^-$	-15.93
PbS (Galena)	$PbS + H^+ \leftrightarrow Pb^{2+} + HS^-$	-12.78
ZnS (Sphalerite)	$ZnS + H^+ \leftrightarrow Zn^{2+} + HS^-$	-11.62

Source: Drever 1997

Table 4-8. 2003 Versus 2004 LC50 Values

	2003		2004	
	C. dubia	***P. promelas***	***C. dubia***	***P. promelas***
SP1	2.21	26.39	2.19	9.29
SP2	4.07	70.71	6.27	25.46
SP3	5.83	90*	4.42	6.93
SP4	95% *	100%*	85% *	89.09

* Indicates percent survival in 100%, non-diluted sample (no LC50 values could be generated)

5. ATS Monitoring Results Evaluation

In the QAPP for this project, the primary objective was to determine the percent reduction of metals for the target constituents by measuring total and dissolved metals concentrations in the ATS influent and effluent.

5.1 Statistical Analysis of the ATS Removal Effectiveness

Project objectives, design information, and data were provided to EPA, and an EPA contractor statistician reviewed the data. Only the representative target analytes listed in the project QAPP were evaluated (Ref. 1).

Statistical data analyses (both descriptive and inferential) were performed for total Zn, Cd, Pb, Fe, Mn, Ca, and Mg. This information is summarized as listed below.

- Descriptive Statistics: Minimum, Median, Maximum, Mean, Standard Deviation (Section 5.1.1).
- Inferential Statistics: Kruskal-Wallis Test and Multiple Comparison Procedure (Section 5.1.1).
- Graphical Displays: Box Plots (Appendix F).
- Graphical Displays: Time Plots (Appendix F).
- How to Interpret Box Plots (Appendix F).

5.1.1 Exploratory Data Analysis

Percent reduction for seven target metals was used to construct Tables 5-1 through 5-7, and the box plots are provided in Appendix F. The percent reduction using total metals concentrations was calculated as

[(SP1 Metal Concentration - SP # Metal Concentration) / SP1 Metal Concentration] x 100

Data collected for February 2003 was not representative of flow-through conditions at the ATS and should not be compared to other data that do represent flow through conditions.

For Zn, the box plots show a high (> 80%) reduction for Tank 4 at SP4. Time plots indicated the reduction was independent of the influent concentration (see Appendix F box plots for Zn), which almost doubled over the duration of the project (Figure 4-15). Over the duration of the project, Tanks 2 and 3 on average showed more modest reductions (20% to 70%) where the reduction was considered to be a function of the influent concentration. The results from the Kruskal-Wallis testing for Zn were statistically significant (p-value < 0.002) (Table 5-8). The Kruskal-Wallis multiple comparison procedure indicated that the Zn reduction at each sampling port (i.e., treatment tanks) was statistically different from one another (p-value = 0.05) (Table 5-8). This is reflective of the variability between treatment tanks throughout the duration of the project, with respect to flow rates and associated residence time, metals concentrations, and measured physical parameters.

Concentrations for Cd and Pb were very low in the influent resulting in below laboratory instrument detection limits (IDLs) for several months. Even so, the average percent reduction was evaluated for the two metals. The Cd box plots showed a high (> 75%) reduction for Treatment Tanks 2 and 4 (Appendix F). Evaluation of the time plots indicated the reduction was independent of the influent concentration. This did not hold for Tank 3, where the reduction in loading was a function of the influent concentration. Time plots are provided in Figure 4 of Appendix F, where the time plots indicate that Tank 3 was not removing Cd in a similar manner as Tanks 2 and 4. This observation was confirmed with the Kruskal-Wallis test (Table 5-9). The result of the Kruskal-Wallis test was statistically significant (p-value < 0.002). The Kruskal-Wallis multiple comparison procedure indicated that Tanks 2 and 4 were statistically different from Tank 3 (p-value = 0.05), thus, confirming the evaluation from the time plots and the geochemical results.

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The Pb box plots showed a similar reduction for all three sampling ports (20% to 80%) (Appendix F, Figure 2). The time plots in Appendix F, Figure 5 indicate the reduction was independent of the influent concentration for Tanks 2 and 4. This does not hold for Tank 3, where the reduction was determined to be a function of high influent concentrations. The result of the Kruskal-Wallis test was statistically significant (Table 5-10). The Kruskal-Wallis multiple comparison procedure indicated that Tanks 2 and 3 were statistically different (p-value = 0.05) than results from Tank 4.

In an additional statistical analysis, Fe, Mn, Ca, and Mg concentrations and load reductions were evaluated. The reviewed data did not have any outlying reductions for the metals (Appendix F, Figures 1-4). Neither Ca nor Mg concentrations were reduced by the treatments (Tables 5-6. 5-7. 5-11, 5-12, and Appendix F, Figures 3, 4, 7, and 9). In fact, Ca and Mg were released into solution as depicted by the geochemical modeling and were not evaluated further.

For the two remaining metals, Fe and Mn, SP2 provided the greatest reduction at 95.6% and 67.82%, respectively (Tables 5-4 and 5-5). The Kruskal-Wallis tests for both metals were statistically significant (p-value < 0.002), as were all treatment differences (p-value = 0.05) (Tables 5-13 and 5-14). For both metals, as reflected by the statistical analysis, SP3 was the worst performer having the smallest percent reduction and largest variability. There was a slight negative correlation between initial and final concentrations for both metals for SP3, where Fe = 0.32 and Mn = 0.55 and for SP2, where Fe = 0.25 and Mn = 0.41. This trend was positive for SP4, where Fe = 0.67 and Mn = 0.01. However, over the duration of the project, Tank 3 treated an increased amount of influent through the ATS (49% of the flow) and had reduced retention times, which were not accounted for in the calculations for the average percent metal reduction.

5.2 Water Quality Monitoring Evaluation

5.2.1 Percent Reduction of Metals at the NSM

The average percent reduction of dissolved metals and total metals for the ATS system was determined to evaluate the effectiveness of the ATS for metals removal from solution (Table 5-15).

As illustrated in Figure 5-1, the average percent metals reduction of dissolved metals achieved by the ATS was greater than 50% for the 2-year duration of the project for Cd, Fe, Mn, and Zn. The percent reduction for Cd and Fe was as high as 85% and 72%, respectively. For Zn, Tank 4 provided the highest average percent reduction of 94.5%, where Tank 3 average percent reduction was only 40%. However, upon evaluation, Tank 4 treated only one-third of the volume of influent when compared to the other treatment tanks, and the total digested Zn concentrations and metals loading values from each treatment tank indicate that Tank 3 retained a greater amount of Zn than Tank 4. Most of the Zn was retained in Tank 3 during the first year of the project, even though the average percent reduction recognized for Zn was 40%. The total amount of Zn retained in the ATS was 335 pounds (lb) over the 22-month demonstration period.

Table 5-16 presents a comparison of influent and effluent concentrations to regulatory discharge limits for the first and last sampling events of the project.

5.2.2 Apatite Retained Metals in the ATS

In prior studies, it was recognized that the Apatite II™ technology was successful with stabilizing from 5% to 50% of its weight in metals depending upon the metal and environmental conditions. The 5% value was strictly for adsorption and did not address dissolution/precipitation reactions, etc. (Ref. 8). For the Nevada Stewart ATS, the total weight of the apatite medium in the three treatment tanks was 10,000 lb, meaning that the apatite medium at the NSM had the ability to retain a minimum of 500 lb of metal. After 2

years of functioning, a conservative estimate of the total amount of metal retained by the ATS was calculated at approximately 495 lb (Figure 5-2). Each treatment tank retained different percentages of metals due to the flow variances through each tank on a monthly basis. Figure 4-14 provides a monthly graphical presentation of the total amount of heavy metals removed on a monthly basis when comparing the influent and the effluent This shows that air sparging the tanks to enhance permeability improved the ATS's ability to remove metals. However, over time, the effect was less due to the exhaustion of the attenuation capacity of the ATS. There appears to be several other processes at work that should be addressed.

Even though Tank 4 maintained the highest removal efficiency for Zn (greater than 90%), its low rate of flow allowed the removal of only 28 lb of Zn from the treated influent. For Zn, Tank 3 maintained an overall removal efficiency of only 40%, but approximately 269 lb of Zn was removed from the influent water treated by Tank 3. This amount of metal exceeded the theoretical adsorption capacity of metal for the Apatite II™ in the treatment tank. The fluctuations in attenuation for Zn are depicted in Figure 5-3 and as detailed, Tank 2 was nearing adsorption metal capacity exhaustion at 5% because it had retained 334 lb Zn and 160 lb Fe and Mn. However, absorption is not the only removal mechanism functioning in the ATS system; therefore, to determine the adsorption capacity of the apatite medium would require further detailed analysis that was not funded within this study.

5.2.3 ATS Attenuation Mechanisms

5.2.3.1 Sulfide Mineral Precipitation

Precipitation of ZnS was determined to be the main mechanism for Zn attenuation within all three of the treatment tanks. This process appeared to have dominated the removal scenario within Tank 4 and, to a lesser effect, in Tank 2 or Tank 3. Additionally, the precipitation of ZnS occurred in Tank 3 at times throughout the project duration.

A minor amount of Fe attenuation within the treatment tanks (in particular Tank 4) may be attributed to the precipitation of FeS. The reducing conditions in the NSM ATS, specifically the presence of hydrogen sulfide, suggests that metal attenuation through sulfide precipitation occurred at the NSM. The Golder thermodynamic modeling also confirmed this. Golder's report is contained in Appendix D. The lowest effluent Zn concentrations occurred in association with elevated sulfide concentrations. Mineralogical evaluation, however, is the best way to conclusively identify controlling secondary mineral phases. Mineralogical analysis by Montana Tech confirmed the presence of a ZnS (Ref. 23).

Attenuation of Cd and Pb due to sulfide precipitation was inconclusive. Speciation modeling showed supersaturation with respect to both CdS and PbS. However, the relatively low solid phase concentrations of these metals in the treatment tanks prevented the identification of any Cd/Pb secondary mineral phases by Montana Tech (Ref. 23). Correlation analysis results for the treatment tank elemental concentrations suggest an alternative attenuation mechanism to sulfide precipitation. If the dominant mechanism for Cd and Pb removal was sulfide precipitation, a correlation between Cd, Pb, and Zn (Appendix F, Figure 23, Table 5) should be observed. A positive correlation was not observed from the September 2004 data set. As such, an alternative mechanism for the removal of Pb and Cd is probable.

5.2.3.2 Phosphate Mineral Precipitation

Speciation modeling identified manganese phosphate as a possible control on Mn concentrations. Further evaluation was required to establish if $MnHPO_4$ was indeed a credible secondary mineral phase. Similarly, formation of strengite (Fe-phosphate) was identified as a possible sink for Fe.

Effluent saturation indices indicate undersaturation with respect to hydroxypyromorphite. Because influent Pb concentrations were very low,

adsorption of Pb by hydroxyapatite was unrecognizable. Since the Ca concentrations increased in the effluent relative to the influent, it is highly probable that the organic hydroxyapatite was dissolving not precipitating.

5.2.3.3 Surface Reactions

Adsorption of Pb, Cd, and Mn onto ferrihydrite or the Apatite II™ treatment medium (Ref. 8) would also account for the positive correlation observed between the solid phase concentrations of these metals. Also adsorption onto the whole bone apatite surface was a possibility. Iron oxide staining was observed at the NSM adit and the treatment tank bypass overflow. Large amounts of iron oxide were seen in a photo entitled dewatered apatite with ferric coat, which was taken looking down into one of the reactors. Wright 2004 cites studies that showed Apatite II™ is capable of absorbing up to 5% of its weight in metals. The mineralogical analysis conducted to date was capable of determining that on average 6% of Zn by weight was retained by means of the four listed attenuation mechanisms on the fishbone in the treatment tanks, but it was not capable of characterizing surface reactions such as adsorption. More sophisticated analytical techniques and analysis would be required to make a definitive conclusion regarding the role of this process at the NSM. Figures 5-4, 5-5, and 5-6 are photographs of the apatite medium from this treatment system.

5.3 Effect of Mixing Effluents from the NSM ATS

The configuration of the NSM ATS was such that the effluent waters from the three treatment tanks were mixed before discharge. The variance in the constituents of the effluent waters from each of the treatment tanks induced specific reactions to occur. As the effluents exited the tanks, the water mixed reducing the dissolved contaminants found in the water discharging to Highland Creek. In addition, the bypass water entering the catch basin would be diluted with respect to the concentration of certain constituents, because the bypass water was mixing with the effluent from the ATS.

Geochemical modeling was used to determine the effects of the aforementioned reactions on the quality of the mixed water to determine the quality of water entering Highland Creek and to determine if the catch basin was acting as a hypothetical fourth reactor. The geochemical software PhreeqCI was used in this modeling effort. Six monthly sampling events were selected to be evaluated for this modeling effort. These sampling events were March 19, 2003; May 29, 2003; June 19, 2003; August 19, 2003; February 10, 2004; and May 25, 2004. The events were chosen because a broad range of effluent water compositions as far as oxidizing and reducing conditions and, as such, varying sulfide and Zn concentrations were evident. Additionally, the six samples were representative of the entire project.

The saturation indices results of the geochemical modeling are presented in Table 5-17. According to information in Table 5-17, a ZnS solid species would probably be precipitated from the mixed waters in all of the modeled cases. The specific ZnS specie(s) produced would control the concentration of dissolved Zn in the mixed effluent water. It is also possible that manganese phosphate, elemental sulfur, and FeS would precipitate. Although it is unlikely, due to kinetic considerations, that pyrite would be formed in viable concentrations. The dissolved concentrations of the cationic constituents yielded by the geochemical model for the mixed effluent waters are shown in Table 5-18. The detailed dissolved Zn concentrations in the data were for an amorphous ZnS solid compound. It is entirely probable that the actual concentration of ZnS found in the mixed effluent waters would be substantially lower than the modeled results. Table 5-18 indicates that the modeled concentrations within the mixed effluent water are substantially lower than a simple mixing of the effluents from the three tanks.

5.4 Effect of Mixing Treated Effluent from the ATS and Bypass Water from the NSM

The ATS at the Nevada Stewart consistently treated approximately one-half of the water emanating from the underground mine workings.

The other half of the flow from the mine was allowed to bypass the treatment system. This bypass water was mixed with the treated effluent within the catch basin prior to the entire flow entering Highland Creek.

The chemical composition of these two waters was significantly different in that the treated water was distinctly less aerobic, had low concentrations of dissolved metals, and contained significant quantities of soluble sulfide while the bypass water was more oxidized, contained higher concentrations of dissolved metals, and had very low amounts of soluble sulfide. As was described previously, the variance in the constituents of the bypass water and the mixed effluent water from the treatment tanks induced specific reactions as the waters mixed. These reactions resulted in a reduction in the amount of specific dissolved contaminants found in the mixed water in the catch basin. In addition, the concentration of certain constituents would be reduced in the effluent waters by the effect of dilution.

Geochemical modeling was used to determine the effects of the previous reactions on the quality of the mixed effluent water flowing from the catch basin into Highland Creek. The geochemical software PHREEQCI was used in this modeling effort (Ref. 24). The same six monthly sampling events that were selected for the previous geochemical modeling scenario, which described the mixing of the reactor effluents, were used for this effort.

The saturation indices resulting from the geochemical modeling are presented in Table 5-19. As predicted by the model, a ZnS solid species would very probably be precipitated when the ATS effluent and the NSM bypass waters mixed. The specific ZnS specie(s) produced would control the concentration of dissolved Zn in the mixed effluent water. It is also possible that manganese phosphate, elemental sulfur, and FeS could precipitate. Although, it is unlikely, due to kinetic considerations, that pyrite would be formed in viable concentrations.

The dissolved concentrations of the cationic constituents yielded by the geochemical modeling effort for the mixed effluent waters are shown in Table 5-20. The dissolved concentration of Zn detailed in these data is related to the precipitation of an amorphous ZnS solid compound. It is entirely probable that the actual concentration of ZnS found in the mixed effluent waters would be lower than the modeled results. As can be seen from Table 5-20, the modeled concentrations within the mixed effluent water are significantly lower than a simple mixing of the bypass water and the reactor effluents due to the production of insoluble sulfide-based precipitates.

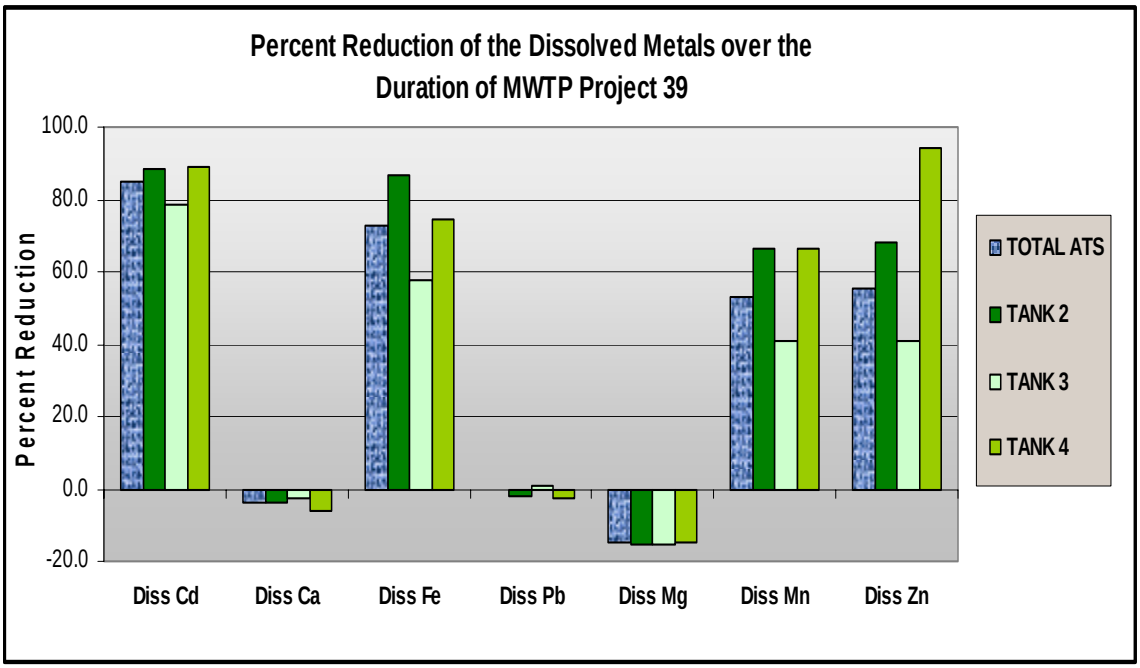

Figure 5-1. Average percent reduction in dissolved metals over the duration of the MWTP, Activity III, Project 39, ATS as compared to the NSM discharge (influent) dissolved metals concentrations.

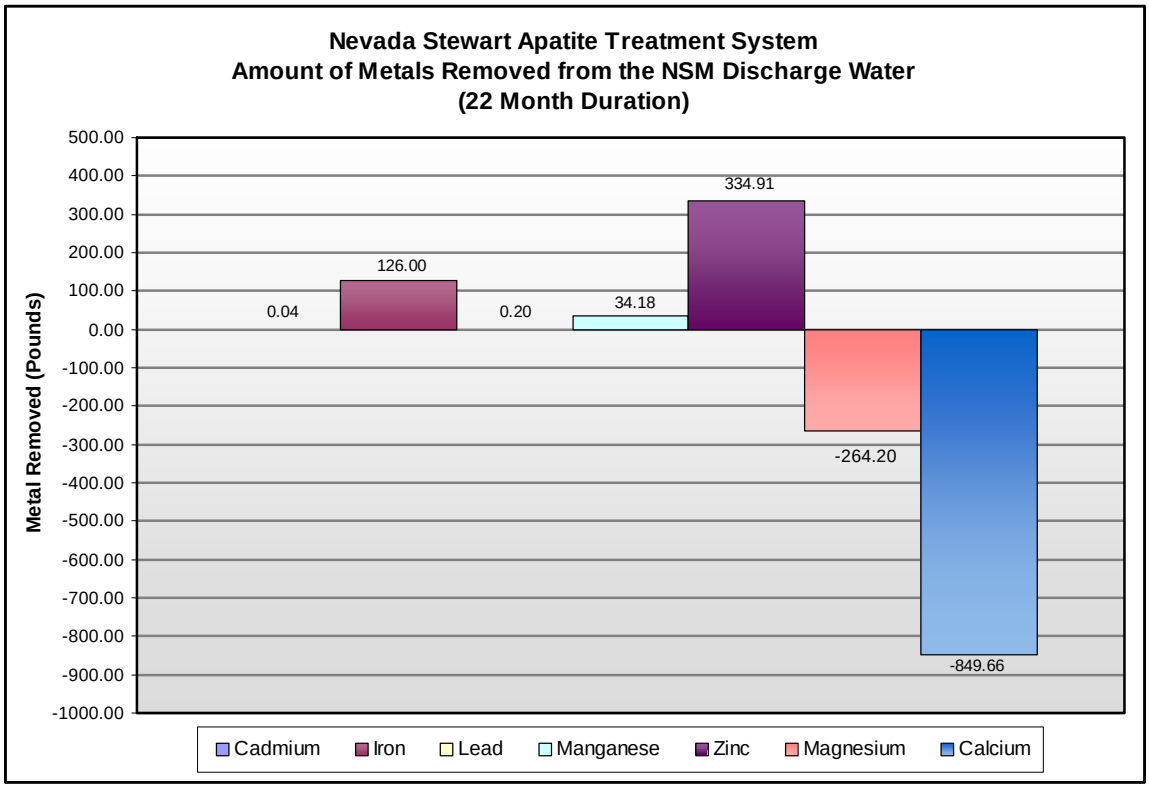

Figure 5-2. Amount of metal removed by the NSM ATS.

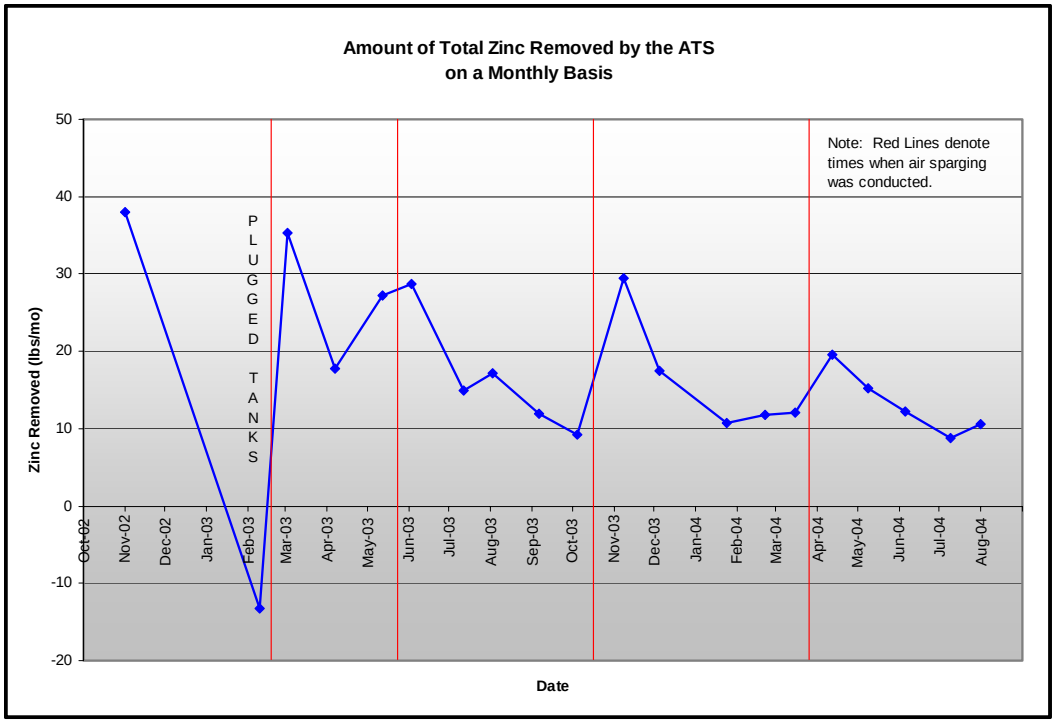

Figure 5-3. Amount of total Zn removed by NSM ATS on monthly basis.

Figure 5-4. Tank 4 (center cell) just prior to the solid phase (total digest) sampling showing the ferrihydrite coated surface.

Figure 5-5. Photo of the fishbone at the end of the project. Bone pieces are from varying depths to compare to the unused bone (Figure 2-16).

Figure 5-6. Tank 4 apatite medium showing the black and white precipitate with minimal ferrihydrite on the surface.

Table 5-1. Zn Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	29.2	58.9	58.4	86.1	15.0
SP3	13.6	34.1	38.6	87.8	20.9
SP4	8.4	93.3	85.9	99.8	20.8
SP4*	72.2	94.1	90.0	99.8	10.3

*Outlier removed for Zn 02/26/2003

Table 5-2. Cd Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	-198.1	89.6	75.1	97.3	66.3
SP2*	82.5	89.9	90.3	97.3	3.7
SP3	-22.1	63.0	57.9	81.6	31.8
SP4	61.4	89.6	88.1	97.3	7.9

*Outlier removed for Cd 08/19/2003

Table 5-3. Pb Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	-214.8	54.2	39.1	94.6	67.0
SP3	-8.4	37.8	35.0	77.5	26.3
SP4	0	52.0	75.5	94.6	29.6

Table 5-4. Fe Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	87.77	96.82	95.60	99.34	3.74
SP3	24.83	54.96	58.87	98.08	26.08
SP4	73.24	92.88	90.47	96.63	6.04

Table 5-5. Mn Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	39.42	73.70	67.82	88.29	16.25
SP3	16.67	43.09	45.43	84.51	22.22
SP4	40.67	63.26	66.90	76.56	9.17

Table 5-6. Ca Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	6.14	3.05	3.27	0	1.64
SP3	4.89	0.21	1.18	2.56	2.11
SP4	9.44	4.99	4.93	1.74	2.75

Table 5-7. Mg Percent Reduction for Selected Metals by Sampling Port

Port	Minimum	Median	Mean	Maximum	Standard Deviation
SP2	1.88	0.12	0.02	1.50	0.98
SP3	1.95	0.23	0.31	2.31	1.05
SP4	2.64	0.23	0.08	2.31	1.18

Table 5-8. Kruskal-Wallis Test and Multiple Comparison Procedure for Zn

Kruskal-Wallis Test: chi-square = 32.4289, df = 2, p-value = 0.0002			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (α = 0.05)**
SP2 versus SP3	11.50	7.55	S
SP2 versus SP4	19.60	7.55	S
SP3 versus SP4	31.10	7.55	S

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-9. Kruskal-Wallis Test and Multiple Comparison Procedure for Cd

Kruskal-Wallis Test: chi-square = 17.0977, df = 2, p-value = 0.0002			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (α = 0.05)**
SP2 versus SP3	19.66	9.16	S
SP2 versus SP4	0.79	9.16	NS
SP3 versus SP4	18.87	9.16	S

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-10. Kruskal-Wallis Test and Multiple Comparison Procedure for Pb

Kruskal-Wallis Test: chi-square = 4.3512, df = 2, p-value = 0.1135			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (α = 0.05)**
SP2 versus SP3	9.53	10.55	NS
SP2 versus SP4	0.37	10.55	NS
SP3 versus SP4	9.89	10.55	NS

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-11. Kruskal-Wallis Test and Multiple Comparison Procedure for Ca

Kruskal-Wallis Test: chi-square = 18.5928, df = 2, p-value = 0.0001			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (= 0.05)**
SP2 versus SP3	13.00	8.98	S
SP2 versus SP4	10.16	8.98	S
SP3 versus SP4	23.16	8.98	S

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-12. Kruskal-Wallis Test and Multiple Comparison Procedure for Mg

Kruskal-Wallis Test: chi-square = 1.2035, df = 2, p-value = 0.5479			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (= 0.05)**
SP2 versus SP3	5.71	10.87	NS
SP2 versus SP4	1.55	10.87	NS
SP3 versus SP4	4.16	10.87	NS

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-13. Kruskal-Wallis Test and Multiple Comparison Procedure for Fe

Kruskal-Wallis Test: chi-square = 29.33, df = 2, p-value = 0			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (= 0.05)**
SP2 versus SP3	29.05	7.59	S
SP2 versus SP4	12.32	7.59	S
SP3 versus SP4	16.74	7.59	S

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-14. Kruskal-Wallis Test and Multiple Comparison Procedure for Mn

Kruskal-Wallis Test: chi-square = 12.6285, df = 2, p-value = 0.0018			
Multiple Comparison	**Difference***	**Statistic**	**S/NS (= 0.05)**
SP2 versus SP3	29.05	9.68	S
SP2 versus SP4	12.32	9.68	S
SP3 versus SP4	16.74	9.68	S

*If the difference > statistic, then statistically significant at the 0.05 level.

Table 5-15. Average Percent Metals Reduction Achieved for the Duration of the MWTP, Activity III, Project 39, NSM ATS for Full ATS and Each Treatment Tank

Average Percent Reduction for the Duration of the Project – Apatite Treat System				
Parameter	**Total ATS**	**Tank 2**	**Tank 3**	**Tank 4**
Dissolved Cd	84.9	88.3	78.8	88.7
Dissolved Ca	-3.5	-3.9	-2.6	-6.2
Dissolved Fe	72.9	86.7	57.8	74.4
Dissolved Pb	-0.3	-2.2	0.9	-2.4
Dissolved Mg	-14.9	-15.2	-15.3	-14.7
Dissolved Mn	52.8	66.6	40.7	66.3
Dissolved Zn	55.4	68.0	40.8	94.5
Sulfate (mg/L)	0.8	0.2	2.1	3.4

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Table 5-16. Comparison of Regulatory Discharge Limits with the NSM ATS Effluent and Influent Values for the First and Last Sampling Events of the Project

Dissolved Metals (mg/L)	Zn	Cd	Pb	Fe	Mn	Sulfate
Drinking Water Standards[1]	5.0*	0.01	0.05	0.30*	0.05*	250*
Influent (SP1) 11/02	5.64	0.0005	0.0013	0.731	0.691	257
Influent (SP1) 8/04	8.00	0.0005	0.0012	0.496	0.608	349
Tank 2 11/02	0.039	0.00005	0.0013	0.142	0.349	254
Tank 2 8/04	3.70	0.00003	0.0012	0.031	0.071	351
Tank 3 11/02	0.0243	0.00007	0.0013	0.077	0.235	191
Tank 3 8/04	4.400	0.00003	0.0012	0.108	0.182	349
Tank 4 11/02	0.686	0.00005	0.0013	0.142	0.384	259
Tank 4 8/04	0.0096	0.00003	0.0012	0.160	0.155	315

All values on the table are as mg/L.
* National Secondary Drinking Water Regulations.
[1] Federal maximum contaminant level for protection of drinking water.

Table 5-17. Saturation Indices for Mixed Effluent

Sample Date	$MnHPO_4$	Pyrite	Sphalerite	Wurtzite	ZnS (am)	Hydroxyapatite	Sulfur	Mackinawite
3/19/03	2.46	22.56	3.06	1.04	0.37	4.00	10.05	0.40
5/29/03	1.92	20.07	4.63	2.61	1.95	- 0.19	8.63	- 0.68
6/19/03	2.11	22.64	3.46	1.44	0.78	2.53	10.13	0.39
8/19/03	1.89	18.01	6.02	4.00	3.33	1.50	7.83	- 1.93
2/10/04	1.85	19.23	5.73	3.79	3.16	1.31	9.74	- 2.23
5/25/04	0.85	15.82	5.03	3.02	2.35	- 3.73	7.59	- 3.89
8/17/04	0.73	19.94	5.94	3.91	3.27	0.38	9.97	-2.01

Table 5-18. Dissolved Concentrations of Cationic Constituents for Mixed Effluent

Sample Date	Ca mg/L	Fe mg/L	Mg mg/L	Mn mg/L	Zn mg/L
3/19/03	93.80	0.05	40.21	0.02	0.52
5/29/03	92.71	0.30	41.70	0.01	0.17
6/19/03	97.53	0.18	41.67	0.01	0.18
8/19/03	92.83	0.17	41.2	0.01	0.02
2/10/04	94.99	0.19	39.08	0.01	1.62
5/25/04	93.84	0.07	41.47	0.04	4.77
8/17/04	105.00	0.07	45.00	0.01	0.96

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Table 5-19. Saturation Indices for a Mixture of Bypass Water and the Reactor Effluents

Sample Date	$MnHPO_4$	Pyrite	Sphalerite	Wurtzite	ZnS (am)	Hydroxyapatite	Sulfur	Mackinawite
3/19/03	1.98	20.33	4.06	2.39	0.87	1.41	9.64	- 0.59
5/29/03	1.74	19.09	6.24	4.06	3.27	- 2.08	7.91	- 1.28
6/19/03	1.83	19.13	5.63	3.49	2.42	1.32	8.63	- 1.86
8/19/03	1.28	18.35	5.71	3.54	2.61	- 1.81	8.27	- 2.07
2/10/04	1.13	16.49	4.39	2.77	1.08	- 2.27	7.19	- 2.94
5/25/04	0.79	12.71	3.16	1.52	0.21	- 6.36	6.14	- 4.71
8/17/04	1.61	17.86	5.03	3.47	1.89	-3.77	7.84	- 3.64

Table 5-20. Dissolved Concentrations of Cationic Constituents for a Mixture of Bypass Water and the Reactor Effluents

Sample Date	Ca mg/L	Fe mg/L	Mg mg/L	Mn mg/L	Zn mg/L
3/19/03	91.40	0.27	40.36	0.01	0.23
5/29/03	90.75	0.46	41.40	0.01	0.09
6/19/03	96.61	0.43	41.63	0.01	0.78
8/19/03	91.77	0.35	26.05	0.02	0.84
2/10/04	93.35	0.47	39.04	0.03	1.96
5/25/04	89.62	0.17	39.83	0.05	5.14
8/17/04	104.00	0.28	45.17	0.02	0.89

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6. ATS Cost Analysis

A cost analysis was performed for the ATS demonstration installation and long-term monitoring/evaluation performed by DOE and the EPA MWTP, respectively. Required elements for the ATS included the scope of work, system design, pre-installation materials testing, ATS installation, simple analytical analysis, monthly monitoring, reporting, ATS maintenance (quarterly permeability enhancement), and project closure. The additional research used to determine the effectiveness of the ATS involved geochemical modeling, extensive analytical analysis, SEM/EDX, XRD, physical analysis, monthly sampling, extensive reporting, statistics, toxicology testing, and increased project management all under the guidance of the project QAPP.

For this analysis, a hypothetical real-world cost for implementation of an ATS system in a field setting is presented.

Included in Table 6-1 are estimations of the total unit cost for an ATS project without the research aspects attached to this specific projects. The assumptions are that these costs include installation of a system for remediation of a site that would not require the extensive oversight, research, analytical, modeling, and reporting needs of the demonstration project presented in this report. Discount rates are based on Office of Management and Budgets projected discount rates for Cost-Effectiveness, Lease –Purchase, Internal Government Investment, and Asset Sale Analyses that are published yearly. The results of the cost analysis indicate that the net present value of the unit cost to treat a thousand gallons of water ranges from $6.30 over 2 years to $1.20 over 30 years.

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Table 6-1. Estimations of the Percent Total Unit Cost for an ATS Project Without Research Aspects Attached

Items for Hypothetical Barrier Costs	Cost
Installation Costs,	
Manager, 6 months	$1,800
QAPP	$5,000
Testing	$3,100
Design and Specifications	$6,500
Documentation	$1,400
Install Monitoring Wells	$1,500
Construct Barrier	$67,700
Total Installation Costs	$87,000
Operating and Maintenance (O&M) Costs	
Repairs	$10,300
Sampling and Surging	$14,500
Analysis	$3,800
Total O&M costs for 22 months	$28,600
Equivalent yearly O&M costs	$15,600
2 years	
Installation	$87,000
Net present value (NPV) of cost for O&M, $15,600 per year for 2 years at 3.7%	$29,600
NPV of cost	$116,600
Unit cost per 1,000 gallons treated	$6.30
10 years	
Installation	$87,000
NPV of cost for O&M, $15,600 per year for 10 years at 4.6%	$122,800
NPV of cost	$209,800
Unit cost per 1,000 gallons treated	$2.30
20 years	
Installation	$87,000
NPV of cost for O&M, $15,600 per year for 20 years at 4.9%	$196,000
NPV of cost	$283,000
Unit cost per 1,000 gallons treated	$1.50
30 years	
Installation	$87,000
NPV of cost for O&M, $15,600 per year for 30 years at 5.2%	$234,400
NPV of cost	$321,400
Unit cost per 1,000 gallons treated	$1.20

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7. Summary of Quality Assurance Activities

7.1 Background

The following is a summary of the quality assurance (QA) activities associated with MWTP Activity III, Project 39, *Permeable Treatment Wall Effectiveness Monitoring, Nevada Stewart Mine Site*. Analytical samples and field data were collected according to the schedule outlined in the approved project-specific QAPP document. All field and laboratory data available has been evaluated to determine the usability of the data. Critical analyses were flume/weir water depth and dissolved metals [Al, Sb, As, Be, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Ni, K, P, Na, Se, Ag, Si, titanium (Ti), and Zn]. In February 2004, an addendum to the QAPP was written to reflect a reduction in the amount of dissolved metals that were analyzed for As, Al, Ca, Cu, Cd, Fe, Pb, Mg, Mn, K, Na, Si, and Zn. A critical analysis is an analysis that must be performed to determine if project objectives were achieved. Data from noncritical analyses were also evaluated.

7.2 Project Reviews

An external technical systems audit of the project field activities was performed by David Gratson of Neptune and Company (subcontractor to EPA) on September 23, 2003. There were no findings, three observations, and one additional technical comment identified during the audit.

The observations included using expired pH calibration buffer solutions, using an ORP different than the meter specified in the QAPP, and other general comments on minor revisions to the QAPP. Efforts were made to ensure that pH calibration buffer solutions used after the audit were fresh solutions and the expiration data was documented in the field logbook during each sampling event. An addendum to the QAPP was developed to correct the other two observations. The additional technical comment pertained to communications between the MSE and EPA project managers. Significant operational modifications were documented and communicated to the EPA project manager.

7.3 Data Evaluation

Data that was generated throughout the project was validated. The purpose of data validation is to determine the usability of data that was generated during a project. Data validation consisted of two separate evaluations: an analytical evaluation and a program evaluation.

7.3.1 Analytical Evaluation

An analytical evaluation of all data was performed to determine the usability of the data that was generated by HKM Laboratory for the project. Laboratory data validation was performed using *USEPA Contract Laboratory Program (CLP) National Functional Guidelines for Inorganics Data Review* (USEPA 1994) as a guide. The data quality indicator objectives for critical measurements were outlined in the QAPP and were compatible with project objectives and the methods of determination being used. The data quality indicator objectives were method detection limits (MDLs), accuracy, precision, and completeness. Control limits for each of these objectives are summarized in Tables 7-1 and 7-2. The quality control (QC) criteria were also used to identify outlier data and to determine the usability of the data for each analysis.

Measurements that fell outside of the control limits specified in the QAPP, or for other reasons were judged to be outlier, were flagged appropriately to indicate that the data was judged to be estimated or unusable. All data requiring flags are summarized in Table 7-3.

At the beginning of the project, HKM Laboratory used influent samples for QC. The CLP spiking levels were appropriate for all analytes except Zn. The concentration of Zn in the influent samples ranged from six to ten times higher than the spiking level. Because the sample concentration for Zn was greater than four times the spike concentration, HKM Laboratory was not required to meet a recovery limit; however, MSE calculated spike recoveries. With only two exceptions

(February 2002 and May 2002), the spike recoveries for Zn were within the acceptable range of 75% to 125%. Serial dilutions were also within acceptable limits. This indicated that there were no matrix effects for Zn in these samples. December 2003 samples were first set where HKM Laboratory began using the effluent samples for QC, thereby, rectifying the issue of the sample concentration for Zn being greater than four times the spike concentration. All spike recoveries for Zn from December 2003 through August 2004 samples were within the acceptable range.

7.3.2 Program Evaluation

Program evaluations include an examination of data generated during the project to determine that all field QC checks were performed and within acceptable tolerances. Program data that was inconsistent or incomplete and did not meet the QC objectives outlined in the QAPP were viewed as program outliers and were flagged appropriately to indicate the usability of the data.

7.3.2.1 Flume/Weir Water Depth

A 60-degree trapezoidal flume was used to measure total groundwater flow from the adit. This flume was located upstream of the retention basin and the bypass pipe.

Weir water levels and flows were measured with a Thel-Mar volumetric weir. Thel-Mar weirs were installed in 10-inch pipes to measure the outflow from each of the three apatite treatment tanks and also in a single 6-inch pipe to measure flow into the ATS.

Untreated flow was calculated by simple subtraction: total flow measured in the flume minus flow measured in the weir leading to the ATS equals flow that bypassed the treatment system.

The surface water flow rate measurements were obtained in accordance with the procedures outlined in the QAPP. No surface water flow rate data were judged to be outlier.

7.3.2.2 Dissolved Metals

Dissolved metals analysis was a critical analysis for this project. Aqueous samples were collected from the four sampling locations during each sampling event, as well as a field duplicate sample from a predetermined sampling location and a field blank. Sampling procedures for the collection of the aqueous samples outlined in the QAPP were followed. The samples were taken to HKM Laboratory for analysis by ICP Emission Spectrometer (ICP-ES). No dissolved metals data were judged to be outlier.

7.4 Quality Assurance Summary

In general, sampling personnel conducted QA/QC activities for this project in accordance with the procedures outlined in the QAPP. All field duplicates and field blanks were collected, field instrumentation properly calibrated, and critical activities documented in the field logbook. The sample NSM SP1 052504 collected May 25, 2004 was flagged unusable because the repeatability of the field duplicate was outside the acceptable range of ≤ 20% relative percent difference (RPD) for total and dissolved metals. During this sampling event, other personnel not previously used on this project collected the samples. If at all possible, the same personnel should be used for sampling activities; otherwise, other personnel need to receive proper training.

Table 7-1. QA objectives for Accuracy, Precision, MDL, and Completeness

Measurement	Units	MDL	Precision[1]	Accuracy	Completeness[2]
Flume/Weir water depth	Inches	0.03	N/A	±5%[3]	95%
Dissolved Metals	mg/L	See Table 7-2	≤20% RPD	75%-125% spike recovery	95%

[1] Precision will be determined by the RPD of duplicates, unless otherwise indicated.
[2] Completeness is based on the number of valid measurements, compared to the total number of samples.
[3] Accuracy of weirs/flumes will be ensured by installing flumes and weirs according to SOP H6-6 and by avoiding installation locations that could adversely affect weir/flume accuracy (i.e., approach conditions do not allow uniform velocity distribution, damage to weirs or flumes, changes in weir or flume dimensions). In addition, manual flow rate measurements will give an indication of whether the weirs and flumes are returning reasonable flow rate measurements.

Table 7-2. IDLs for ICP Analysis of Dissolved Metals

Analyte	IDL (µg/L)	ICP CRDL (µg/L)
Al	24.0	200
Sb	29.5	60
As	29.5	59.1
Be	2.4	5
Cd	4.52	5
Ca	14.1	5000
Cr	10.0	10
Cu	2.4	25
Fe	10.0	100
K	21.2	5000
P	36.8	184.2
Mg	40.0	5000
Mn	2.6	15.0
Ni	10.9	40
Se	57.2	114.3
Ag	3.7	10
Na	16.3	5000
Ti	3.2	15.8
Zn	5.9	20
Pb	24.0	48.0

Table 7-3. Summary of Flagged Data for Activity III, Project 39

Date of Collection	Sample ID	Analysis	Quality Criteria	Flag	Comment
6/19/03	NSM SP4 061903	Total Zn	≤ 20% RPD	J	RPD > 20%; the associated samples should be flagged J for total Zn
7/280/03	NSM SP2 072803 NSM SP3 072803 NSM SP4 072803	Total Fe	Blank concentration > CRDL	UJ	The field blank sample showed significant contamination; the associated samples should be flagged UJ for total Fe
11/25/03	NSM SP4 112503	Dissolved Zn	≤ 20% RPD	J	RPD > 20%; the associated samples should be flagged J for dissolved Zn
5/25/04	NSM SP1 052504	Dissolved and Total Metals	≤ 20% RPD	R	RPD > 20% for all dissolved and total metals; the associated samples should be flagged R for dissolved and total metals
8/17/04	NSM SP1 081704	NH_4	≤ 20% RPD	J	RPD > 20%; the associated sample should be flagged J for NH_4
8/17/04	NSM SP4 081704	Dissolved Se	75% – 125% recovery of spike	J	Spike recovery < 75%; the associated sample should be flagged J for dissolved Se
8/17/04	NSM SP1 081704 NSM SP2 081704 NSM SP3 081704 NSM SP4 081704	Total Si Dissolved Si	Blank concentration > CRDL	UJ	The field blank sample showed significant contamination; the associated samples should be flagged UJ for total and dissolved Si

Data Qualifier Definition:
J – The measurements are estimated.
UJ – The measurements are estimated and may be inaccurate or imprecise.

8. Conclusions and Recommendations

The MWTP, Activity III, Project 39, *Permeable Treatment Wall Effectiveness Monitoring, Nevada Stewart Mine Site* was conducted to determine the effectiveness of an ATS and to identify the attenuation mechanisms functioning to reduce the dissolved metals in the adit mine discharge. Overall, the system was effective at reducing the metals loading in the treated NSM adit discharge. Main conclusions drawn from MSE's, EPA's, Golder's, and Montana Tech's contributions regarding this demonstration project are as follows.

- The system effectively attenuates Zn, Cd, Pb, Fe, and Mn, as evidenced by decreases in the aqueous phase concentrations between the influent and effluent, and the increases in the solid phase concentrations of these constituents within the treatment tanks.
- The possible attenuation mechanisms reducing the metals loading in the treated NSM water include:
  - Phosphate mineral precipitation, where Apatite II™ continuously supplies phosphate to solution to exceed the solubility limits of various metal-phosphate phases. It is possible that Mn was removed by this process and because this is a slower process, the characteristics of Tank 4 provided optimal conditions for this process to occur, even though the process could have occurred in Tanks 2 and 3.
  - Biological reduction, resulting in sulfide precipitation, where Apatite II™ supplies both P and readily-bioavailable organics (collagen) at concentrations that stimulate microbial activity within the treatment tanks, occurred in all of the tanks. However, Tank 4, which had the lowest flow rate, recorded the highest hydrogen sulfide gas concentrations, SRB counts, and sulfide concentrations reflective of a strong biological reductive environment. The other tanks also, exhibited the same characteristics but not to the same degree.
  - Nonspecific metal adsorption (surface chemi-adsorption), where Apatite II™ adsorbs metals was another potential metals attenuation mechanism. A quantitative amount of metals adsorbed by the apatite is unknown because the laboratory instrumentation was not capable of determining this.
  - Buffering, where neutral pH is effective at precipitating many metal phases, the NSM near-neutral water at the NSM was minimal. However, increasing pH and alkalinity, especially during the spring of 2003, possibly affected Fe oxidation and, therefore, precipitation and subsequent adsorption of other metals.
- All direct analytical evidence pointed to the precipitation of ZnS as the dominant mechanism for Zn attenuation within the treatment tanks. The lowest effluent Zn concentrations occurred in association with elevated sulfide concentrations, primarily in Treatment Tank 4, which had the lowest ORP and DO. Additionally, mineralogical analysis and evaluation by Montana Tech confirmed the presence of ZnS on the surface of the fishbone apatite.
- No direct analytical evidence could be developed to ascertain the manner in which the treatment process removed Cd and Pb from the influent water. However, speciation modeling by Golder showed supersaturation with respect to CdS and PbS (Appendix D). Correlation analysis results, also by Golder, for the treatment tank elemental concentration suggested but could not verify alternative mechanisms for Pb and Cd removal (i.e., phosphate mineral precipitation and/or surface adsorption).

- Speciation modeling identified manganese phosphate as a possible control on Mn concentrations, especially in Tank 4 as its effluent had high concentrations of total phosphate, but this was not directly verified.
- Depending on the redox conditions within each treatment tank, precipitation of ferrihydrite**,** or iron phosphate (strengite), potentially controlled the Fe concentrations. Substantial quantities of ferrihydrite were visible in the center cell of Tank 3 (Figure 5-4).
- Treatment tanks having lower flows and longer retention times removed metals to a greater degree. Tank 4, having the lowest flow rate, had approximately 95% Zn removal efficiency.
- The mineralogical analysis conducted was not capable of characterizing the surface reactions such as adsorption. However, the solid phase analysis indicated that between 6% and 36% Zn was precipitated onto the surface of the Apatite II™ on a microscopic basis. The sulfide adhered to the surface of the bone probably due to the presence of sulfide producing colonies of bacteria. Smooth surfaces exhibited less metal than rough surfaces.
- The increase in dissolved Ca concentrations in the effluent was caused by the dissolution of the Ca from the fishbone in the treatment tanks.
- A detrimental effect of Fe deposition on the surface of the bone pieces is that it armors the surface that decreases the number of sites available for adsorption of the other target ions and the surface area that is available for dissolution.

Recommendations for further field installation include the following.

- Residence time needs to be increased either by increasing the volume (length of flow path) of the treatment system, decreasing the flow rate, or both.
- Higher concentrations of Fe should be eliminated by some other means, with apatite used as a polishing step within a treatment system to avoid adsorption capacity being diminished in the presence of iron and to avoid likely plugging problems.
- Future apatite treatment systems need to enhance the permeability of the system to maximize the efficiency of the treatment medium for metals removal. Periodic air sparging of the media proved to be an effective way to enhance permeability of the media and reestablish flow when the system was plugged. Future system designs need to improve the hydraulics of the tank systems, thus, preventing clogging and the formation of preferential flow paths through the treatment system. Furthermore, the systems need to be designed to process fluctuating flows resulting from seasonal flow impacts. Also, to ensure that tanks remain level throughout operation, a stable base is necessary to avoid settling of the tanks and associated disruptions in flow.
- The media at the treatment tank entrance becomes loaded first because of precipitation of metals, biological metal reduction, and adsorption of metal on the surface of the apatite medium. As a result, there is a gradual loss of effectiveness of the treatment provided by the media. This process will need to be addressed in the design of future systems.

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9. References

1. U.S. Environmental Protection Agency's National Risk Management Research Laboratory, *Quality Assurance Project Plan–Permeable Treatment Wall Effectiveness Monitoring, Nevada Stewart Mine*, Cincinnati, Ohio, MWTP-223, May 2003.

2. Box, S.E., A.A. Bookstrom, W. Kelly, *Surficial Geology of the Valley of the S. Fork of the Coeur d'Alene River, Draft*, October 1999.

3. Fortier, David H., *Data, Adit 2003 – Graphs.xls, Pine Creek Water 2004 USGS copy.xls, Pine Creek Water – Sort.xls;* BLM Coeur d'Alene Field Office, August 2004.

4. Funk, William H., Rabo, F., et al., *An Integrated Study of the Impact of Metallic Trace Element Pollution in the Coeur d'Alene – Spokane Rivers-Lake Drainage Systems*, Washington State University, University of Idaho Joint Project Completion Report to OWRT (Title II Project C-4145), 1975.

5. U.S. Environmental Protection Agency, Region 10, *Record of Decision, Bunker Hill Mining and Metallurgical Complex, Operable Unit 3 (Coeur d'Alene Basin)*, DCN: 4162500.07099.05.a, EPA DCN 2.9, Contract No. 68-W9-0054/0031, Sect. 12, September 2002.

6. U.S. Department of Energy, National Energy Technology Laboratory, *Evaluation of Apatite Media for Use in Reactive Barriers and Treatment Systems to Remove Metals and Radionuclides from Contaminated Groundwater Final Report*, Contract No. DE-AC22-96EW96405, TTP No. FT10WE21, TASK E. ECCP-38, September 2002.

7. Manecki, M., P. A. Maurice, S. J. Traina, "Kinetics of aqueous Pb reaction with apatites," *Soil Science*, 165(12): 920-933, 2000.

8. Wright, J.V., J.L. Conca, K.R. Rice, B. Murphy, *PIMS Using Apatite II^{TM}: How It Works to Remediate Soil and Water*, Proceedings of the Conference, ISBN 1057477-144-2, B4-05, Battelle Memorial Institute, Columbus, OH, 2004.

9. Nriagu, J. O., P. B. Moore (Eds.), *Phosphate Minerals*, Springer-Verlag, New York, 1984.

10. Morse, J. W., W. H. Casey, "Ostwald processes and mineral paragenesis in sediments," *American Journal Science*, 288: 537-560, 1988.

11. Koeppenkastrop, D., E. J. De Carlo, "Sorption of rare earth elements from seawater onto synthetic mineral phases," *Chem. Geol*, 95: 251-263, 1990.

12. Ma, Q. Y., T. J. Logan, S. J. Traina, "Lead immobilization from aqueous solutions and contaminated soils using phosphate rocks," *Environ. Sci. Technol.*, 29: 1118-1126, 1995.

13. Wright, J. V., L. M. Peurrung, T. E. Moody, J. L. Conca, X. Chen, P. P. Didzerekis, E. Wyse, "In Situ Immobilization of Heavy Metals in Apatite Mineral Formulations," *Technical Report to the Strategic Environmental Research and Development Program*, Department of Defense, Pacific Northwest Laboratory, Richland, WA, 154 p., 1995.

14. Chen, X., J. Wright, J. L. Conca, L. M. Peurrung, "Effects of pH on heavy metal sorption on mineral apatite," *Environ. Sci. Technol*., 31: 624-631, 1997a.

15. Chen, X., J. Wright, J. L. Conca, L. M. Peurrung, "Evaluation of heavy metal remediation using mineral apatite," *Water, Air and Soil Pollution*, 98: 57-78, 1997b.

16. Conca, J. L., N. Lu, G. Parker, B. Moore, A. Adams, J. Wright, P. Heller, "PIMS–Remediation of Metal Contaminated Waters

and Soils," In G.B. Wickramanayake, A.R. Gavaskar, J.T. Gibbs, J.L., Means (Eds.), *Remediation of Chlorinated and Recalcitrant Compounds, vol. 7.*, p. 319-326, Battelle Memorial Inst., Columbus, Ohio, 2000.

17. Ruby, M. V., A. Davis, A. Nicholson, "In situ formation of lead phosphates in soils as a method to immobilize lead," *Environ. Sci. Technol*., 28: 646-654, 1994.

18. Golder Associates, *Final Report on September 2002 to June 2003: Effectiveness Monitoring Groundwater Treatment Facility, Success Mine and Mill Site, Wallace, ID*, Submitted to TerraGraphics Environmental Engineering by Golder Associates, September 8, 2003.

19. Calabretta, M., B. Hansen, G. Harvey, D. Morell, *Treatment of Metals Impacted Groundwater with a Semi-Passive Organic Apatite System, Paper submitted to Society of Mining Engineering, November 2001*.

20. MSE Technology Applications, Inc., *Evaluation of Apatite Media for Use in Reactive Barriers and Treatment Systems to Remove Metals and Radionuclides from Contaminated Groundwater – Final Report*, for U.S. DOE, 2002.

21. MSE Technology Applications, Inc., *Definitive Design for Apatite Treatment Technology Deployment at the NS Tunnel Site, Pinehurst, ID*, for U.S. DOE, September 12, 2002.

22. Xu, Y. and F.W. Schwartz, *Lead* "Immobilization by Hydroxyapatite in Aqueous Solutions", *Journal of Contaminant Hydrology*, 15: 187-206, 1994.

23. Clary, D.J., "Determining the Removal Mechanisms of Fishbone Apatite for Cadmium, Lead, and Zinc From the Nevada Stewart Adit Discharge Water," Thesis submitted to Department of Environmental Engineering, Montana Tech of the University of Montana, April 29, 2004.

24. Parkhurst, D.L., C.A.J. Appelo, *User's Guide to PHREEQC (Version 2)—A Computer Program for Speciation, Batch Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations*, US Geological Survey Water Investigation Report 99-4259, Denver, CO, 1999.

Appendix A

Nevada Stewart Mine Monthly Field Data Results

Appendix B

EPA Toxicity Testing Reports

Appendix C

Montana Tech's Final Report
on the Evaluation of Apatite II™ Media
from the Nevada Stewart Mine Apatite Treatment System

Appendix D

Golder Associates Geochemical Report

Appendix E

Solid Phase Digestion Results

Appendix F

EPA Statistical Analysis

Remediation of Groundwater Contaminated with Zn, Pb and Cd using a Permeable Reactive Barrier with Apatite II

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Introduction

Phosphate-Induced Metal Stabilization (PIMS) using Apatite II stabilizes a wide range of metals, especially Pb, Cd, Zn, U and Pu, *in situ* or *ex situ*, by chemically binding them into new stable phosphate phases and other low-solubility phases that are stable over geologic time. The concept resulted from paleochemical oceanographic and chemostratigraphic studies, in the 1970s and 1980s, of phosphatic sedimentary materials from the Cambrian period (570 million years ago) to the Present [1,2]. These studies showed that apatite hard parts of marine animals, and even abiotic phosphorite deposits, developed identical trace metal signatures of the seawater with which they were in contact, but with concentrations enriched by six or seven orders of magnitude. The chemical reactions were relatively fast and the chemical signatures were retained over geologic time, even in the face of multiple destructive events such as burial, lithification, heating, and weathering. Recent laboratory and field studies have demonstrated the applicability of this concept towards remediation of metal-contaminated waters and soil. Results are presented from a field site at Success Mine in Idaho, where a permeable reactive barrier (PRB) filled with Apatite II has been operating for just under two years to remediate Zn, Cd and Pb [3]).

Some form of mineral apatite is necessary for efficient metal remediation, especially for instigating the heterogeneous nucleation of metal-apatite phases necessary for remediation under environmental conditions [4]. A special form of biogenic apatite, Apatite II, has been developed that is the most reactive and the most cost-effective apatite available. Unlike any other apatite, Apatite II has the optimal structural and chemical characteristics for metal and radionuclide remediation: 1) no substituted fluorine, 2) a high degree of substituted carbonate ion, 3) low initial trace metal concentrations, 4) extremely poor crystallinity (basically amorphous) coupled with random nanocrystallites, and 5) high microporosity. The ultimate driving force for the robust performance of reactive phosphate with respect to metals is the extreme stability of these metal-phosphate phases, some of which are listed in Table 1. These metal phosphates are twenty to seventy orders of magnitude more insoluble than quartz. Combined with this stability, the rapid kinetics of the metal-phosphate precipitation ensures immobilization of the metals in the face of most possible transport mechanisms. Non-apatite phosphate and mixtures of precursor constituents will not perform as well, if at all, under most environmental conditions. The apatite can be emplaced down-gradient as a permeable reactive barrier (PRB) to capture

TABLE 1

Mineral Phase	*Solubility Product (log K_{sp})*	*Mineral Phase*	*Solubility Product (log K_{sp})*
$Pb_5(PO_4)_3(OH,Cl)$	-76.5	$Am(PO_4)$	-24.8
$Ca(UO_2)_2(PO_4)_2 \bullet 10H_2O$	-49.0	$Pu(PO_4)$	-24.4
$Sr_5(PO_4)_3(OH)$	-51.3	$UO_2(HPO_4)$	-10.7
$Zn_3(PO_4)_2$	-35.3	Quartz (SiO_2)	-4.0
$Cd_3(PO_4)_2$	-32.6	Salt (NaCl)	0.0

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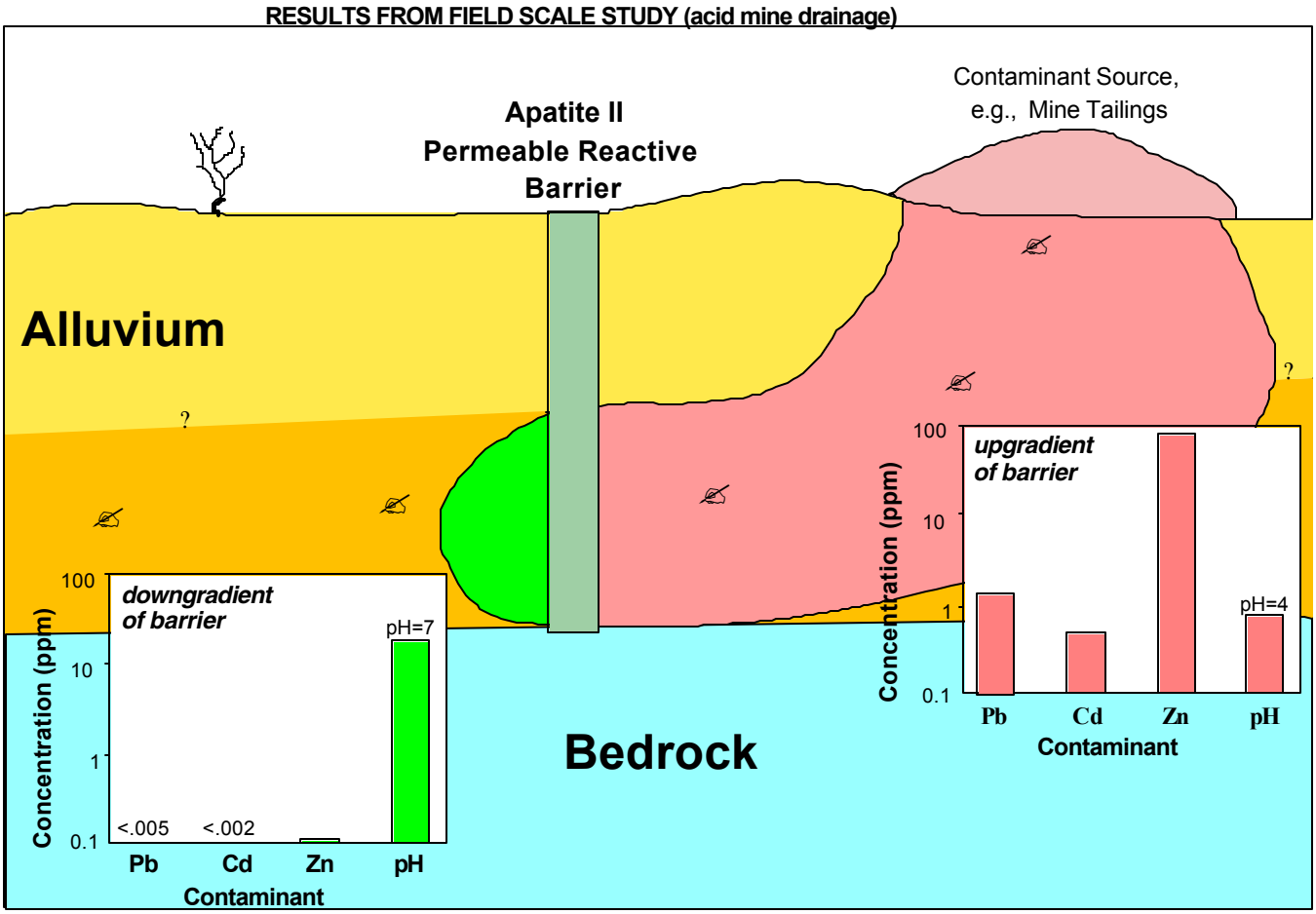

FIGURE 1. Schematic of a permeable reactive barrier showing actual results from the field.

groundwater or seeps, mixed into contaminated soil or waste, used as a disposal liner, or emplaced by any method that brings the soluble metal into contact with the apatite surface. Figure 1 shows the concept of a PRB along with actual monitoring results from the field (Success Mine, Idaho).

Material and Methods

Various reactive media were investigated to remove metals and radionuclides from groundwater and soils [2,5]. Analytical techniques included Ion Chromatography, Inductively-Coupled Plasma (ICP) Emission and Mass Spectroscopy, Liquid Scintillation Counting, Transmission Electron Microscopy, and Potentiometric Stripping, plus standard methods for measuring pH, dissolved oxygen and other field and laboratory parameters. Batch tests and flow-through column tests were used to determine relative performance and to provide media for solids characterization. Batch sorption studies were performed on materials to determine the reactive sorption or distribution coefficient (K_d), which is a ratio of the amount of contaminant sorbed onto the media to the amount remaining in solution [6]. Column studies are run until the contaminant begins to appear in the column effluent, referred to as breakthrough.

Results and Discussion

The metal-stabilization potential of reactive phosphates from different sources was investigated along with other materials for remediation of contaminated soil and groundwater from the Bunker Hill/Success Mine Site in northern Idaho [7,8,9]. Materials included zeolites (clinoptilolite and chabazite), compost,

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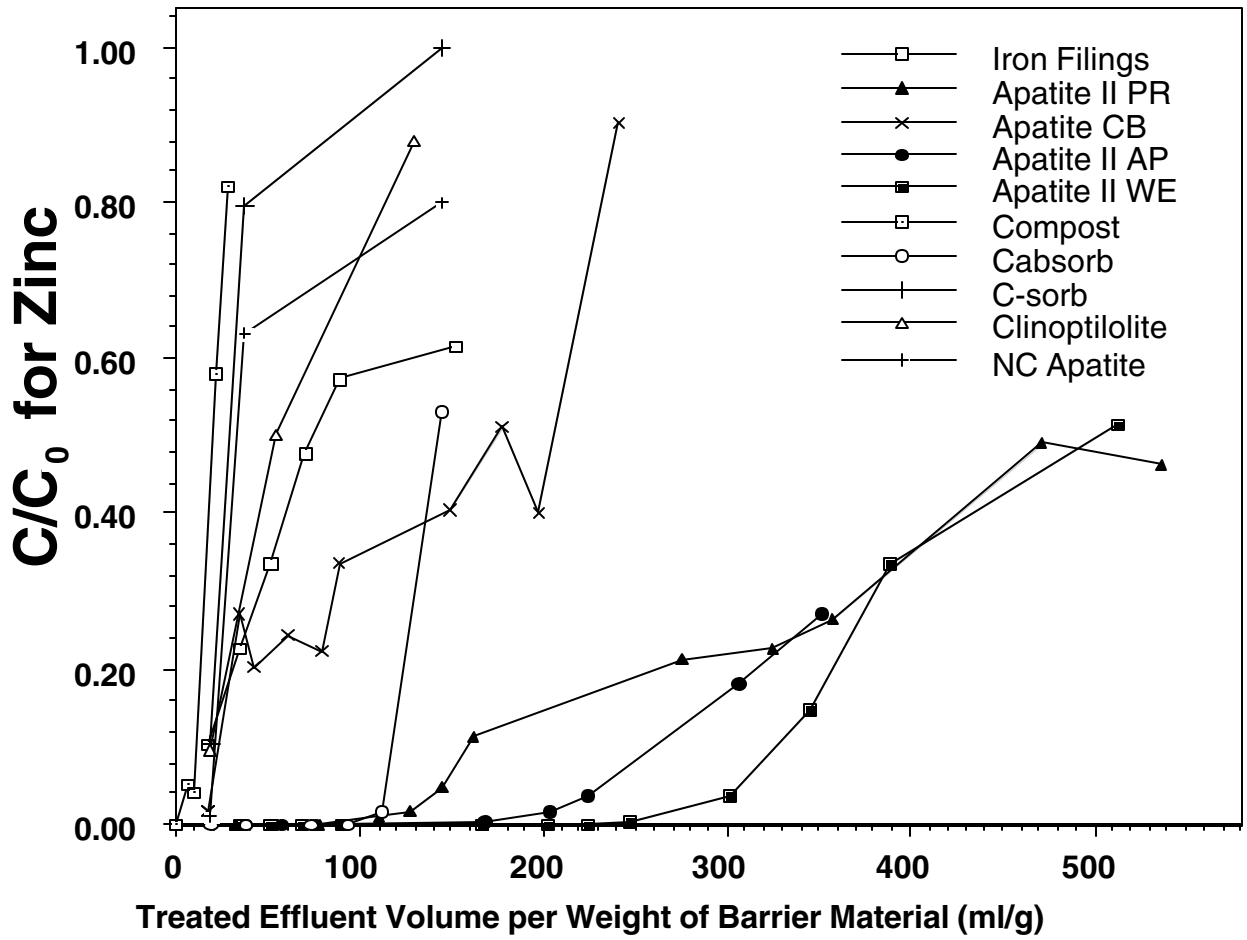

FIGURE 2. Breakthrough of dissolved Zn through various permeable reactive barriers using contaminated groundwater from the Success Mine Site. C_{0zn} = 250 ppm.

various polymers, iron filings and oxides, and apatites [different formulations of Apatite II (WE, PR, and AP), cowbone (CB) and phosphate rock (NC)]. Soils in this area are contaminated with 1000-4000 mg kg^{-1} (ppm) of Pb, Zn, Cd and Cu, and groundwaters are contaminated with Zn, Pb, Cd and Cu up to concentrations of 250 ppm, 10ppm, 1 ppm and 20ppm, respectively. Apatite II performed best with respect to stabilization of these three metals, sequestering almost 20% of its weight in Pb, and about 5% of its weight in Zn and Cd. The bioavailability of the metals from the contaminated soil was also greatly reduced using Apatite II even when the metal was not in an apatite phase [8]. Pb precipitated as lead-pyromorphites while Zn and Cd both sorbed onto particles and precipitated as hopeite, zincite, hydrocerrusite, otavite and other phases [7,8,9]. Results showed that the leachates from untreated soils were 100 to 1000 ppm for Pb and Zn, and hundreds of ppm for Cd, well in excess of regulatory Maximum Contamination Levels for drinking water. However, leachates from Apatite II-treated soils showed Pb, Zn and Cd below the detection limits of 5 ppb. Performance was successfully predicted using MINTEQ-A2, a thermodynamic speciation model [10], was substantiated by XRD results on the contaminated soils after apatite treatment [9] and was also consistent with results by other researchers [4,11]. The results for Zn are shown in Figure 3 which plots contaminant concentration in the effluent normalized to the influent, C/C_0, versus the volume of water passing through the column normalized to the weight of barrier material. Similar results occurred for Cd [8]. As a result of these tests, a PRB of

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Apatite II was emplaced between the Success Mine Tailings pile and Nine Mile Creek and has been operating for almost two years [3]. It is a 13.5-ft high, 15-ft wide and 50-ft long baffled vault filled with 100 tons of Apatite II that reaches down to bedrock and is designed to capture most of the subsurface drainage from the 500,000-ton tailings pile. The concentrations of metals entering the barrier over this time period has averaged 780 ppb Cd, 1,210 ppb Pb and 116,000 ppb Zn. The pH has been between 4.5 and 5.0. The average concentrations of metals leaving the barrier has been < 2 ppb Cd, < 5 ppb Pb and about 115 ppb Zn. The exiting pH has been between 6.5 and 7.0 [3]. Flow rates are seasonal and vary between 1 gpm and 50 gpm. Based on periodic daily metal-loading averages, it is estimated that the Apatite II barrier has sequestered over 1000 lbs of Cd, over 2,500 lbs of Pb and over 20,000 lbs of Zn over the 1.7 years since it was emplaced. This barrier is estimated to last over ten years for Cd and Pb, but Zn should begin to breakthrough in another year because of the higher-than-expected Zn loading. Either the Apatite II can be replaced, or more desirable, a second barrier can be emplaced behind the first one, allowing the first one to continue to sequester Cd and Pb and condition the pH while the second captures Zn as it begins to breakthrough the first barrier. The cost of the Apatite II was about $500/ton for the approximately 100 tons used in this barrier. Emplacement used traditional backhoe and earth-moving equipment to trench the vault. The Apatite II was gravel-sized for easy flow.

References

1. Wright, Judith, Schrader, H. and Holser, W.T. 1987. Paleoredox Variations in Ancient Oceans Recorded by Rare Earth Elements in Fossil Apatite. *Geoch. Cosmoch. Acta* **51**, 631-644.
2. Wright, Judith. 1990. Conodont apatite: structure and geochemistry, in *Metazoan Biomineralization: Patterns, Processes and Evolutionary Trends* (J. Carter, ed.), Van Nostrand Reinhold, NY, 445-459.
3. Calabretta, M., Hansen, B., Harvey, G. and Morel, D. 2001. Treatment of Metals-Impacted Groundwater with a Semi-Passive Organic Apatite System. In *GeoDestiny - Resources for the Future, Proceedings of the Northwest Mining Association's 107th Annual Meeting*, December 2001, Northwest Mining Association, Spokane, WA, p. 1-10.
4. Lower, S. K., P. A. Maurice, S. J. Traina, and E. H. Carlson. 1998. Aqueous Pb sorption by hydroxylapatite: Applications of atomic force microscopy to dissolution, nucleation and growth studies. *Amer. Min.* **83**, 147-158.
5. Conca, J.L., Lu, N., Parker, G., Moore, B., Adams, A., Wright, Judith, and Heller, P. 2000. PIMS – Remediation of Metal Contaminated Waters and Soils, in *Remediation of Chlorinated and Recalcitrant Compounds* (G.B. Wickramanayake, A.R. Gavaskar and A. Chen, eds.) Battelle Memorial Institute, Columbus, Ohio, **7**, 319-326.
6. Bouwer, H. 1991. Simple Derivation of the Retardation Equation and Application to Preferential Flow and Macrodispersion. *Ground Water* **29**, 41-46.
7. Wright, Judith, L. M. Peurrung, T. E. Moody, J. L. Conca, X. Chen, P. P. Didzerekis, and E. Wyse. 1995. *In Situ Immobilization of Heavy metals in Apatite Mineral Formulations*, Technical Report to the SERPD, DoD, Pacific Northwest Laboratory, Richland, WA.
8. Conca, J. L. 1997. *Phosphate-Induced Metal Stabilization (PIMS).* Final Report to the U. S. Environmental Protection Agency #68D60023, Res. Triangle Park, NC.
9. Chen, X.-B., Judith Wright, J. L. Conca, and L. M. Peurrung. 1997. Evaluation of Heavy Metal Remediation Using Mineral Apatite. *Water, Air and Soil Pollution* **98**, 57-78.
10. Moody, T.E., and Judith Wright. 1995. *Adsorption Isotherms: North Carolina Apatite Induced Precipitation of Lead, Zinc, Manganese and Cadmium from Bunker Hill 4000 Soil*, Technical Report BHI-00197, Bechtel Hanford, Richland, WA.
11. Ma, Q. Y., S. J. Traina, and T. J. Logan. 1993. In Situ Lead Immobilization by Apatite. *Env. Sci. Tech.* **27**, 1803-1810.

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TREATMENT OF ACID MINE DRAINAGE USING FISHBONE APATITE II™ [1]

Neal A. Yancey[2] and Debby Bruhn[3]

ABSTRACT. In 2000, a reactive barrier was installed on the East Fork of Ninemile Creek near Wallace, Idaho to treat acid mine discharge. The barrier was filled with fishbone derived Apatite II™ [4] to remove the contaminants of concern (Zn, Pb, and Cd) and raise the pH of the acidic mine discharge. Metal removal has been achieved by a combination of chemical, biological, and physical precipitation. Flow for the water ranges from 5 to 35 gallons per minute. The water is successfully being treated, but the system experienced varying degrees of plugging. In 2002, gravel was mixed with the Apatite II™ to help control plugging. In 2003 the Idaho National Laboratory was ask to provide technical support to the Coeur d'Alene Basin Commission to help identify a remedy to the plugging issue. Air sparging was employed to treat the plugging issues. Plastic packing rings were added in the fall of 2005, which have increased the void space in the media and increased flows during the 10 months of operation since the improvements were made.

Additional Key Words: reactive barrier, heavy metals, mining.

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[4] Product Disclaimer:

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BACKGROUND

The Coeur d'Alene Basin of Northern Idaho is known as Silver Valley because of the huge volume of silver mined in the area in the early 1900s. As a result, thousands of acres of land and miles of streams have been contaminated with metals from the mining and milling activity (Gillerman 2002). Stabilizing stream banks and tailings piles that are sources of sediment and particulate metals in the creeks is one cleanup activity that is being implemented in the Coeur d'Alene Basin. In some locations, tailings have been piled on the canyon floors and cover the original creek channels. Water now flows through the tailings, where it picks up dissolved and suspended metals (Figure 1). The Success Mine site was identified as the largest remaining source of metals loading in the Ninemile Creek drainage (EPA 2002). Zinc, cadmium and lead concentrations are significantly higher in this area than background areas. During high flows in the spring, sediments that were trapped during low flow periods are resuspended and carried downstream. The pH of the water is also lower in this area due to the presence of pyrite formations (Golder Associates Inc., 2002).

Figure 1.0 Ground and Surface Water Passing through Mine Tailings

Groundwater flows from the adjacent hillsides and comes up in various locations in the canyon floor. Portions of this water comes up through the tailings pile and flows down gradient until it enters the creek, again carrying with it increased levels of dissolved and suspended metals with a lowered pH level.

INTRODUCTION

In 2000, a 45 foot long 12 foot deep reactive barrier was constructed to treat acid mine drainage resulting from surface and groundwater passing through mine and mill tailings at the Success Mine on the East fork of Ninemile Creek near Wallace, Idaho. The reactive barrier was constructed having two separate sides, each 6 foot wide, 12 feet deep, and 45 feet long (See Figure 2). On each side of the reactive barrier, water flows over and under alternating baffles to

create as much contact between the media and contaminated water as possible. Each side of the reactive barrier has 5 cells separated by these alternating baffles (Figure 2).

The reactive barrier was filled with fishbone Apatite II™ as a media to remove the metal contaminants and to raise the pH of the water. Apatite II™, derived from fish bones, stabilized a wide range of metals, including Zn, Pb, and Cd (Write et al., 1995). Depending on the metal concentration and water chemistry, the Apatite II™ works by four possible processes: heterogeneous nucleation, pH buffering, chemisorption, and biological stimulation (Wright and Conca 2005). From the start, the reactive barrier successfully removed metals from the contaminated discharge, as well as early on, the system began experiencing plugging problems.

Figure 2.0. Construction of the Reactive Barriers at the Success Mine Site.

Gravel was added in 2001 to help control plugging. This provided only a short benefit and plugging was again an issue. The INL received funding in 2003 to assist the Coeur d'Alene Basin Commission in remediating the plugging issues associated with the reactive barrier. Chemical and biochemical analysis was performed on the media to determine the forms of metal precipitates, biological conditions, and physical and chemical conditions of the media.

In May of 2005, the compressed air was injected into the Apatite II™ to break up sediments deposited in the media in order to increase flow through the media. MSE Technology Applications, Inc., in Butte, Montana had demonstrated that injecting air into a similar reactive barrier at the Stewart Mine on Pine Creek had successfully increased flow in the Apatite II™ media at that location (McCloskey et al., 2006).

In November 2005, the old gravel/ Apatite II™ mixture was removed and disposed onsite to make room for the new Apatite II™ /plastic packing ring mixture. New Apatite II™ media mixed with plastic packing rings was used to replace the plugged media in the East side of the reactive barrier. The plastic packing rings were used to increase the void space in the media and alleviate the plugging problem.

Material and Methods

Biological Analysis of the Apatite II™ Media

The Apatite II™ media was sampled to determine if sulfate reducing bacteria (SRB) were active in the barrier. These bacteria are responsible for precipitating metal ions found in acid mine drainage. SRBs are a ubiquitous group of prokaryotic microorganisms found in anaerobic environments. In the process of anaerobic respiration these organisms can use a variety of electron donors (AH_2) and can couple oxidation of those compounds to reduction of sulfate and elemental sulfur as shown in the following equation:

$$4\ AH_2 + SO_4^{-2} + H^+ \rightarrow 4\ A + HS^- + 4\ H_2O$$

It is in the anaerobic zone that the remediation takes place. The sulfide produced then precipitates with the soluble metals (such as Fe, Cu, Mn, Zn, Pb, and Cd) as insoluble metal sulfides, and the net consumption of protons due to formation of hydrogen sulfide gas generates bicarbonate alkalinity, which raises the pH of the waste stream.

The media used to isolate and identify SRB was Bacti control bottles API Anaerobic media which includes ammonium phosphate, dipotassium phosphate, yeast extract yeast extract, sodium lactate and magnesium sulfate and a nail to provide iron manufactured by Sherry Laboratories. Water samples were collected from each cell in both sides of the reactive barrier and from the outflow. One mL of each water sample was injected into a Bacti vial, using sterile methods. Each sample was collected in triplicate and diluted out to 10^{-8}. Medium used for heterotrophic and enteric bacteria was 2% PTYG Agar (2% Peptone-Tryptone-Yeast Extract-Glucose and 1.5 % agar) and Luria-Bertani Agar (10 g tryptone, 5 g yeast extract, 5 g NaCl, and 15 g agar per liter of water). One mL and 0.1 mL samples were plated in duplicate on both medium. Eh and pH of water samples were also taken.

Chemical Analysis of the Apatite II™ Media

Apatite II™ samples were collected from below the water level in each side of the reactive barrier to be representative of the conditions where chemical and biological reactions occur. The samples were collected and stored in polypropylene containers and put on ice until they were received at the laboratory.

Both the sediments and the Apatite II™ were oven dried for 24 hours at 90º C. The samples were sieved to separate the sediments from the Apatite II™ media. The Apatite II™ media was also washed with tap water (tap water) to remove any surface attached material from the fish bones. The samples were pulverized with a mortar and pestle in preparation for analysis. The samples were analyzed for both metal concentrations and speciation using Powder X-Ray Diffraction and XRF and by Scanning Electron Microscopy.

Injection of Compressed Air to Improve Flow

The covers to the reactive barriers were removed to provide access to the media. A 10 foot galvanized hollow wand was fabricated to inject compressed air deep into the media. Compressed air was injected in at least two locations in each of the 5 cells for both the East and West side of the reactive barrier (See Figure 3).

Figure 3. Injecting Compressed Air in the Apatite II™ Media.

Replacing the Media in the Reactive Barrier with Apatite II™ and Plastic Packing Rings

Attempts to improve flow on the East side of the reactive barrier were only temporarily successful. The addition of gravel to the media did not improve flow through the system. Aerating the Apatite II™ media was successful for a short time, but it soon returned to the original flows. As a result, an alternative mixture of Apatite II™ and plastic packing rings was used to help increase the percent of void space in the reactive barrier. Plastic packing rings (produced by Jaeger Products Inc.,) are used in many aspects of water treatment to increase the

surface area for microbial attachment and increase the reactive area of the media. They are also used to increase the void space in the media (Figure 4).

Figure 4. Plastic Packing Rings.

Results and Discussion

Water samples were taken at the discharge of both sides (East and West) of the reactive barrier to determine if SRBs were present in the discharge. Water was also sampled in each of the 5 cells on each side of the reactor. The Apatite II™ was plugged on the East side and required mechanical mixing and injection of compressed air to get water flowing again through the reactive barrier. This would have affected the true Eh values being measured in the field at the time. Table 1 shows the results of the field measurement for pH and Eh and Table 2 shows the laboratory results for the SRB counts.

Table 1. Field Measurements for Eh, pH, and SRB Counts.

Sample	Eh	pH
Inflow water	468	4.5
Cell 1 West	211	7
Cell 2 West	-48	6
Cell 3 West	245	6
Cell 4 West	238	6
Cell 5 West	-199	7
Outflow West	150	7
Cell 1 East	236	6
Cell 2 East	310	6
Cell 4 East	Not sampled	Not sampled
Cell 5 East	Not sampled	Not sampled
Outflow East	224	7
E.fork Nine Mile Creek	550	

Table 2. Sulfate Reducing Bacteria Counts.

Sample	Sulfate Reducing Bacteria
Cell 1 West	3×10^4 /mL
Cell 2 West	3×10^4 /mL
Cell 3 West	4×10^4 /mL
Cell 4 West	4×10^3 /mL
Cell 5 West	7×10^5 /mL
Outflow West	1×10^2 /mL
Outflow West	present
Cell 1 East	1×10^5 /mL
Cell 2 East	7×10^3 /mL
Cell 3 East	Not Done
Cell 4 East	1×10^3 /mL
Cell 5 East	7×10^3 /mL
Outflow East	1 /mL
Outflow East	Present

The most obvious finding is that there was in fact SRBs present in the reactive barrier as expected, so some treatment (precipitation) of should occur. The Eh values indicate that most samples are not anaerobic (negative value). This is probably due to the low levels of water in the barrier, which was a consequence of the time of year and weather conditions. Several locations in the West cells had negative Eh values, indicating that the water was deep enough in the barrier and anaerobic activity was present. However, not all location in the West cells had negative Eh values. The micro anaerobic zones did exist throughout the barrier, as shown by the presence of SRB's in most samples. If more water was present in the barrier, a larger anaerobic zone could be created and a larger population of SRB would be present (1×10^8 /mL). This would hopefully lead to complete precipitation of the metal and an increase of the pH to neutral (7.0). The East cells had little to no water flow and no anaerobic zones as indicated by the positive Eh values. It is not likely that treatment was occurring in this cell. If flow can be maintained, and anaerobic zones created, SRB should grow and metal precipitation and pH increase should occur.

Chemical Analysis of the Apatite II™ Media

The presence of zinc, cadmium and lead were measured in the Apatite II™ using scanning electron microscopy (SEM). The SEM provided a relative concentration for each metal. Figure 5 shows the relative weight percents observed in the Apatite II™ for each of the metals of concern. In addition, the concentration of sulfur was also measured. Sulfate is present in the feed water. Under anaerobic conditions, the metals form insoluble sulfide precipitates. The presence or absence of sulfur can be used to determine if metal sulfides are being formed under the conditions present in the reactive barrier. In the Apatite II™ samples, there was no appreciable amount of sulfur detected (Figure 5).

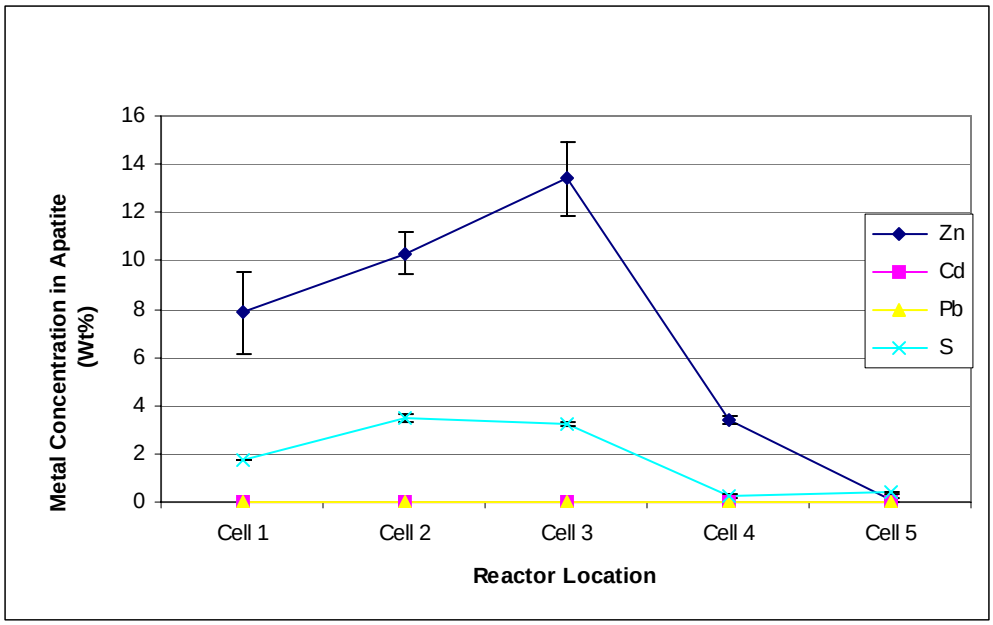

Figure 5. Metal concentration in the Apatite II™ material from the West Side of the Reactive Barrier.

The sediments around the Apatite II™ were also analyzed for metal concentration. Slightly higher concentrations of zinc and lead were present in the sediment than in the Apatite II™. There was also a notable amount of sulfur present in the sediment. This suggests that the metal precipitates formed in the sediments were resulting at least in part due to metals sulfides being formed under anaerobic conditions.

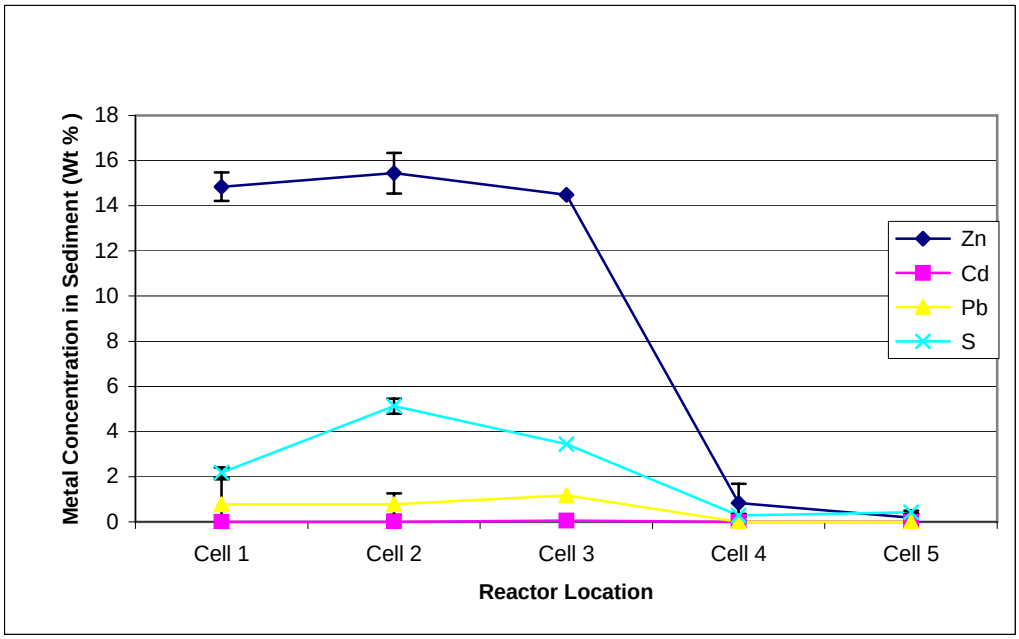

Figure 6. Metal concentrations in the sediment of the West Reactive Barrier.

The same analysis was performed on the East side of the reactive barrier. Figure 7 shows the zinc, cadmium, lead and sulfur concentrations found in the Apatite II™ from the East side of the reactive barrier. This figure shows that the concentrations of the contaminant metals were lower in the East side than the West side. It also shows that most of the reaction occurs in the first two cells and that the subsequent cells are not removing metal from the contaminate water.

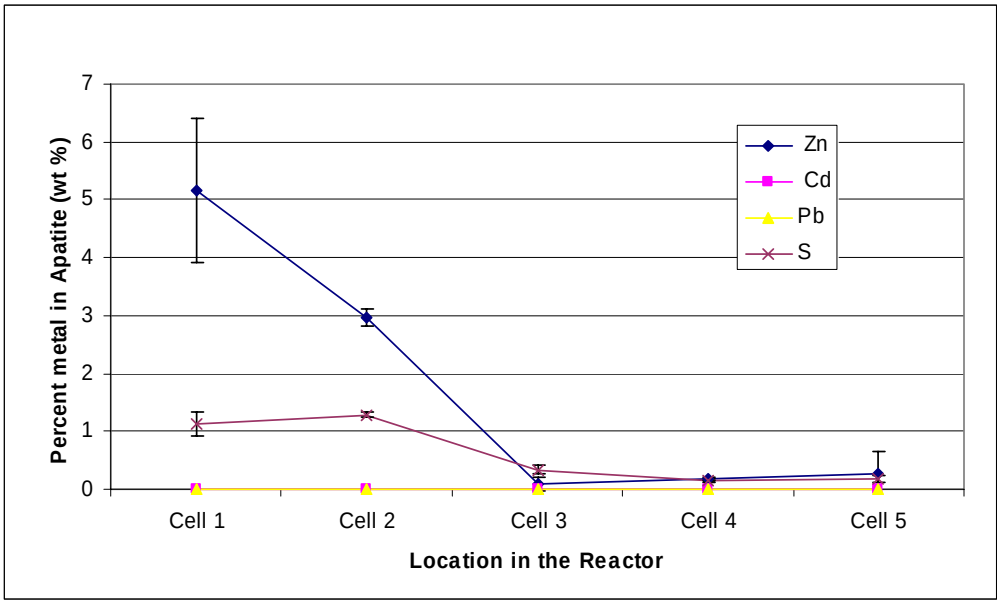

Figure 7. Metal concentration in the Apatite II™ from the East side of Reactive Barrier.

Figure 8 illustrates the concentrations of the metals of interest in the sediment of the East side of the reactive barrier. Most of the precipitation that does occur, takes place within the first two cells of the barrier. The concentration is about half the measured values observed in the West side of the reactive barrier.

Injection of Compressed Air

The reactive barrier was constructed in 2000 and the first Apatite II™ was placed in the barrier in January of 2001. Other than adding new media to the East side of the reactive barrier in 2002, nothing had been done to deal with the plugging issues associated with the reactive barrier. The cause of the plugging was a combination of sediment buildup from the influent stream and sedimentation occurring from the breakdown of the Apatite II™. Figure 9 illustrates the sediment buildup that had occurred in the West side of the reactive barrier. Note the buildup of sediment in the Apatite II™ and notice how the water has formed preferential paths in the media resulting in inefficient contact of water and the reactive media.

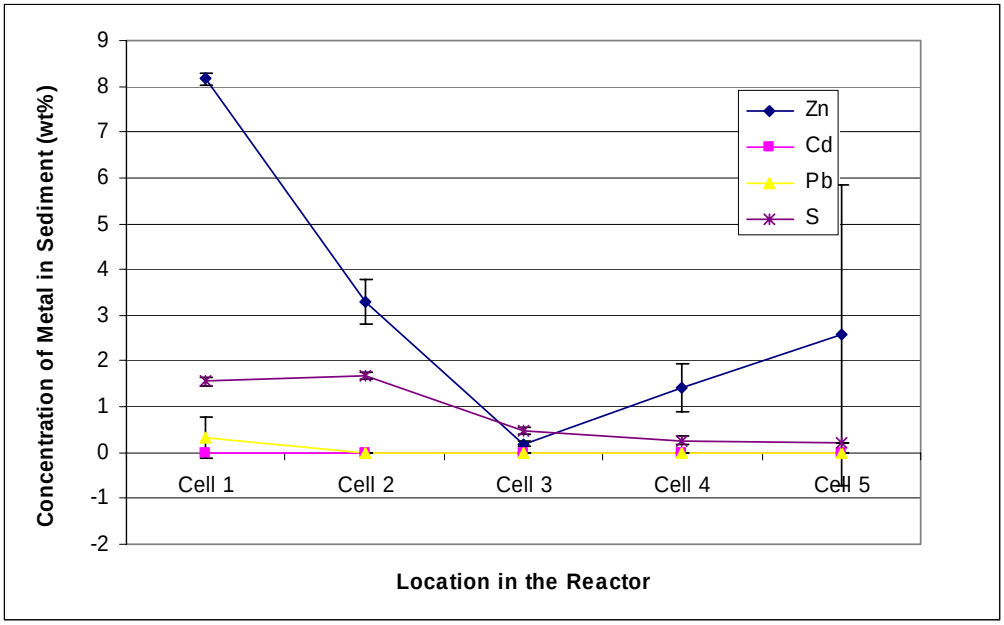

Figure 8. Metal Concentration in the Sediment of the East side of the reactive barrier.

Another similar site in the Coeur d'Alene basin is using Apatite II™ to treat acid mine drainage at the Nevada Stewart Mine. At this location, compressed air is injected into the media combat the effects of plugging on the reactive barrier. This results in temporarily increased flow in the media at the Nevada Steward Mine site. For the reactive barrier at Success, a ten-foot hollow wand was constructed to inject air deep into the media at the Success Mine reactive barrier. Figure 10 shows the workers injecting air into the media at the Success Mine.

Figure 9. Sediment buildup in the Reactive Media.

Figure 10. Injection of Compressed Air into the Reactive Media.

The result of the injection of compressed air into the media was an immediate increase in flow through the reactive barrier, primarily on the West side. The presence of the gravel on the East side made it difficult to get the metal wand into the media to successfully inject the air into the media. This resulted in only limited success on the East side of the reactive barrier.

Figure 11 shows the flow rate measured at the discharge of the reactive barrier. Note that before injecting air into the reactive media, there was a steady stream of water measured in the overflow for the system. Following the air injection, the flow through the reactive media increase and the overflow went to zero meaning that the system was again treating all of the water. The flow rates in general continued to decrease over time following the air injection, but this is primarily due to a seasonal decrease in flow. Note that there was no flow observed in the overflow following the air injection and that the flow in the West side increased again in the Spring of 2006 when flows came back up. Flow on the East side also increased at that time, but it should be noted that the increase in flow on the East side could be directly attributed to the addition of new media in November of 2005. From this it can be observed that injecting compressed air into the media does provide at least temporary improvement to flow in the Apatite II™ media.

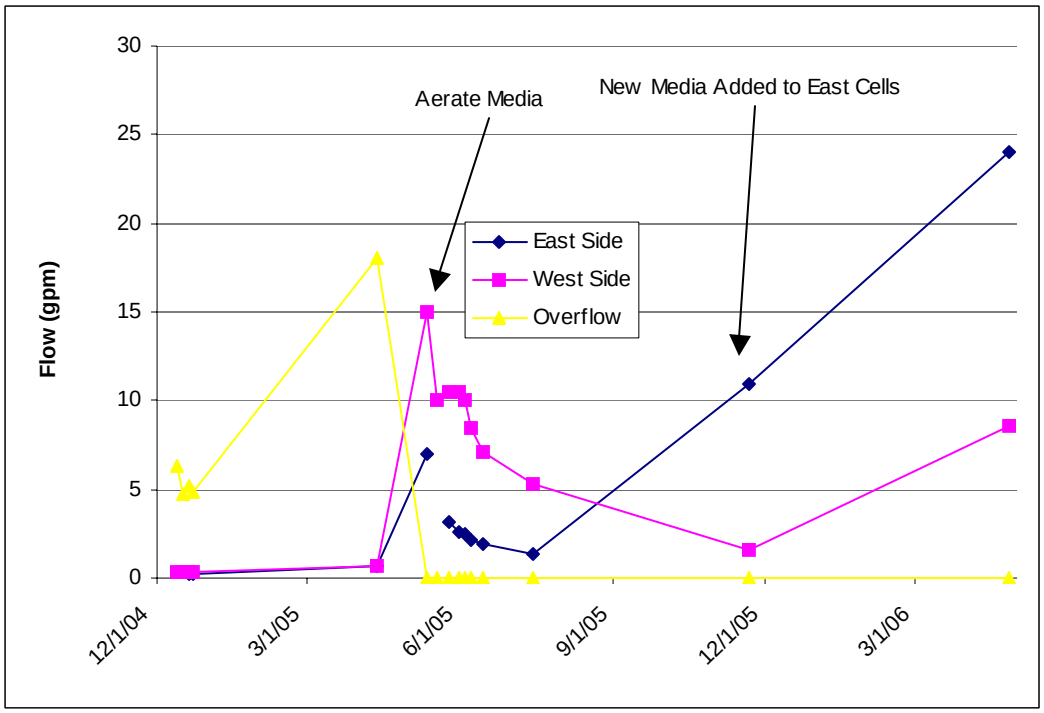

Figure 11. Flow rates measured in the outlet and overflow of the reactive barrier.

<u>Replacing the Media in the Reactive Barrier with Apatite II^{TM} and Plastic Packing Rings</u>

In November of 2005, the media in the East side of the reactive barrier was replaced with new Apatite II^{TM} mixed with plastic packing rings at a ratio of 30 volume % plastic packing rings. Two inch Jaeger plastic packing rings were used to provide an increase in void volume in the reactive barrier. The increase in void volume was desired to provide more area for water to flow through in the Apatite II^{TM} media and to provide more volume for sediments and precipitates to form without impacting the flow. Figure 4 is a picture of the packing rings used in the reactive barrier. By themselves, the plastic rings have a void volume of 92%. Information on the void space of Apatite II^{TM} was not available, but had noticeably less void volume than the plastic rings alone.

Prior to the removal of the old Apatite II^{TM} /gravel mixture and the placement of the new Apatite II^{TM} /plastic packing ring mixture, the flow from the East side of the reactive barrier was less than 1.5 gallons per minute. After replacing the media, the flow increased to over 10 gallons per minute in December of 2005. It further increased to 24 gallons per minute in April of 2006 (primarily due to high Spring water runoff). This is the highest flow produced from the East side of the reactive barrier since it was constructed. In June of 2006 the flows had gone back down to just over 5 gallons per minute, but there was no water flowing out the overflow. This still was the highest flow from the East side of the reactive barrier since May of 2002. Figure 12 illustrates the flow rates through the reactive barrier since it was constructed. Since the change out of the

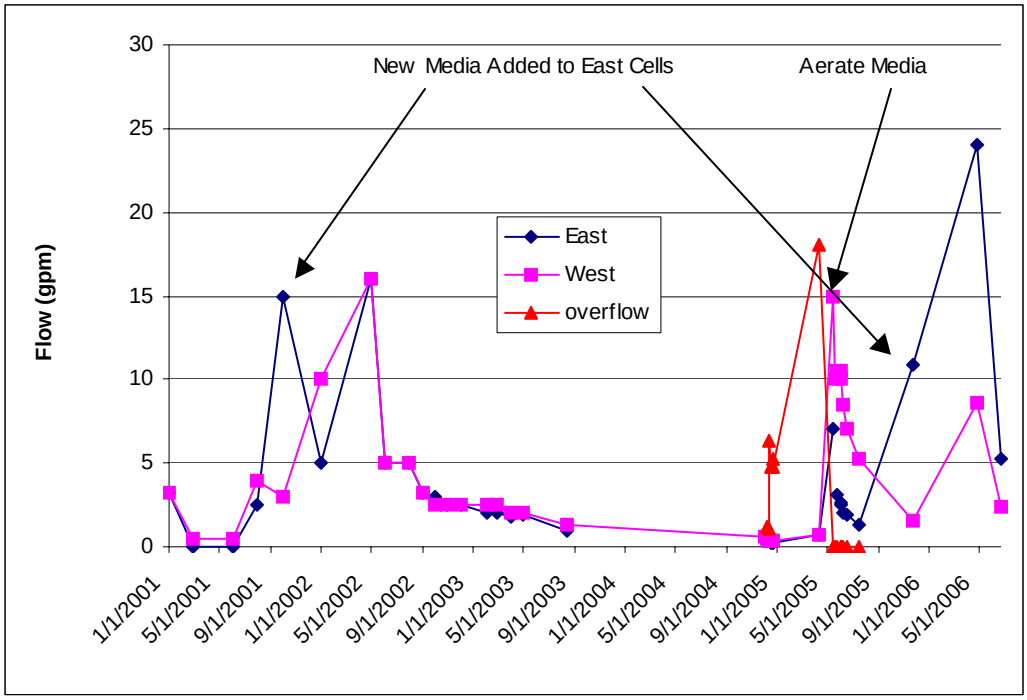

Figure 12. Flow rate (gallons per minute) for the Success Reactive Barrier.
*data from 1/1/2001 to 9/1/2003 was taken from Golder 2003 – overflow data was not always collected

media in the fall of 2005, the East side of the reactive barrier has produced higher discharge flow rates than the West side of the reactive barrier for a longer period of time since the barrier was constructed.

Ph was measured from November 2004 through September of 2005. The pH of the water has been improved by treatment with the Apatite II™ media. Influent pH levels average 4.8. Effluent pH values average 6.7 in the West side of the reactive barrier and 6.6 from the East side of the reactive barrier.

Removal efficiency

The average concentration of the metals of concern in the influent to the reactive barrier are 0.52 mg/L Cd, 1.01 mg/L Pb, and 83.6 mg/L Zn. The average concentration in the discharge for the West side of the reactive barrier is 0.007 mg/L Cd, 0.014 mg/L Pb, and 1.06 mg/L Zn. On the East side of the reactive barrier the outlet average outlet concentration is 0.002 mg/L Cd, 0.005 mg/L Pb, and 0.374 mg/L Zn. The removal efficiencies for the metals are presented in Figure 13. In each case, the removal efficiency is greater than 98% removal.

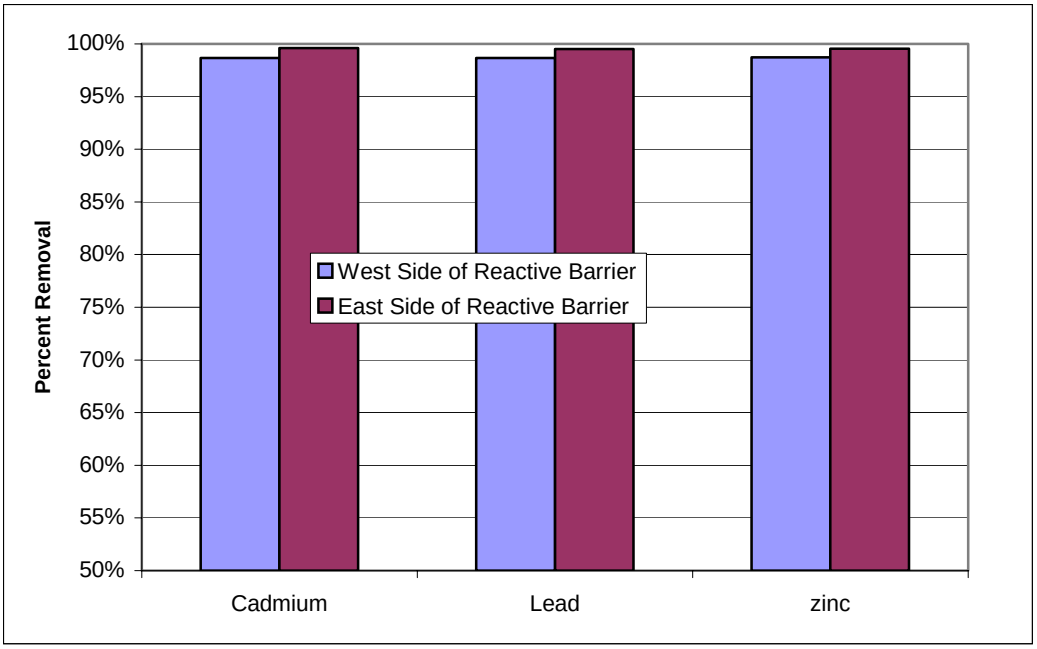

Figure 13. Removal Efficiency for Cd, Pb, and Zn from the Reactive Barrier.

Summary

The biological and chemical analysis of the Apatite II™ showed that the reactive barrier is utilizing more than one single method to remove metal contaminants from the mine drainage, specifically both biological reduction and chemical sorption are causing the reduction in metal concentrations in the contaminated waters.

The injection of compressed air does improve the performance of the reactive barrier by breaking up preferential flow paths created over time in the media. The process of injecting compressed air will need to be reviewed on a case-by-case basis, but in this case annual injection of air would lengthen the life of the media.

Since the construction of the reactive barrier in 2001, the media in the East side of the reactive barrier has been replaced twice. It is not clear why the problem started so early on in the system when both sides of the barrier appeared to have been constructed in the same manner. It is apparent that mixing the Apatite II™ with gravel does not improve the efficiency of the system. Two problems resulted from this. First, the addition of gravel to the Apatite II™ did not have the desired effect of increasing the void space of the media; it simply reduced the amount of media present. Second, it created a media with a much higher bulk density. The two sides appear to have similar void volumes. Water entering the two sides of the reactive barrier enters from the same distribution box or manifold. Water naturally tends to flow to the path of least resistance which in this case is the side without the gravel.

Since the new Apatite II™ mixed with plastic packing rings was put in the East side of the reactive barrier in November 2005, the flows in the East side of the reactive barrier have surpassed the West side for the longest period of time since construction. While continued monitoring needs to take place, we are optimistic that this will be a beneficial solution to the plugging experienced at the Success Mine.

Using the average flow rates and average concentrations in the source water and the treated water, it is estimated that the system has removed 44 pound of cadmium from the East side and 49 pounds of cadmium from the West side of the reactive barrier, 85 pounds of lead from the East side and 95 pounds of lead from the West side of the reactive barrier, and 7003 pounds of zinc from the East side and 7850 pounds of zinc from the West side of the reactive barrier over the 5 years of operation. While this paper discusses resolving plugging issues with the Apatite II™ media, it should be noted that the systems has continued to successfully reduce metal concentrations in acid mine drainage to below drinking water standards and raise the pH to near neutral levels. With the addition of the plastic packing rings to the Apatite II™, it is anticipated that the system will continue to operate for several more years.

Literature Cited

EPA. "Record of Decision Bunker Hill Mining and Metallurgical Complex OU 3, Part 1, Declaration". ORS DCN: 4162500.07099.05.a, EPA DCN: 2.9 September 2002.

Gillerman Virginia S., "Idaho Mining and Geology". GeoNote #40. Idaho Geological Survey. 2002.

Golder Associates Inc. "Second Quarter 2002 Monitoring Report for Groundwater Treatment Facility Success Mine and Mill Site, Wallace, Idaho". September 2002.

Golder Associates Inc. "September 2002 to May 2003 Effectiveness Monitoring Groundwater Treatment Facility Success Mine and Mill Site, Wallace, Idaho". June 2003.

McCloskey, Lynn, J. V. Wright, B. Stasney, N. A. Yancey, and N. Lewis. Comparison of Apatite II ™ Treatment System at Two Mines for Metals Removal. ICARD Poster Presentation 2006.

Wright, Judith and J.L. Conca. Geochemistry of Anthropogenic Lead Stabilization by Apatite II™, Goldschmidt Conference Abstracts, 2005, A64.

Wright, J.V., L.M. Peurrung, R.E. Moody, J.L. Conca, X. Chen, P.P. Didzerekis, and E. Wyse. In Situ Immobilization of Heavy Metals in Apatite Mineral Formulations: Milestone Five Report: September 1995. UFA Ventures, INC. Richland, WA.

APPENDIX G

Aquifer Test Data [GeoSyntec, 2000]

Prepared For:

INTERIM PEDRICKTOWN SITE GROUP

PHASE II GROUNDWATER EVALUATION TECHNICAL MEMORANDUM

NL INDUSTRIES, INC. SUPERFUND SITE

PEDRICKTOWN, NEW JERSEY

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Project Number ME0015-15
January 2000

500323

9. AQUIFER TEST

9.1 Overview

In 1983, Geraghty & Miller performed an aquifer test at the NL site. The EPA questioned some of the techniques used in Geraghty & Miller's evaluation and required the Group to perform an aquifer test. This section includes a description of the aquifer test performed in June 1999 by GeoSyntec. The aquifer test was conducted to: (i) confirm the hydraulic parameters determined by Geraghty & Miller in 1983; (ii) predict the performance of a groundwater extraction system that might be designed to remove lead and cadmium from the aquifer; and (iii) establish input parameters for capture zone modeling as requested by the EPA.

Aquifer parameters have been estimated based on the results of the aquifer test completed in June 1999. Standard analytical methods were employed in the analysis of the aquifer test data to determine transmissivity, hydraulic conductivity, and storativity. AQTESOLV™ for Windows™ (HydroSOLVE, Inc., 1999) was used to perform the analyses. The hydraulic parameters, combined with other site-specific data such as average grain size, depth to the underlying clay layer, saturated thickness, etc., were used to refine the conceptual hydrogeologic model of the site originally presented in the *Phase I Groundwater Evaluation Technical Memorandum.*

The aquifer testing included ambient water-level monitoring, a variable-rate pumping test (step test), and a 72-hour constant-rate pumping test. Groundwater was pumped from pumping well PW, a six-inch diameter, fully-penetrating well installed and developed for the conduct of this aquifer test. Drawdown was measured in several nearby wells throughout the testing process, including observation well OW, the nearest well to pumping well PW. The relative locations of PW, OW, and all other observation wells used during the test are presented on Figure 9-1. Boring logs are provided in Appendix A for each of the new wells at the site. The following subsections describe the aquifer testing procedures and present the analysis of the results.

9.2 Procedures

9.2.1 Ambient Water-Level Monitoring

Prior to the on-set of aquifer testing, passive water-level monitoring was conducted using PXD-60 pressure transducers and a Hermit datalogger manufactured by In-Situ, Inc. This monitoring was conducted for approximately 13 days beginning on 20 May 1999 and measurements were collected once per hour. Measurements were obtained from six wells including: PW, OW, 27, 28, KS, and KD. Figure 9-2 shows a hydrograph throughout the 13-day monitoring period at observation well OW. After approximately 95 hours of monitoring, at approximately 12:30 p.m. on 24 May 1999, the water level began to rise in Well OW, increasing approximately one foot over a 13-hour period. This increase in water level was also evident in the other wells monitored. This rise was coincident with an 11-hour precipitation event that included more than two inches of rain over the area (precipitation data derived from Wilmington, Delaware weather station, NOAA, 1999). Following the peak water level, the head in the wells gradually declined toward the seasonal low, approaching static conditions just prior to the step test.

GeoSyntec obtained additional ambient water-level data after the step test and constant-rate test were completed to further evaluate the characteristics of the aquifer. This monitoring began on 23 July 1999 and continued through 9 August 1999. The hydrograph for pumping well PW is shown on Figure 9-3. The graph indicates a steady decline in the water table as no precipitation occurred during the monitoring period. The decline is approximately 0.04 feet per day, with diurnal fluctuations of approximately 0.02 feet. The diurnal peaks generally occur between 3:00 and 4:00 am and the diurnal troughs generally occur between 8:00 and 10:00 p.m. Figure 9-4 shows the first 4,500 minutes of this monitoring period in greater detail.

9.2.2 Step Test

After obtaining the pre-test ambient water-level data, a step test was conducted on 2 June 1999 in pumping PW. This step test was performed to determine an optimal pumping rate for the subsequent constant-rate test by measuring the pumping rate and drawdown and establishing a rate that adequately stressed the aquifer without dewatering the well. A submersible centrifugal pump, powered by a portable 440 amp generator was used. Pumped water was conveyed to a 20,000 gallon portable tank, and the pumping rate was determined with a graduated, five-gallon bucket and a stop watch.

Seven steps were conducted over a period of approximately 200 minutes. Figure 9-5 shows the hydrograph at PW during the step testing and a table of respective pumping rates. Based on the results of the test, a target pumping rate of approximately 20 gallons per minute (gpm) was selected for the constant-rate test. Appendix G contains the raw transducer data from the step test.

9.2.3 Constant-Rate Test

On 7 June 1999, a 72-hour constant-rate pumping test (CRT) was conducted at pumping well PW. Pumping-rate determination, water containerization, and water-level measurement procedures were similar to those used during the step test. In addition, a total of 33 site wells were monitored with portable water-level indicators (WLIs) to calibrate the datalogger and to serve as a backup in the event of datalogger/transducer failure. Appendices H and I contain tabulated data from the datalogger and WLIs, respectively. Prior to the onset of pumping, static water level elevations were determined for each of the wells monitored throughout the aquifer testing (Figure 9-6). The map includes only those wells screened within the upper portion of the unconfined aquifer. Some wells, such as HS and 22 are excluded from the map because they are screened in clay. The water levels measured throughout the testing period are summarized on Table 9-1.

9.3 Evaluation and Results

9.3.1 Hydraulic Analysis

Figure 9-7 shows the hydrograph of observation well OW throughout the testing period. The hydrograph depicts a rapid drop in water level at the start of the constant rate test with minor fluctuations caused by minor adjustments in the pumping rate, followed by steady drawdown over a period of approximately one day. After approximately 1,500 minutes of pumping, the portable generator failed and pumping ceased for 68 minutes until a replacement generator could be brought on-line and the test resumed. Slight fluctuations in the data are evident as the pumping rate was adjusted to original pumping conditions. The maximum fluctuation in pumping rate was 10 percent, and generally, the pumping rate varied by only five percent. Variations occurred only over short periods during the test; therefore, the resultant data are valid for the hydraulic evaluation. The average pumping rate throughout the entire 72-hour period was 18.75 gpm.

Figure 9-8 is the same hydrograph shown on Figure 9-7, but it is extended to show the aquifer recovery following the CRT and includes barometric pressure data collected during the same period. Barometric pressure is monitored during pumping tests to determine the influence, if any, of fluctuating atmospheric pressure on the potentiometric surface in the aquifer. Such an effect is primarily observed in confined aquifers, but prudent practice dictates the monitoring of barometric pressure during all aquifer tests. If an effect is seen, the barometric efficiency of the well is calculated and the drawdown data are adjusted accordingly. For this test, a barometric pressure transducer was connected to the datalogger to record pressure in feet. As shown on Figure 9-8, and as expected for an unconfined aquifer, there was no observed barometric effect on the water table and adjustments were not necessary. The small peak in the recovery data at approximately 11,000 minutes after the start of the CRT resulted when water containerized during the test was released. Figure 9-9 depicts the potentiometric surface on 10 June 1999 near the end of the pumping test.

The drawdown data indicate a delayed-yield response typical of unconfined aquifers. Figure 9-10 shows one example of this response. In Segment 1 of Figure 9-10, the data initially reveal a drawdown curve similar to that expected from a confined aquifer, because water is being released from the elastic storage of the aquifer, not from the pore spaces of the aquifer. Thereafter, in Segment 2, the drawdown rate decreases and the data reveal a more gradual curve as gravity drainage contributes water that was previously held in storage (i.e., within the pore spaces of the sand grains). Eventually, as in Segment 3, the effects of gravity drainage are diminished as the aquifer becomes unsaturated above the cone of depression. Neuman (1974) devised an analytical solution for unconfined aquifers with delayed gravity response. Use of this solution provides estimates of transmissivity, storage coefficient, specific yield, and Beta, a term that relates the aquifer anisotropy and radial distance to the observation well.

Figures 9-11, 9-12, and 9-13 are AQTESOLV™ for Windows™ results of Neuman solutions conducted on drawdown and recovery data from Wells OW, KD, and 28, respectively. Because AQTESOLV™ incorporates the principle of superposition in the analysis to accommodate variable pumping rates (Streltsova, 1988), it is possible to combine both drawdown and recovery (including the short stoppage in pumping when the generator failed) at a well in one solution. Prior to analysis, late drawdown data were corrected for dewatering using Jacob's correction method (Jacob, 1944). The results of the analyses shown on Figures 9-11, 9-12, and 9-13 are summarized below.

Well	T (gpd/ft)	S	Sy	B	b (ft)	k (gpd/ft^2)
OW	3800	5.03E-04	4.69E-02	4.30E-03	23	165
28	4200	1.60E-03	2.29E-02	2.70E-01	18	233
KD	4300	2.40E-04	1.00E-02	1.33E-02	23	187
Mean	*4100*	*7.81E-04*	*2.66E-02*	*9.59E-02*	*21*	*195*

Notes: T = Transmissivity
S = Storativity
Sy = Specific yield
B = Beta
b = Aquifer thickness
k = Hydraulic conductivity

The results indicate a relatively transmissive aquifer, with: (i) an average transmissivity of approximately 4,100 gpd/ft; (ii) a storativity of 8 x 10^{-4} during the earliest portion of the data, a result that is reasonable for the segment of the test that exhibits a confined aquifer response; and (iii) a specific yield (equivalent to storativity near the end of the test) of approximately 3 x 10^{-2}, a result that is a reasonable storativity estimate for an unconfined aquifer. At an average saturated thickness of 21 feet, these results yield a hydraulic conductivity estimate of approximately 195 gpd/ft^2 or 26 ft/day. These results are similar to the results obtained previously by Geraghty & Miller.

9.3.2 Chemical Analysis

Throughout the CRT, pH and turbidity were monitored. These results are presented on Table 9-2. In addition, groundwater samples were obtained from the pumping well and analyzed for lead, cadmium, VOCs and general chemical parameters. The results of the chemical analyses of groundwater samples obtained from pumping well PW during the CRT are summarized on Tables 9-3 through 9-5. Trace concentrations of VOCs were detected. The data for lead, cadmium, pH, and turbidity were plotted with time on Figures 9-14 through 9-17. As indicated on Figures 9-14 through 9-17, the concentrations of lead and cadmium in the extracted groundwater were low, relative to the ambient concentrations of lead and cadmium in the groundwater where the extraction well is located. More significantly, the concentrations of lead and cadmium declined during the test. For lead, the concentration was below the level of detection during most of the test. On one occasion, the generator supplying power to the pump stopped. Upon restarting the generator and pump, an increase in turbidity and lead concentration occurred briefly. Thereafter, the flow rate of the pump was altered slightly several times, which also

resulted in minor variations in turbidity and lead concentrations (Figures 9-14 and 9-15).

For cadmium, a steady decline in concentration was noted during the aquifer test. It is anticipated that the concentration of cadmium could have declined to below the level of detection within 12 to 15 days of pumping. However, because the test was performed for only three days, the time required for the concentration of cadmium to decline to the detection level is estimated.

9.3.3 Anticipated Extraction of Lead and Cadmium

When groundwater is extracted for an extended period, the concentrations of any constituents either dissolved in groundwater or entrained in the flow of groundwater tend to asymptotically decline to a minimum as geochemical reactions and dilution occur. In this case, the level to which the concentration of lead is expected to decline is below the level of detection. It is also anticipated that for cadmium, the concentration will be at or below the detection level. Under a long-term pumping scenario, the concentration of inorganics such as lead and cadmium in extracted groundwater may be significantly lower than the respective detection levels.

Assuming that 1 ppb of lead could be extracted continuously at an estimated flow rate of 37 gpm (Section 10) it is estimated that approximately 60 years of pumping would be required to extract a significant amount of the lead remaining in groundwater (Table 9-6). For cadmium, assuming the same extraction rate and an average concentration of 2 ppb in the extracted groundwater, it is estimated that 50 years of pumping would be required to extract a significant mass of the cadmium remaining in groundwater (Table 9-6). These timeframes are theoretical. Achievement of RAOs may occur in shorter periods as a result of the naturally occurring improvement of groundwater quality described above. Therefore, it is expected that extracting small amounts of lead and cadmium through the use of the pump-and-treat technique will not significantly enhance improvement of groundwater quality.

As described in Section 12, the results of modeling confirm that extracting significant amounts of lead and cadmium from the aquifer is infeasible. In fact, extracting lead and cadmium by pumping groundwater is so ineffective that it will not contribute significantly to achievement of RAOs. Therefore, the implementation of a pump-and-treat remedy for this site is impractical.

GROUNDWATER LEVELS PRIOR TO AND AFTER COMPLETION OF THE PUMPING TEST

Phase II Groundwater Evaluation
NL Industries Superfund Site
Pedricktown, New Jersey

PRE-TEST GROUNDWATER ELEVATIONS 6/7/99 BETWEEN 1300 AND 1400 HRS.				PUMPING-TEST GROUNDWATER ELEVATIONS 6/10/99 BETWEEN 1300 AND 1400 HRS.				DIFFERENCE	DRAWDOWN
WELL	TOC (ft)	DTW (ft)	GW ELEV (ft)	WELL	TOC (ft)	DTW (ft)	GW ELEV (ft)	(ft)	(ft)
SD	13.39	7.15	6.24	SD	13.39	8.17	5.22	1.02	1.02
SS	12.7	6.11	6.59	SS	12.7	7.01	5.69	0.9	0.9
S4-1*	12	5.2	6.8	S4-1*	12	6.2	5.8	1	1
T2-3	11.34	6.76	4.58	T2-3	11.34	7.02	4.32	0.26	--
TC	--	7.25	--	TC	--	7.55	--	--	--
T-4	12.12	7.31	4.81	T-4	12.12	7.66	4.46	0.35	--
T-A	--	7.58	--	T-A	--	7.96	--	--	--
OS	11.95	7.63	4.32	OS	11.95	7.96	3.99	0.33	--
OD	12.47	8.33	4.14	OD	12.47	8.58	3.89	0.25	--
11	11.19	5.41	5.78	11	11.19	5.6	5.59	0.19	--
PD	12.86	6.85	6.01	PD	12.86	7.09	5.77	0.24	--
BR	10.82	5.5	5.32	BR	10.82	5.74	5.08	0.24	--
PS	11.89	5.72	6.17	PS	11.89	5.96	5.93	0.24	--
PW	11.55	6.18	5.37	PW	11.55	14.5	-2.95	8.32	8.32
OW	11.83	6.49	5.34	OW	11.83	9.51	2.32	3.02	3.02
KS	11.54	6.04	5.5	KS	11.54	8.77	2.77	2.73	2.73
KD	11.77	6.27	5.5	KD	11.77	9.27	2.5	3	3
24	13.04	17.56	-4.52	24	13.04	17.92	-4.88	0.36	--
JD	14.02	7.48	6.54	JD	14.02	7.91	6.11	0.43	--
JS	13.89	7.38	6.51	JS	13.89	7.82	6.07	0.44	--
10R	14.02	17.31	-3.29	10R	14.02	17.67	-3.65	0.36	--
ID	17.18	10.55	6.63	ID	17.18	10.83	6.35	0.28	--
IS	17.35	8.19	9.16	IS	17.35	8.43	8.92	0.24	--
HD	18.67	13.65	5.02	HD	18.67	13.89	4.78	0.24	--
HS	18.4	13.8	4.6	HS	18.4	14.03	4.37	0.23	--
28	16.4	10.92	5.48	28	16.4	11.96	4.44	1.04	1.04
27	16.57	11.07	5.5	27	16.57	12.03	4.54	0.96	0.96
30	16.29	11.13	5.16	30	16.29	11.36	4.93	0.23	--
29	16.26	10.79	5.47	29	16.26	11.1	5.16	0.31	--
32	14.28	9.77	4.51	32	14.28	9.97	4.31	0.2	--
31	14.33	9.21	5.12	31	14.33	9.4	4.93	0.19	--
RD	15.56	9.58	5.98	RD	15.56	9.77	5.79	0.19	--
RS	15.4	7.42	7.98	RS	15.18	7.57	7.61	0.37	--

Notes

1) TOC for Wells PW, OW, OS, OD, KS, KD, HS, HD, SS, T-4, RS, RD, PS, 24, 28, 27, 30, 29, 32, and 31 adjusted by adding 1.12 feet to convert from NAVD 1988 to NGVD 1929

2) Shaded cells denote wells used in construction of shallow potentiometric surface maps and flow model

3) Water-level differences less than 0.9 feet are attributed to the natural decline of the water table during the 1999 drought and do not represent drawdown

* TOC is estimated

TABLE 9-2

SUMMARY OF GROUNDWATER pH and TURBIDITY[1] DURING AQUIFER TEST

Phase II Groundwater Evaluation
NL Industries Superfund Site
Pedricktown, New Jersey

Sample Designation	Date	Time	Turbidity[2]	pH [3]
PT-1-060799	06/07/1999	1500	1.40	3.23
PT-2-060799	06/07/1999	1537	0.60	3.11
PT-3-060799	06/07/1999	1630	NT	3.58
PT-4-060799	06/07/1999	1730	0.85	3.15
PT-5-060899	06/08/1999	130	0.30	3.69
PT-6-060899	06/08/1999	930	0.67	3.41
PT-7-060899	06/08/1999	1720	0.86	3.2
PT-8-060999	06/09/1999	1330	0.94	2.94
PT-9-060999	06/09/1999	1020	0.87	3.32
PT-10-060999	06/09/1999	1750	0.92	3.25
PT-11-061099	06/10/1999	130	0.00	3.11
PT-12-061099	06/10/1999	930	1.38	3.28
PT-13-061099	06/10/1999	1415	1.90	3.15

TABLE 9-3

SUMMARY OF VOLATILE ORGANIC COMPOUNDS DETECTED DURING AQUIFER TEST

Phase II Groundwater Evaluation
NL Industies Superfund Site
Pedricktown, New Jersey

Sample Designation	Date	Time	Chloroform, ug/L	Toluene, ug/L
PT-1-060799	06/07/1999	1500	0.23 J	0.17 J
PT-8-060999	06/09/1999	1330	0.25 J	0.25 J
PT-13-061099	06/10/1999	1415	0.19 J	ND
TRIP BLANK	06/09/1999	NA	ND	ND
TRIP BLANK	06/10/1999	NA	ND	ND
QA/QC Samples				
QA-1	06/10/1999	NA	ND	ND
PT-ERB-060799	06/07/1999	930	ND	ND

Notes:

J - estimated concentration below reporting limit

ND - Not detected above the method detection limit

NA - Not applicable

TABLE 9-4

SUMMARY OF LEAD AND CADMIUM IN GROUNDWATER EXTRACTED DURING AQUIFER TEST

Phase II Groundwater Evaluation
NL Industries Superfund Site
Pedricktown, New Jersey

Sample Designation	Date	Time	Total Lead	Dissolved Lead	Total Cadmium	Dissolved Cadmium
PT-1-060799	06/07/1999	1500	6.1	4.6	43.9	45.2
PT-2-060799	06/07/1999	1537	3.0	1.4B	45.7	46.3
PT-3-060799	06/07/1999	1630	1.7B	ND	47.8	48.3
PT-4-060799	06/07/1999	1730	2.7B	ND	46.2	46.1
PT-5-060899	06/08/1999	0130	6.6	ND	44.8	43.9
PT-6-060899	06/08/1999	930	2.2B	ND	42.9	42.9
PT-7-060899	06/08/1999	1720	1.6B	ND	42.2	41.5
PT-8-060999	06/09/1999	0130	9.3	5.3	41.0	38.7
PT-9-060999	06/09/1999	1020	3.4	ND	39.2	38.9
PT-10-060999	06/09/1999	1750	2.9B	ND	39.0	38.2
PT-11-061099	06/10/1999	0130	ND	ND	38.0	37.9
PT-12-061099	06/10/1999	930	7.0	1.5B	36.8	37.2
PT-13-061099	06/10/1999	1415	1.7B	1.2B	37.3	35.3
QA/QC Samples						
PT-DUPLICATE-061099	06/09/1999	--	ND	ND	36.4	36.2
QA-1	06/10/1999	--	4.5	ND	36.5	35.0
PT-ERB-060799	06/07/1999	930	5.5	0.94B	0.85B	ND

Notes:
(1) Measurements obtained using portable field instruments
(2) Turbidity reported in nephelometric turbidity units (NTUs)
(3) pH reported in standard units (SU)
(4) All concentrations in ug/L (ppb)

TABLE 9-5

SUMMARY OF GENERAL GROUNDWATER CHEMISTRY[1] DURING AQUIFER TEST

Phase II Groundwater Evaluation
NL Industies Superfund Site
Pedricktown, New Jersey

Sample Designation	Date	Time	Bicorbonate Alkalinity	Carbonate Alkalinity	Chloride	Sulfate
PT-1-060799	06/07/1999	1500	ND	ND	53.4	3750
PT-8-060999	06/09/1999	1330	ND	ND	46.4	3200
PT-13-061099	06/10/1999	1415	ND	ND	40	2920
QA/QC Samples						
QA-1[2]	06/10/1999	1420	ND	ND	40.3	2780
PT-ERB-060799[3]	06/07/1999	930	13.2	ND	4.9	1.2

Sample Designation	Date	Time	Total Phosphorous	Total Dissolved Solids	Total Suspended Solids
PT-1-060799	06/07/1999	1500	ND	5260	6.4
PT-8-060999	06/09/1999	1330	ND	4300	ND
PT-13-061099	06/10/1999	1415	ND	3780	ND
QA/QC Samples					
QA-1[2]	06/10/1999	1420	ND	3720	ND
PT-ERB-060799[3]	06/07/1999	930	0.12	153	ND

Notes:
1 - Results reported in milligrams per liter (mg/L)
2 - Blind duplicate sample of PT-13-061099
3 - Equipment rinsate blank sample

TABLE 9-6

ESTIMATED PERFORMANCE OF PUMP AND TREAT TECHNIQUE

Phase II Groundwater Evaluation
NL Industries Superfund Site
Pedricktown, New Jersey

From mass calculations (Table 2-1): Mass of lead in groundwater = 9 lbs
Mass of cadmium in groundwater = 14 lbs

From Capture Zone Evaluation (Section 12): Estimate average total groundwater extraction rate = 37 gpm = 0.05 mgd

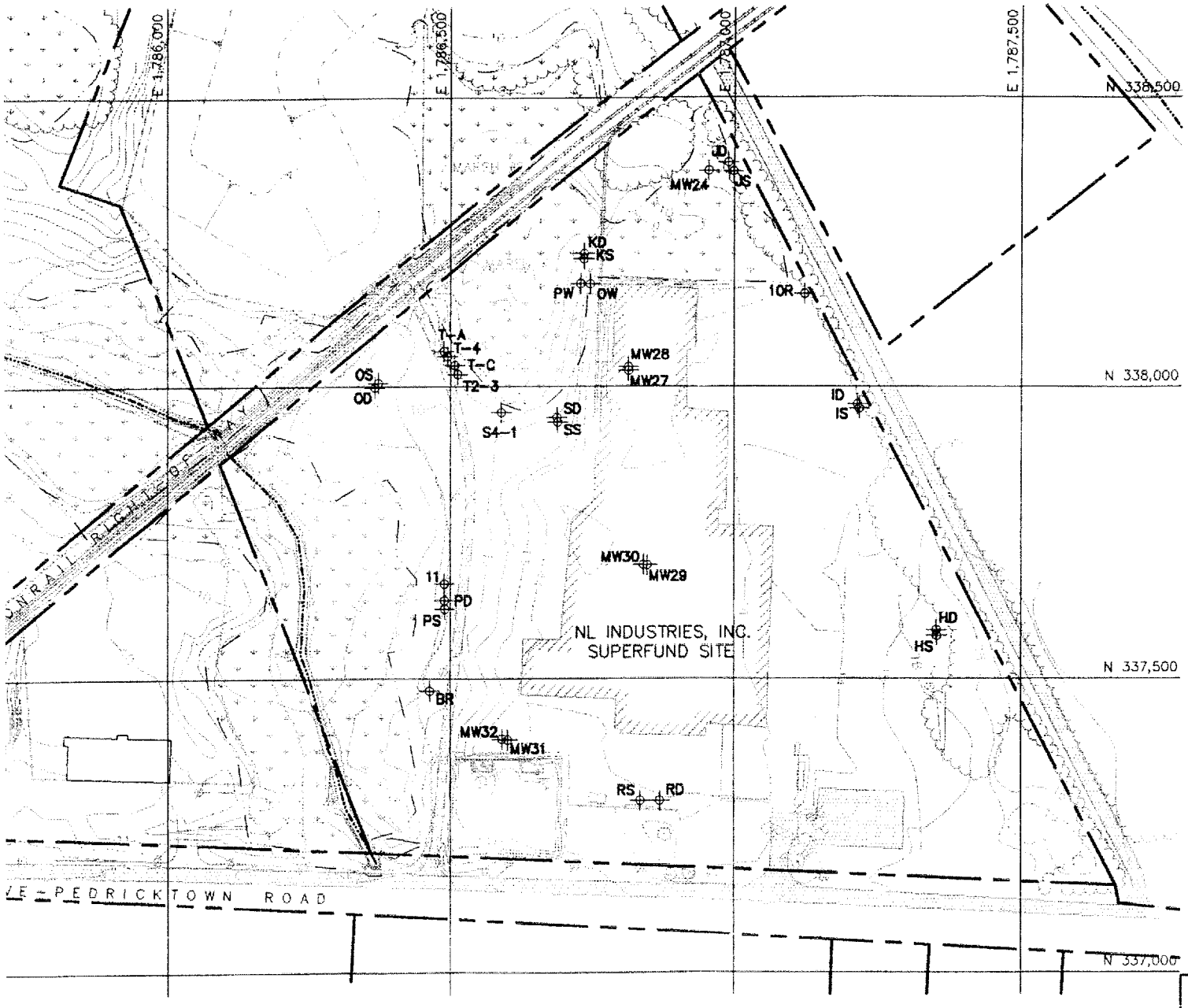
Time required to extract lead (if possible): .001 mg/L*8.34*0.05 mgd = 0.0004 lbs of lead per day extracted

$$\frac{9\text{ lbs}}{0.0004\text{ lbs/d}} = 225\text{ days} = 61\text{ years (if possible)}$$

Time required to extract cadmium (if possible): .002 mg/L * 8.34 x 0.05 mgd = 0.0008 lbs of cadmium per day extracted

$$\frac{14\text{ lbs}}{0.0008\text{ lbs/d}} = 17{,}500\text{ days} = 48\text{ years (if possible)}$$

Note: Concentrations of lead and cadmium in extracted groundwater are expected to be non-detectable at steady state. Therefore, assume average concentrations of lead in extracted groundwater to be 1 ppb. For cadmium, assume the concentration will be up to 2 ppb to be conservative. It is possible that the concentrations of lead and cadmium in extracted groundwater will be lower than estimated.



LEGEND

- PROPERTY BOUNDARY
- CONTOUR OF EXISTING GROUND SURFACE (FT, MSL)
- EXISTING FENCE
- EXISTING RAILROAD LINE
- EXISTING TREELINE
- EXISTING STREAM
- EXISTING ROAD
- EXISTING WETLAND (SEE NOTE 4)
- APPROXIMATE LIMITS OF EXPOSED CONCRETE FOUNDATION
- EXISTING BUILDING
- MW27 — GROUNDWATER MONITORING WELL USED DURING AQUIFER TEST

200 100 0 200
SCALE IN FEET

JNDARY IS APPROXIMATE AND IS BASED ON A TOPOGRAPHIC SURVEY
Y ALBERT A. FRAUNGER, BRIDGETON, NEW JERSEY, MAY 1990.

ACE ELEVATIONS ARE BASED ON AERIAL PHOTOGRAPHY AND GROUND
) MARCH 1996 BY OHM REMEDIATION SERVICES CORP.

RE BASED ON NATIONAL GEODETIC VERTICAL DATUM (NGVD) 1929.
ONTROL BASED ON NEW JERSEY STATE PLANE COORDINATE SYSTEM

4. WETLAND AREAS ALONG THE WEST STREAM WERE DELINEATED BY PENNONI ASSOCIATES, INC. FROM FIELD SURVEYS CONDUCTED BETWEEN 5 FEB AND 13 FEB 1999; ALL OTHER WETLANDS ARE BASED ON AREAS DELINEATED BY TALBOT & ASSOCIATES, DECEMBER 1990.

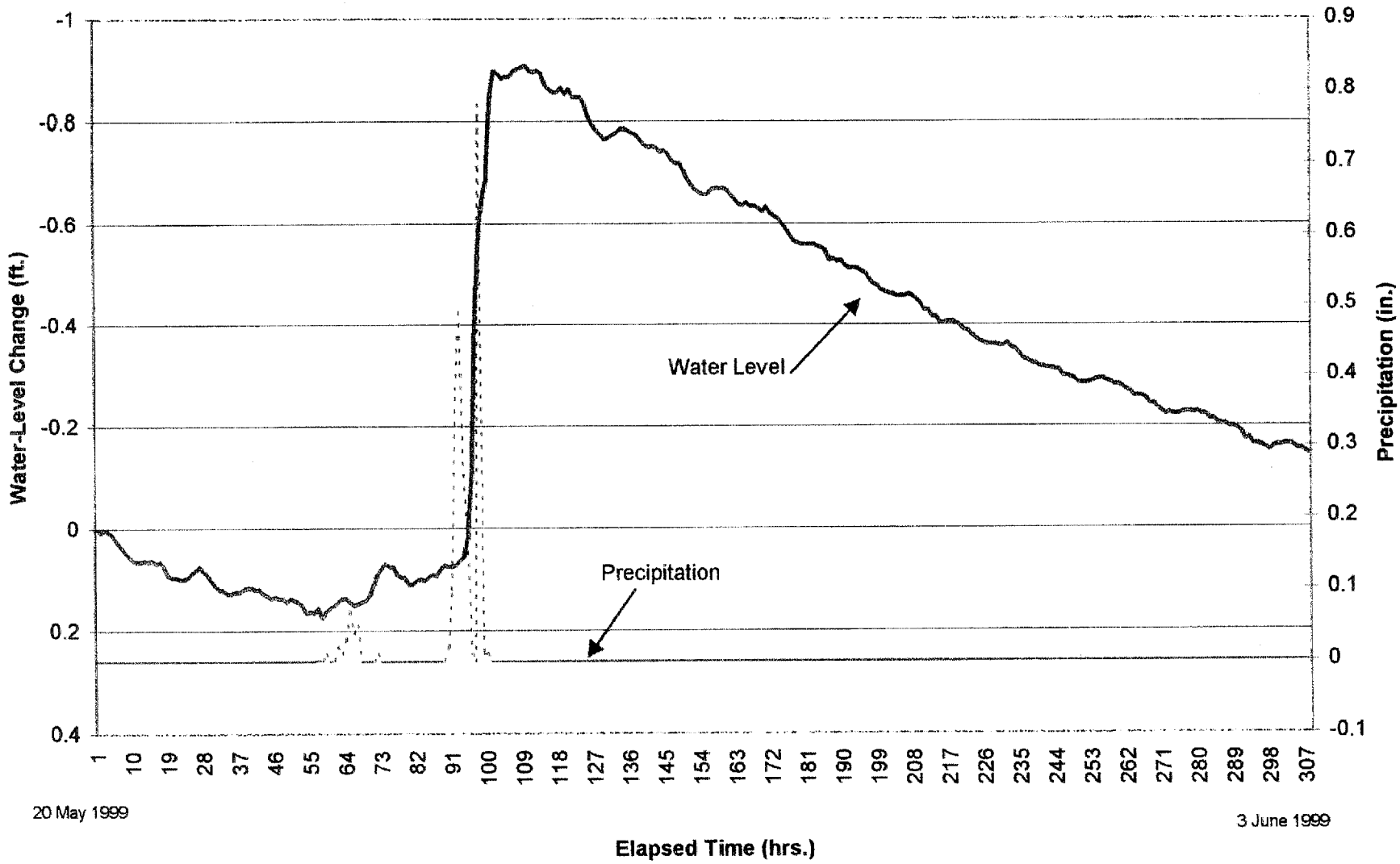
WELL LOCATION PLAN FOR AQUIFER TEST

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

PROJECT NO.	MR0015-15	FIGURE NO.	9-1
DOCUMENT NO.	–	FILE NO.	0015F108

500336

PRE-TEST WATER LEVEL CHANGES AT WELL OW

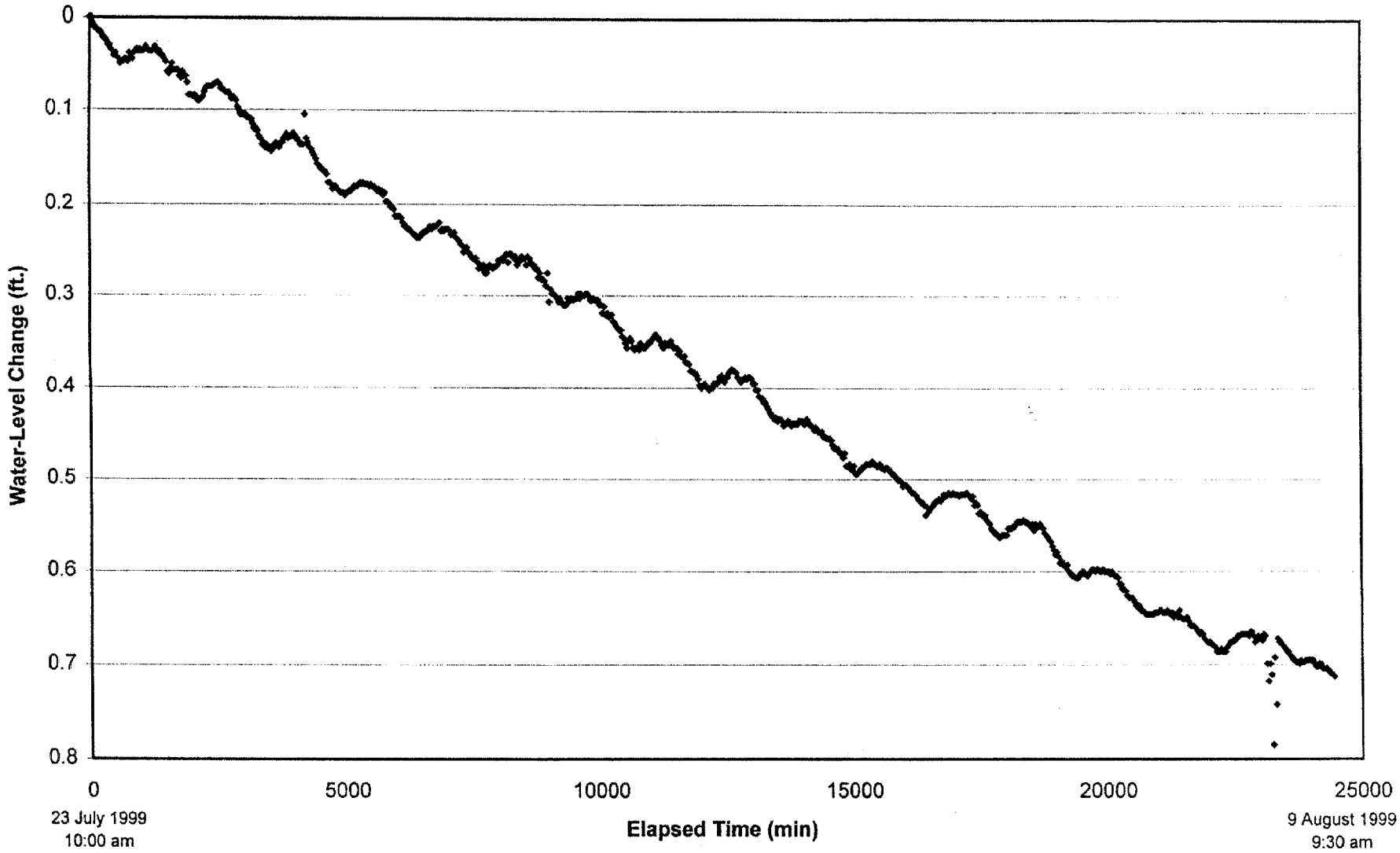


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-2
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500337

POST-TEST WATER LEVELS AT WELL PW

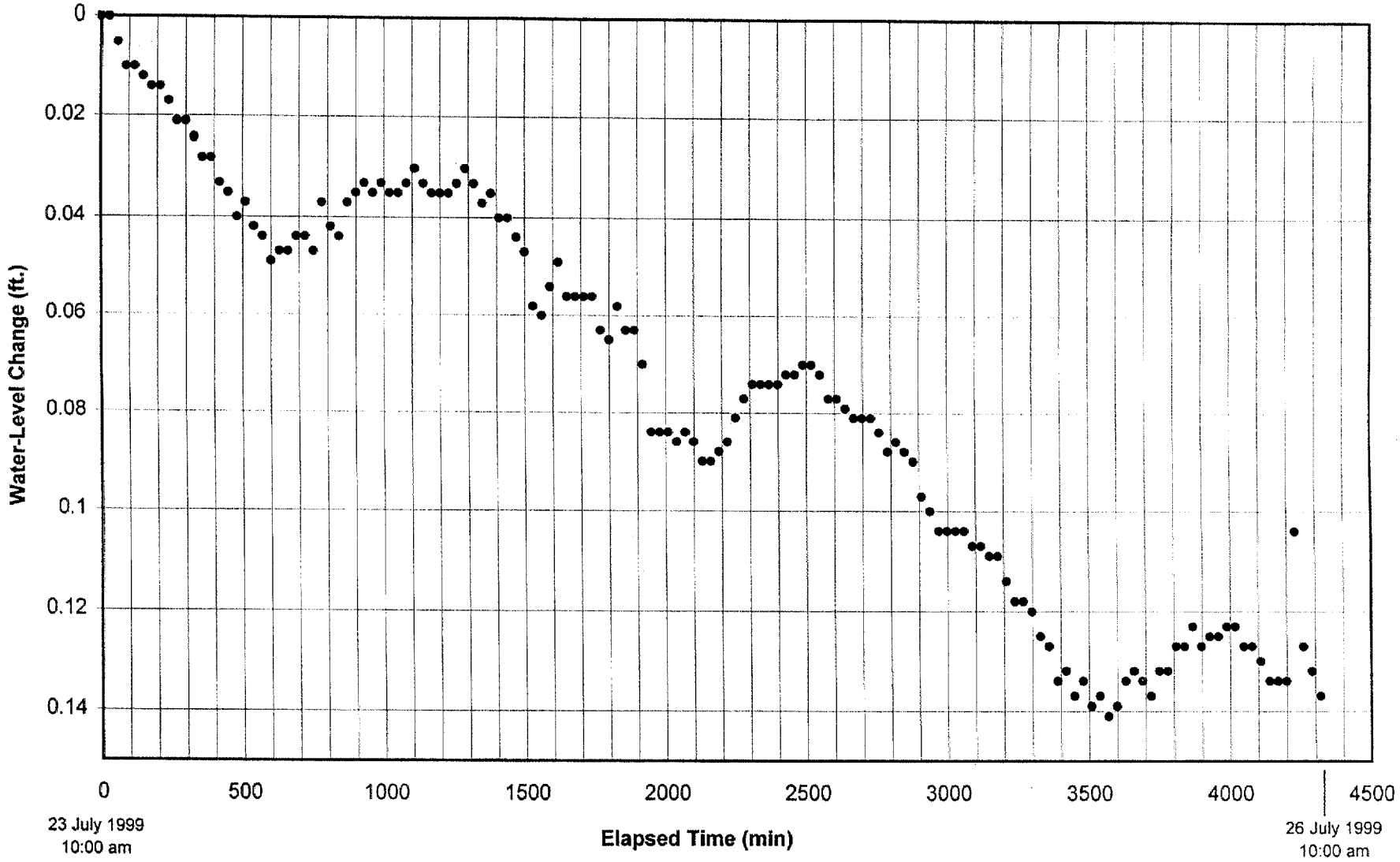


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-3
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500338

POST-TEST WATER LEVELS AT WELL PW (PARTIAL)

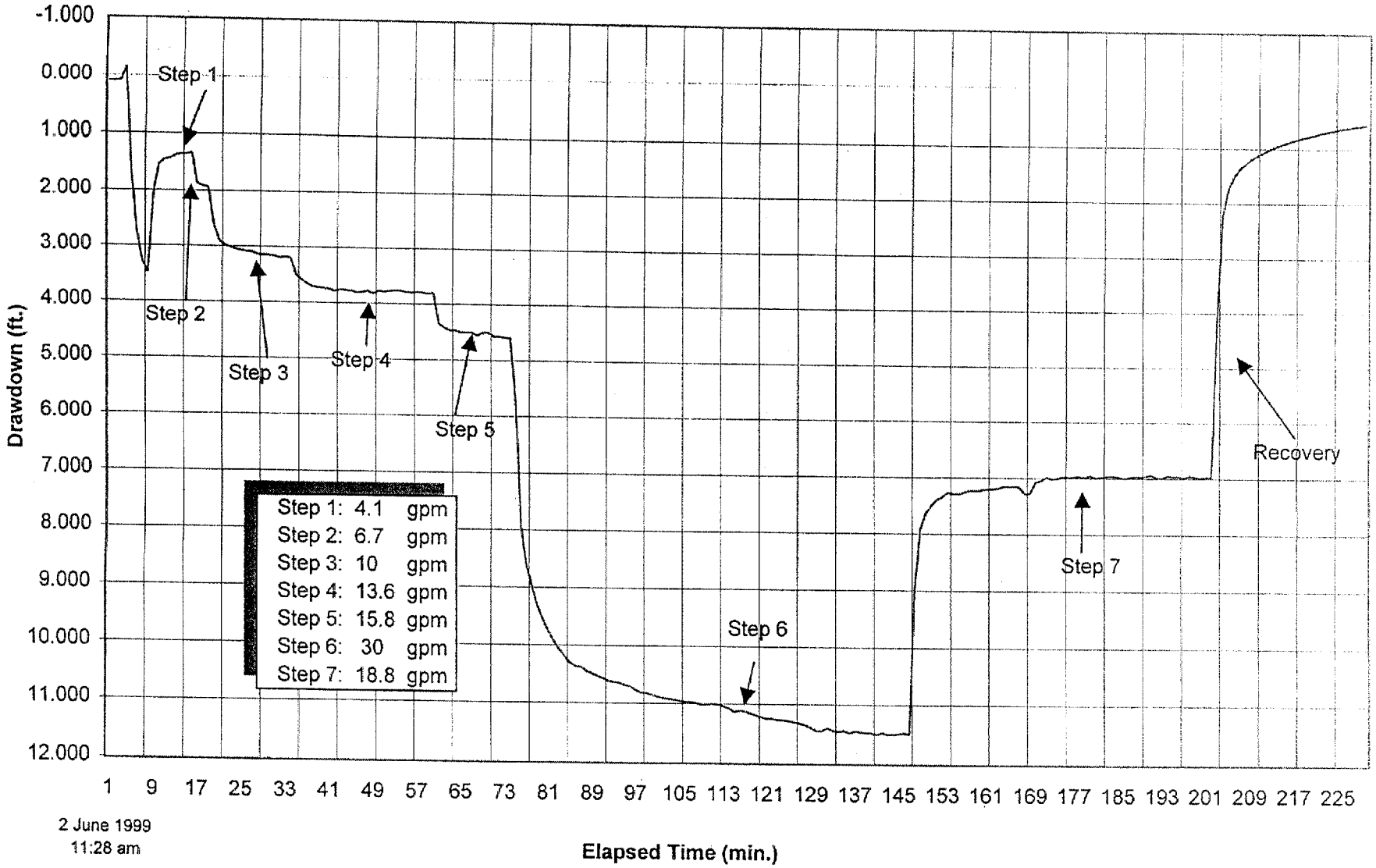


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-4
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500339

STEP-TEST HYDROGRAPH AT WELL PW

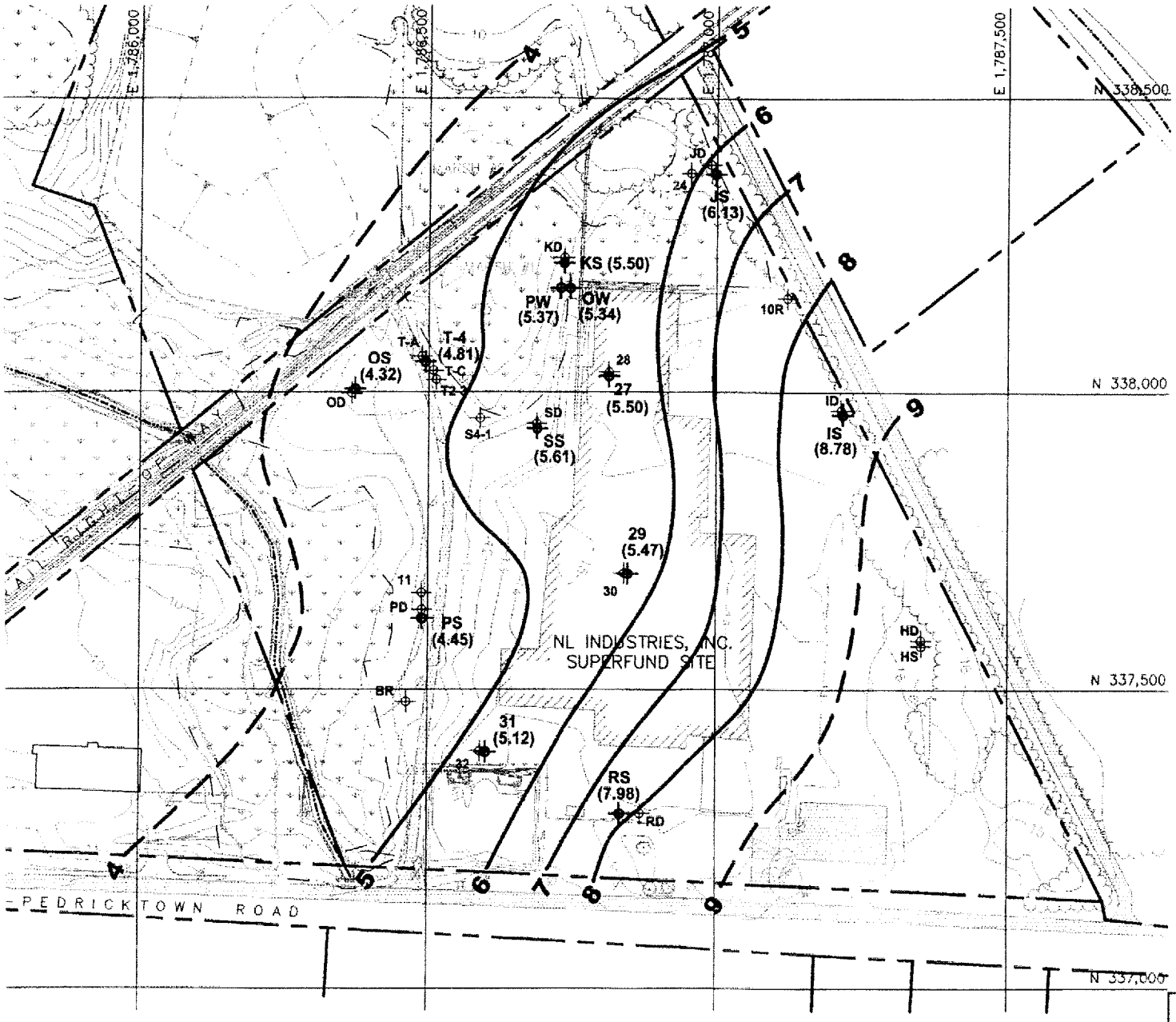


2 June 1999
11:28 am

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-5
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500340



LEGEND

- PROPERTY BOUNDARY
- CONTOUR OF EXISTING GROUND ELEVATION (FT. MSL)
- EXISTING FENCE
- EXISTING RAILROAD LINE
- EXISTING TREELINE
- EXISTING STREAM
- EXISTING ROAD
- EXISTING WETLAND (SEE NOTE 4)
- APPROXIMATE LIMITS OF EXPOSED CONCRETE FOUNDATION
- EXISTING BUILDING
- POTENTIOMETRIC SURFACE CONTOUR (DASHED WHERE INFERRED)
- 29 — GROUNDWATER MONITORING WELL USED DURING AQUIFER TEST
- (5.47) — GROUNDWATER ELEVATION

200 100 0 200
SCALE IN FEET

Y IS APPROXIMATE AND IS BASED ON A TOPOGRAPHIC SURVEY
RT A. FRALINGER, BRIDGETON, NEW JERSEY, MAY 1990.

EVATIONS ARE BASED ON AERIAL PHOTOGRAPHY AND GROUND
CH 1996 BY OHM REMEDIATION SERVICES CORP.

SED ON NATIONAL GEODETIC VERTICAL DATUM (NGVD) 1929.
L BASED ON NEW JERSEY STATE PLANE COORDINATE SYSTEM

4. WETLAND AREAS ALONG THE WEST STREAM WERE DELINEATED BY PENNONI ASSOCIATES, INC. FROM FIELD SURVEYS CONDUCTED BETWEEN 5 FEB AND 13 FEB 1999; ALL OTHER WETLANDS ARE BASED ON AREAS DELINEATED BY TALBOT & ASSOCIATES, DECEMBER 1990.

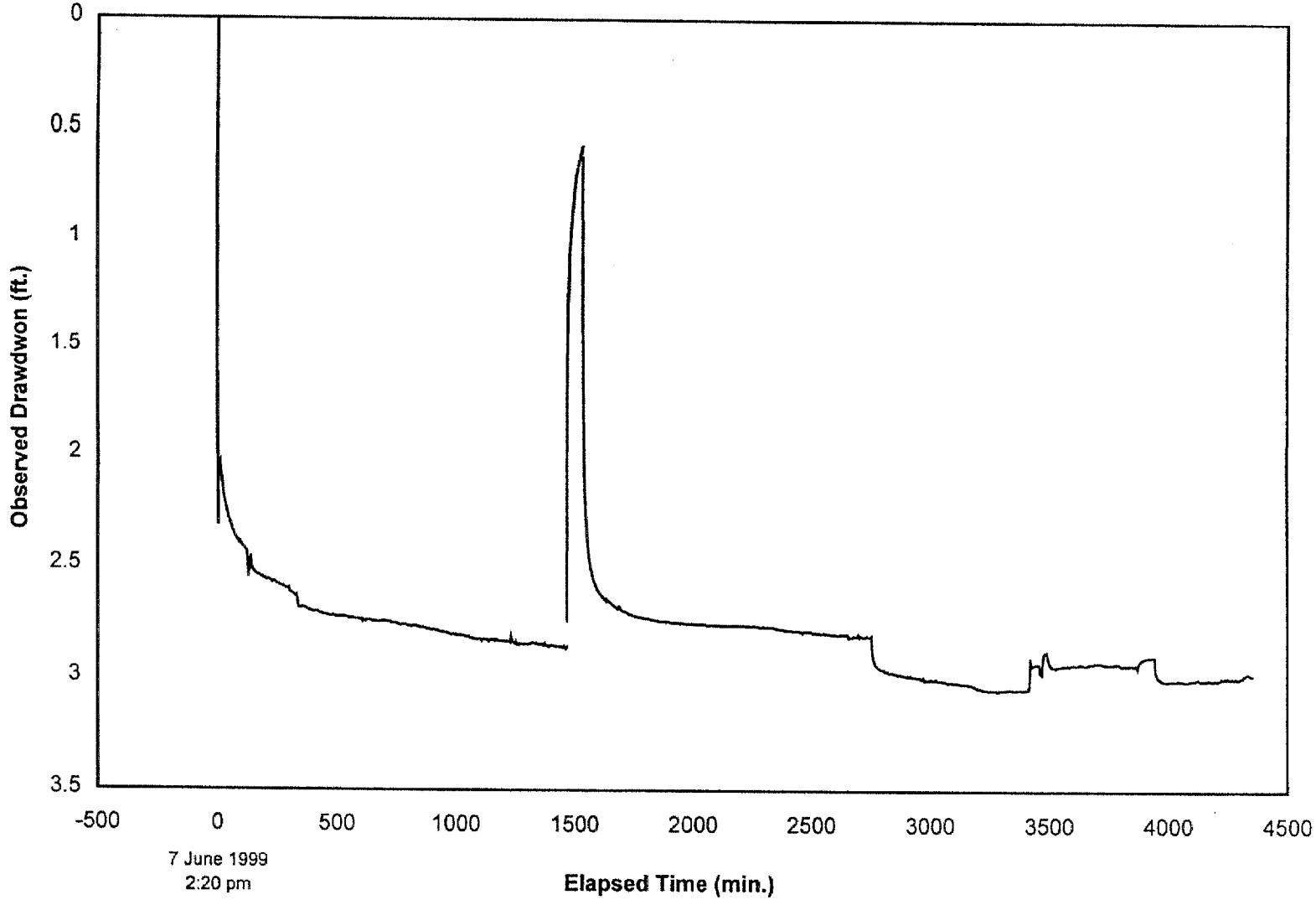
POTENTIOMETRIC SURFACE SHALLOW UNCONFINED AQUIFER 6/7/99 (PRE-PUMPING)

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

PROJECT NO.	MR0015-15	FIGURE NO.	9-6
DOCUMENT NO.	--	FILE NO.	0015F111

500341

HYDROGRAPH AT OW (RAW DATA)

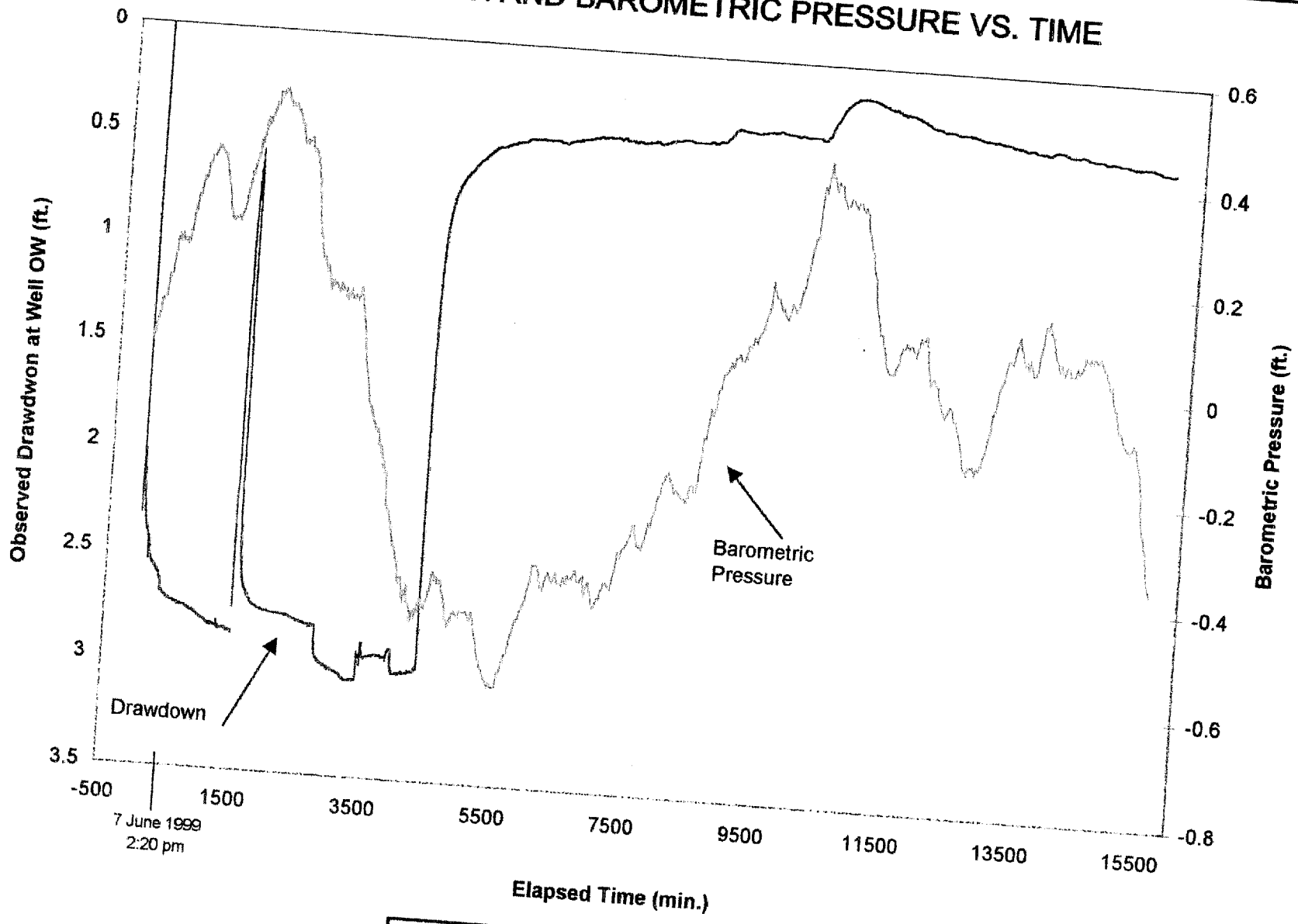


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-7
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500342

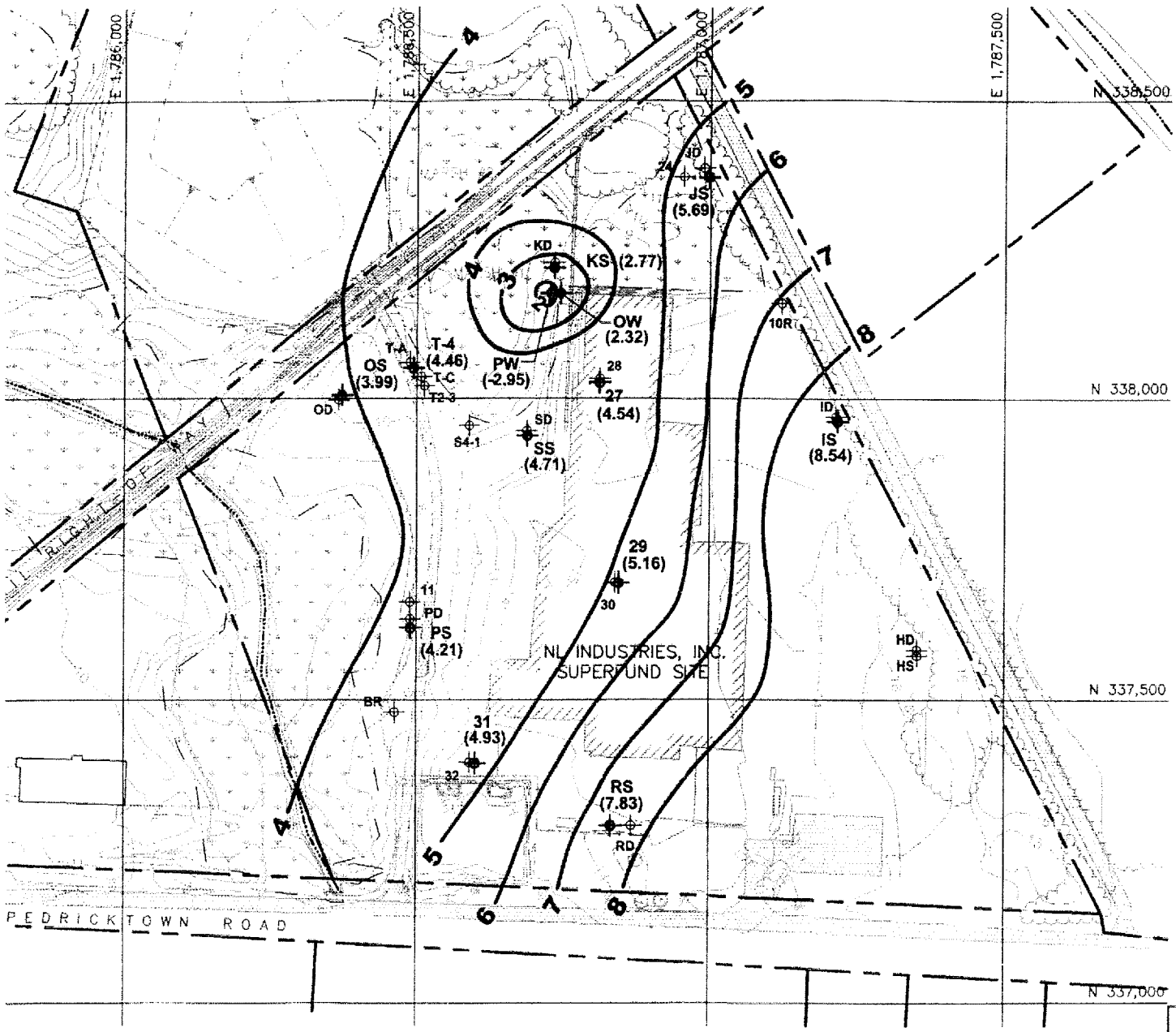
DRAWDOWN AND BAROMETRIC PRESSURE VS. TIME



GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9–8
PROJECT NO.	ME0015–15
DOCUMENT NO.	
FILE NO.	0015F118

500343



LEGEND

- PROPERTY BOUNDARY
- CONTOUR OF EXISTING GROUND SURFACE (FT, MSL)
- EXISTING FENCE
- EXISTING RAILROAD LINE
- EXISTING TREELINE
- EXISTING STREAM
- EXISTING ROAD
- EXISTING WETLAND (SEE NOTE 4)
- APPROXIMATE LIMITS OF EXPOSED CONCRETE FOUNDATION
- EXISTING BUILDING
- POTENTIOMETRIC SURFACE CONTOUR (DASHED WHERE INFERRED)
- 29 — GROUNDWATER MONITORING WELL USED DURING AQUIFER TEST
- (5.16) — GROUNDWATER ELEVATION

200 100 0 200
SCALE IN FEET

S APPROXIMATE AND IS BASED ON A TOPOGRAPHIC SURVEY
A. FRALINGER, BRIDGETON, NEW JERSEY, MAY 1990.

ATIONS ARE BASED ON AERIAL PHOTOGRAPHY AND GROUND
1996 BY OHM REMEDIATION SERVICES CORP.

) ON NATIONAL GEODETIC VERTICAL DATUM (NGVD) 1929.
BASED ON NEW JERSEY STATE PLANE COORDINATE SYSTEM

4. WETLAND AREAS ALONG THE WEST STREAM WERE DELINEATED BY PENNONI ASSOCIATES, INC. FROM FIELD SURVEYS CONDUCTED BETWEEN 5 FEB AND 13 FEB 1999; ALL OTHER WETLANDS ARE BASED ON AREAS DELINEATED BY TALBOT & ASSOCIATES, DECEMBER 1990.

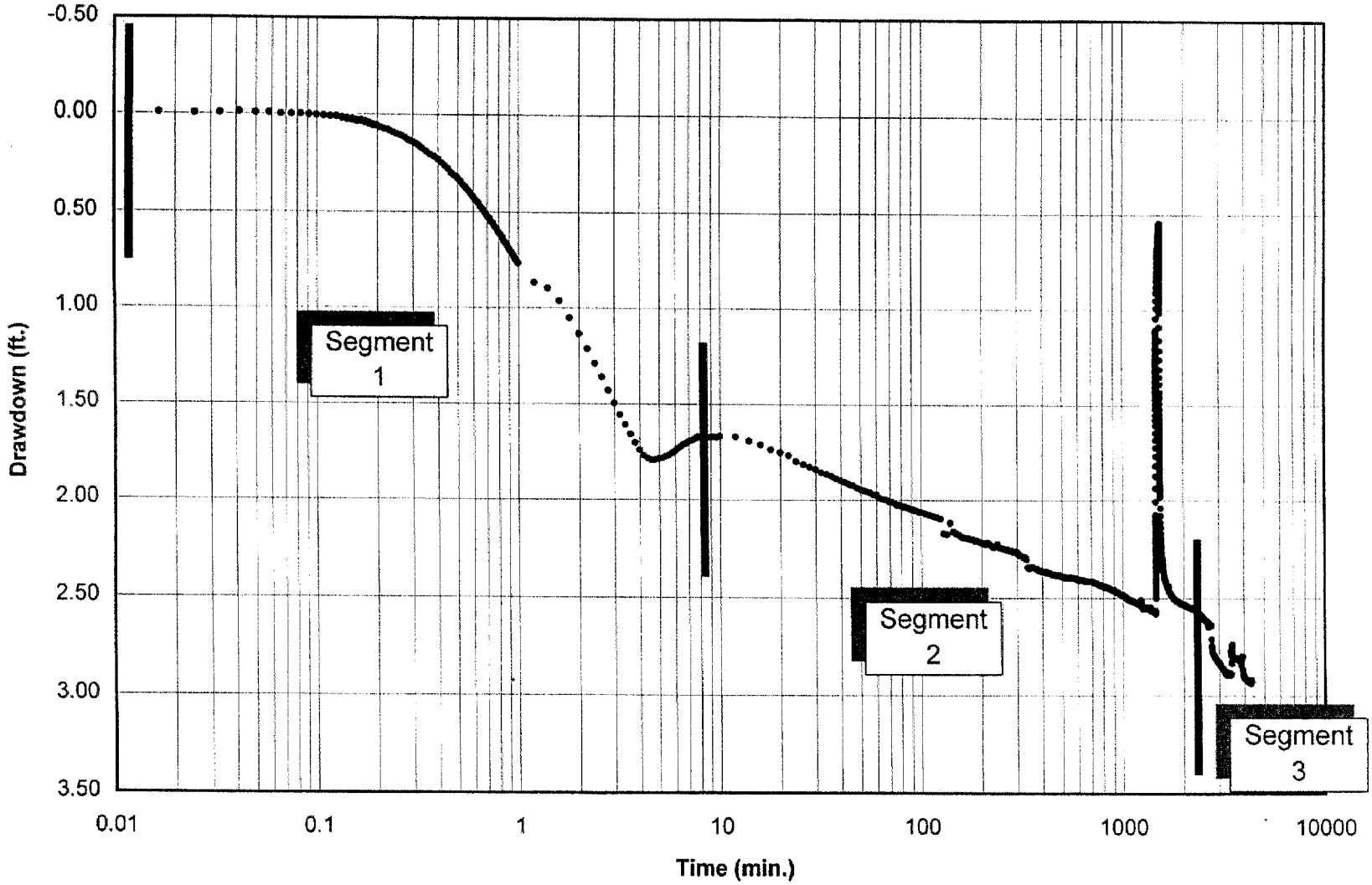
POTENTIOMETRIC SURFACE SHALLOW UNCONFINED AQUIFER 6/10/99 (PUMPING)

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

PROJECT NO. MR0015-15	FIGURE NO. 9-9
DOCUMENT NO. -	FILE NO. 0015F112

500344

DRAWDOWN VS. TIME AT WELL KD

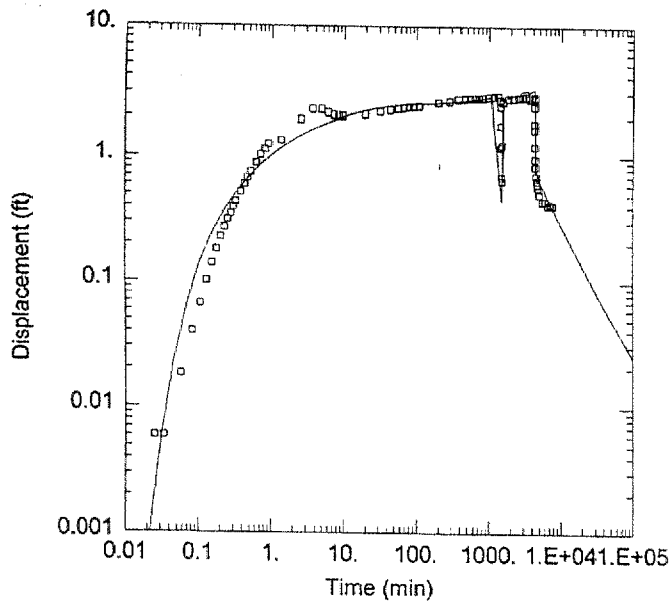


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-10
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500345

NEWMAN ANALYSIS AT WELL OW



WELL TEST ANALYSIS

Data Set: J:\WPWORK\DUANE\NL\Pumping Test\OW-4.AQT
Date: 01/03/00 Time: 16:38:21

SOLUTION

Aquifer Model: Unconfined
Solution Method: Neuman

T = 3828.6 gal/day/ft
S = 0.0005025
Sy = 0.04692
ß = 0.004301

AQUIFER DATA

Saturated Thickness: 23. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW	0	0

Observation Wells

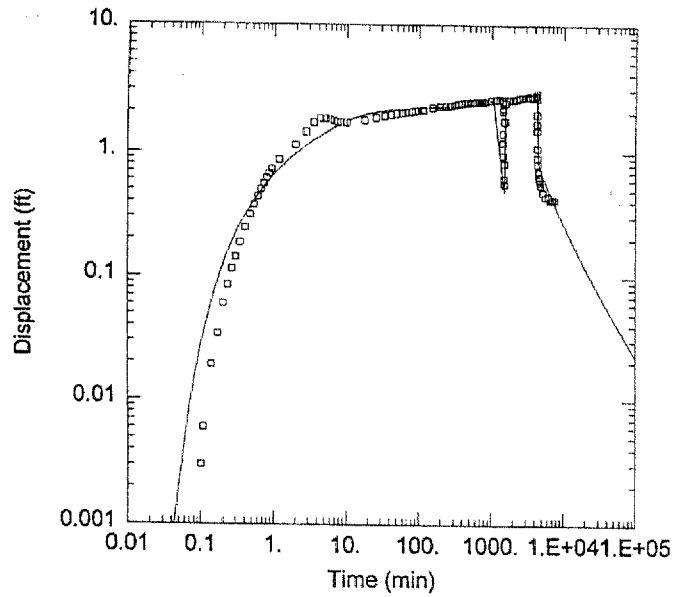
Well Name	X (ft)	Y (ft)
▫ OW	0	16.75

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9–11
PROJECT NO.	ME0015–15
DOCUMENT NO.	
FILE NO.	0015F118

500346

NEWMAN ANALYSIS AT WELL KD



WELL TEST ANALYSIS

Data Set: J:\WPWORK\DUANE\NL\Pumping Test\KD-4.AQT
Date: 01/04/00 Time: 10:18:00

SOLUTION

Aquifer Model: Unconfined
Solution Method: Neuman

T = 4269.3 gal/day/ft
S = 0.0002404
Sy = 0.01
ß = 0.01325

AQUIFER DATA

Saturated Thickness: 23.5 ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW 1	0	0

Observation Wells

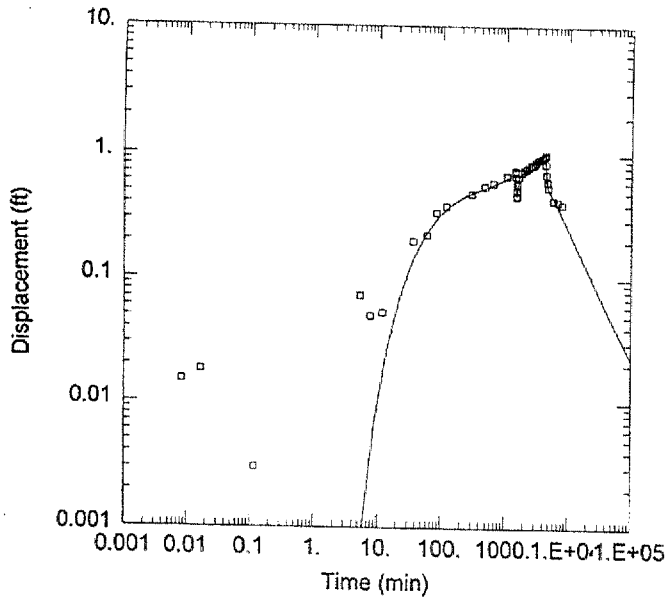
Well Name	X (ft)	Y (ft)
KD	0	36

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-12
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500347

NEWMAN ANALYSIS AT WELL MW-28



WELL TEST ANALYSIS

Data Set: J:\WPWORK\DUANE\NL\Pumping Test\28-4.AQT
Date: 01/04/00 Time: 10:17:38

SOLUTION

Aquifer Model: Unconfined
Solution Method: Neuman

T = 4190.1 gal/day/ft
S = 0.001601
Sy = 0.0229
ß = 0.2702

AQUIFER DATA

Saturated Thickness: 18. ft

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW 1	0	0

Observation Wells

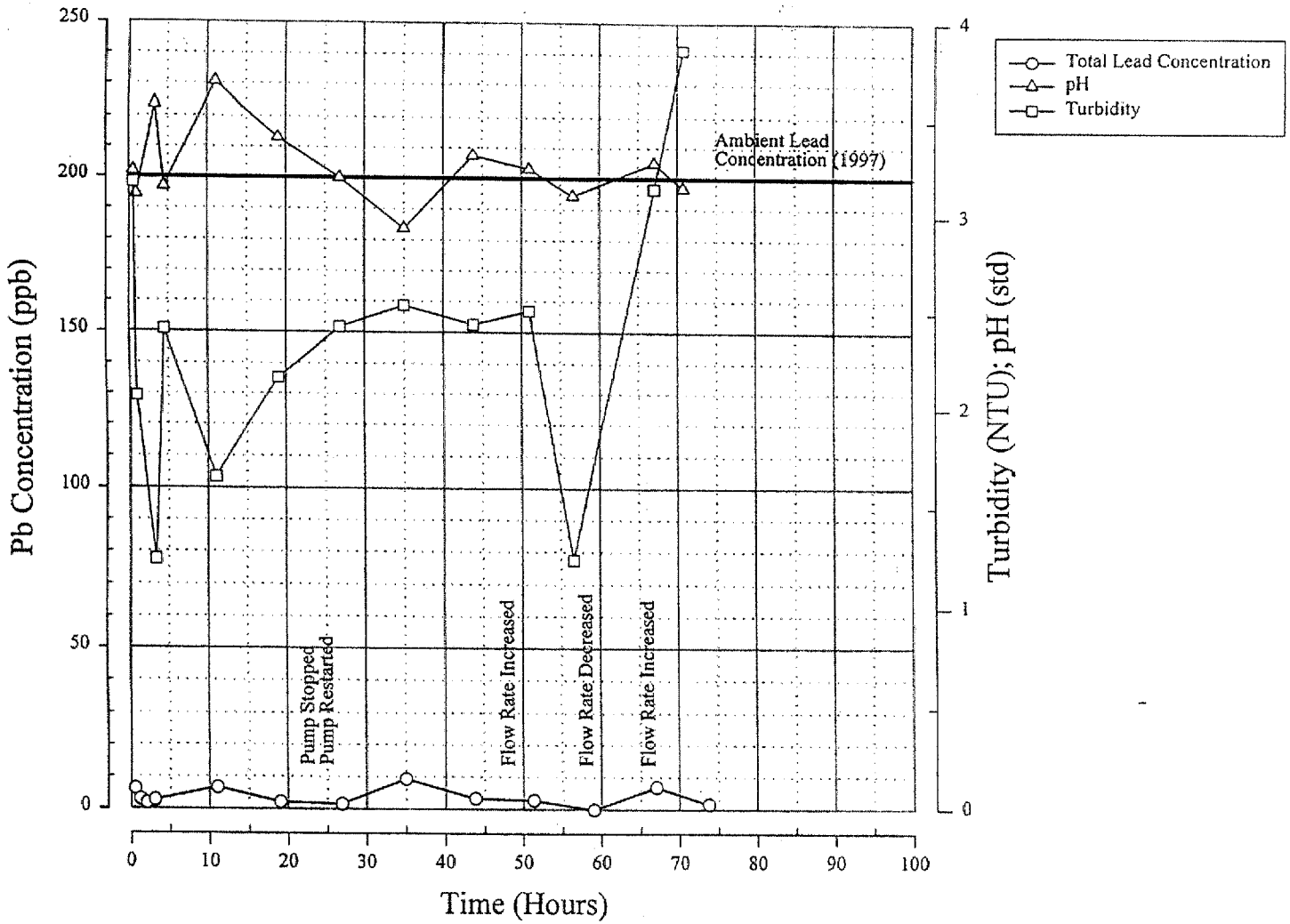
Well Name	X (ft)	Y (ft)
▫ MW-28	0	159

GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-13
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500348

TOTAL LEAD MEASURED IN EFFLUENT DURING AQUIFER TEST

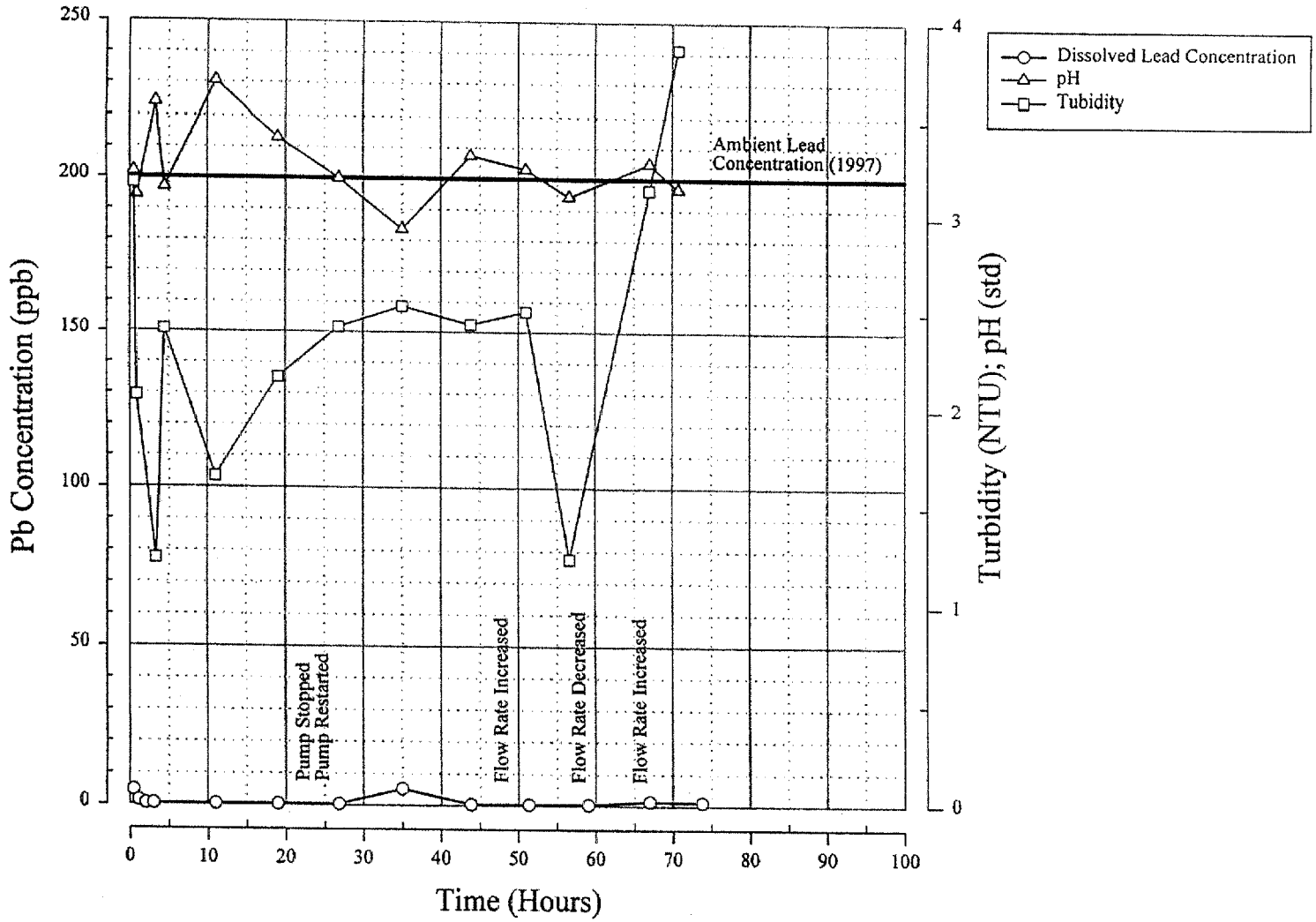


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-14
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500349

DISSOLVED LEAD MEASURED IN EFFLUENT DURING AQUIFER TEST

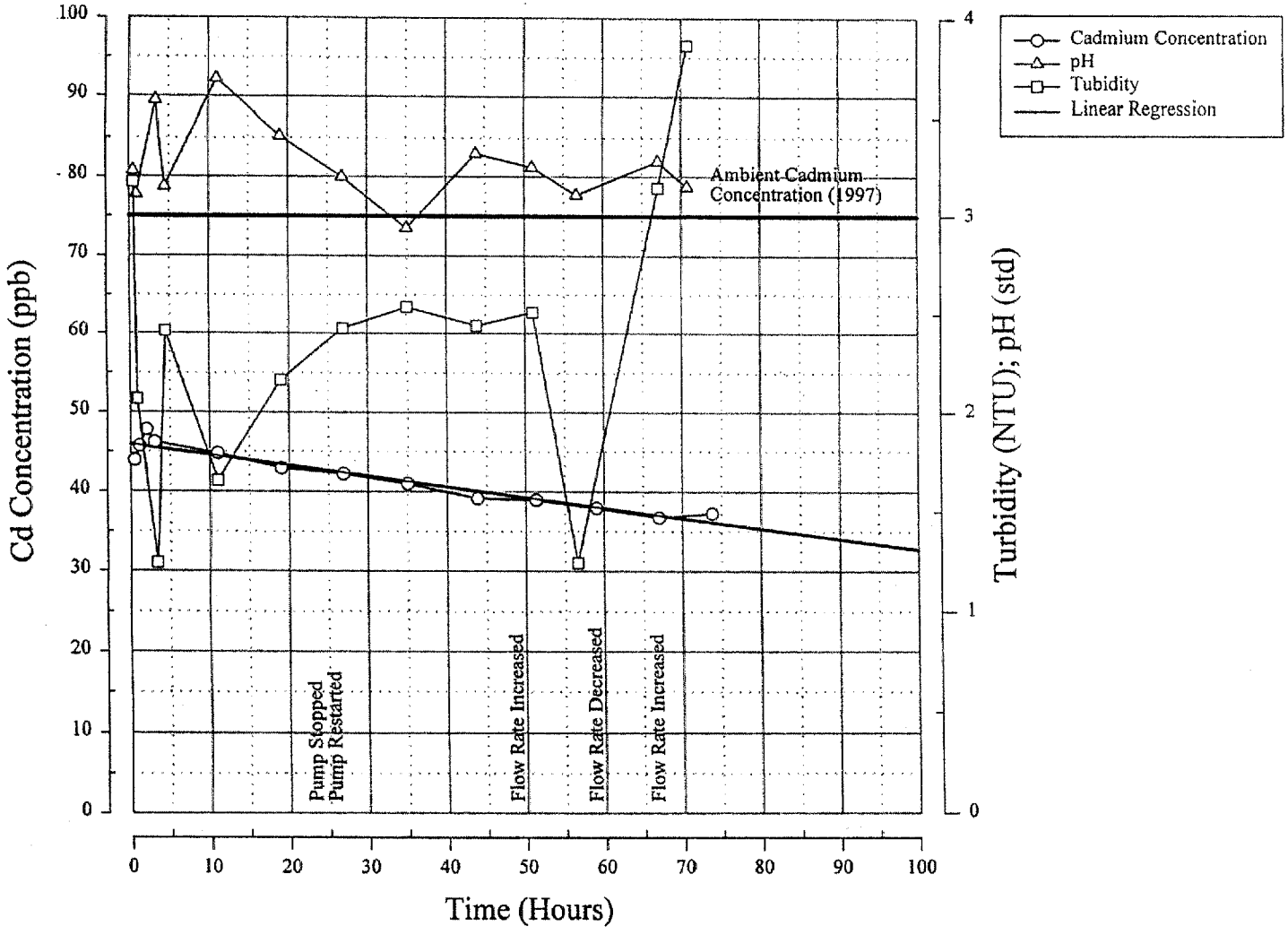


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-15
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500350

TOTAL CADMIUM MEASURED IN EFFLUENT DURING AQUIFER TEST

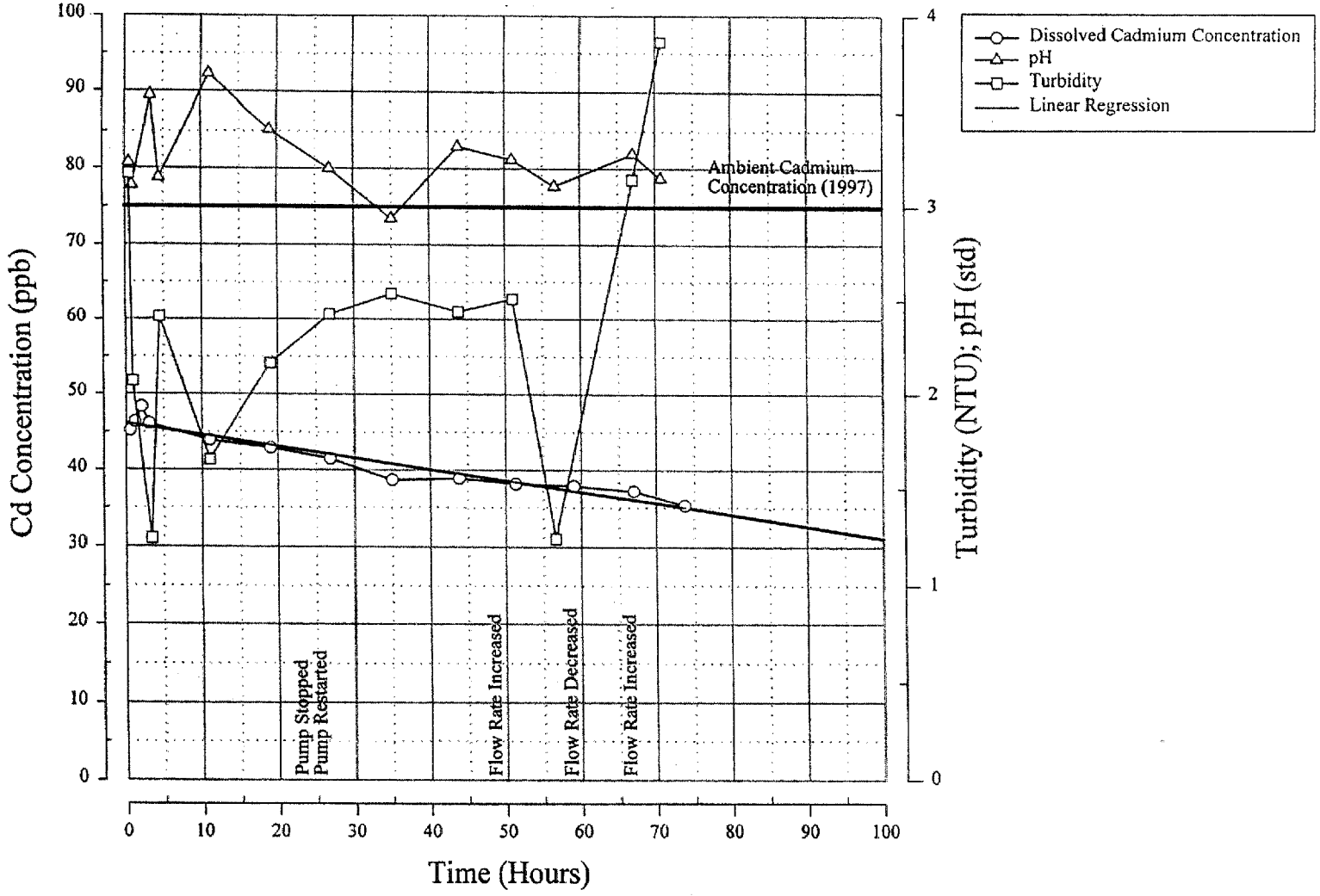


GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-16
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500351

DISSOLVED CADMIUM MEASURED IN EFFLUENT DURING AQUIFER TEST



GEOSYNTEC CONSULTANTS
COLUMBIA, MARYLAND

FIGURE NO.	9-17
PROJECT NO.	ME0015-15
DOCUMENT NO.	
FILE NO.	0015F118

500352

APPENDIX H

Cadmium and Lead in Groundwater Mass Calculations

Table H-1
Mass Calculations Data Tables
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

1988 - Cd				1998 - Cd				2007 - Cd				2010 - Cd			
Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth
11	134	5.94	54.1	11	240	5.27	54.1	11	110	4.08	54.1	11	74	12.22	54.1
JDR	103	6.56	27.3	22	92	10.01	23.1	22	7.3	3.16	23.1	23	16	8.54	34.25
KDR	291	6.49	27.35	23	12.9	9.78	34.25	23	25.8	6.54	34.25	26	42	6.53	21.8
KS	173	6.56	17	26	41.6	11.48	21.8	26	12.6	4.91	21.8	27	7.7	7.86	15
SD	1010	6.18	29.25	27	14.8	11.37	15	27	8.5	6.17	15	28	110	8.37	30
				28	383	11.12	30	28	151	6.7	30	30R	63	7.32	28.71
				30	327	NA	28.71	30R	163	5.97	28.71	JDR	18	7.37	27.3
				JDR	200	7.78	27.3	JDR	54.5	5.49	27.3	KDR	76	3.85	27.35
				BR	16	5.25	39	JS	3.9	5.41	15.5	OS	5.3	6.77	21.22
				JS	1.4	7.68	15.5	KDR	141	2.45	27.35	SD	180	6.9	29.25
				OS	4.7	5	21.22	KS	7.8	2.5	17				
				SD	185	7.07	29.25	OS	3.9	6.37	21.22				
				SS	22.7	6.05	16.4	SD	149	5.72	29.25				
								SS	10.6	5.03	16.4				
average:	**342.2**	**6.35**	**31.00**	**average:**	**118.5**	**8.16**	**27.36**	**average:**	**60.6**	**5.04**	**25.78**	**average:**	**59.2**	**7.57**	**28.90**

1983 - Pb				1988 - Pb				1998 - Pb				2007 - Pb				2010 - Pb			
Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth	Well	Conc	Depth to Water	Depth
11	460	NA	54.1	JDR	14	6.56	27.3	27	19.9	11.37	15	27	6.2	7	15	27	20	7.86	15
JDR	390	NA	27.3	KDR	61	6.49	27.35	28	15.4	11.12	30	OS	388	6.63	21.22	BR	11	5.6	39
KDR	270	NA	27.35	KS	3130	6.56	17	30	37.4	NA	28.71	SD	31	6.25	29.25	31	150	6.56	15
KS	2560	NA	17	SD	294	6.18	29.25	OS	476	5	21.22	SS	82.9	5.57	16.4	NS	48	7.91	16.5
SD	2960	NA	29.25	NS	45	4.86	16.3	SD	25.6	7.07	29.25	31	20.6	6.56	15	OS	1100	6.77	21.22
NS	1180	NA	16.3	BR	18	5.78	39	KS*	328	6.56	17	NS	41.6	7.22	16.5	SD	73	6.9	29.25
BR	250	NA	39									ND	22.2	6.5	24	SS	68	6.17	16.4
average:	**1152.9**	**6.82**	**30.04**	**average:**	**593.7**	**6.07**	**26.03**	**average:**	**150.4**	**8.22**	**23.53**	**average:**	**84.6**	**6.53**	**19.62**	**average:**	**210**	**6.82**	**21.77**

* Well sampled in 1997, added to data set to provide consistent data sets for each year.

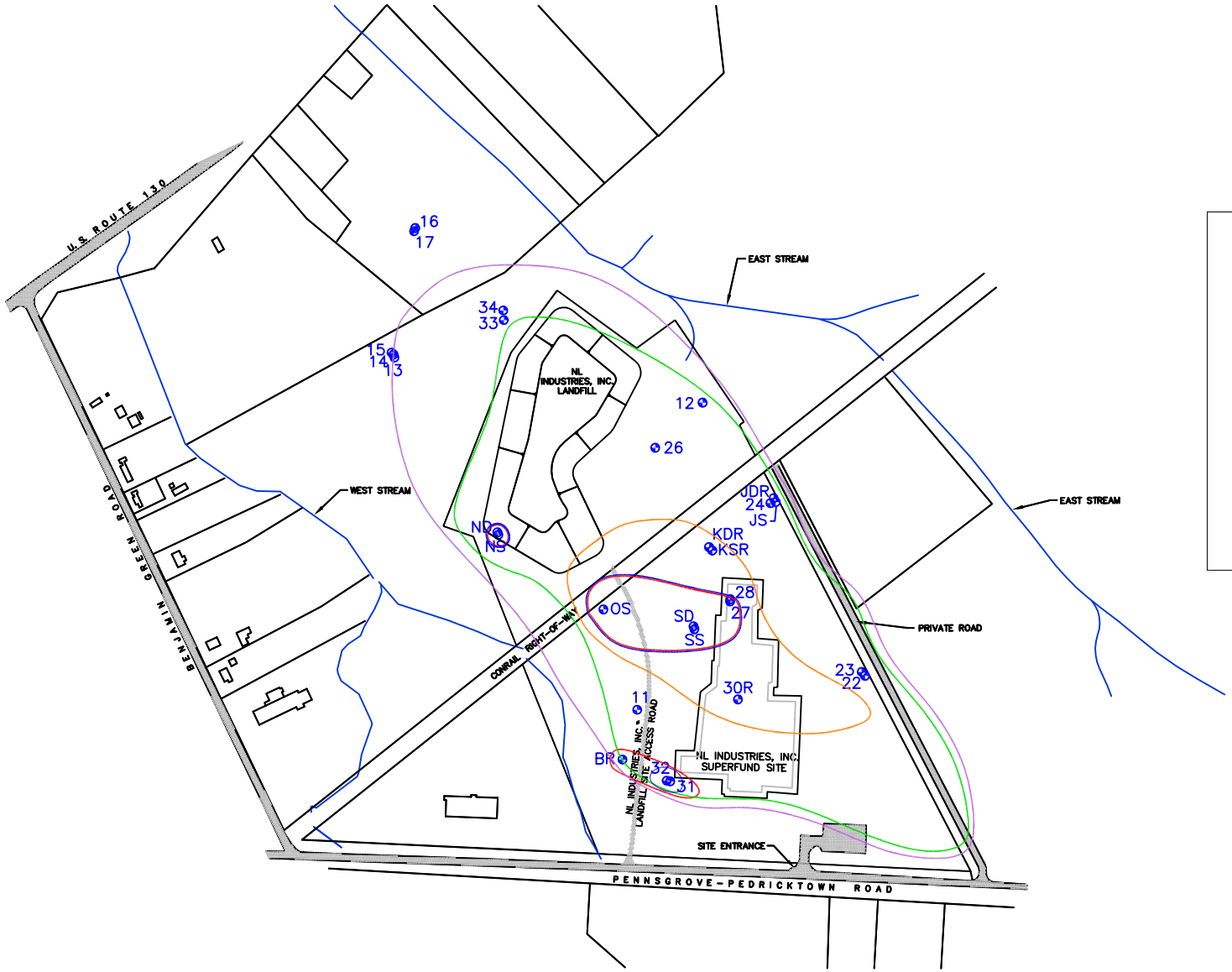
TABLE H-2
Mass of Lead in Groundwater Calculations
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

(A) Avg Concentration (ppb)	(B) Avg Well Depth (ft)	(C) Avg Depth to Water (ft)	(D) Water Column Height (ft)	(E) Area of Impacted GW (ft^2)	(F) Volume of Impacted GW (ft^3)	(G) Assume 30% Porosity of Aquifer	(H) Conversion to Liters of GW	Conversion to Gallon of GW	(I) Conversion to total µg in GW	(J) Conversion to total lbs in GW
Average of all wells with detections	Average of all wells with detections	Average of all wells with detections	= (B) - (C)	Determined from GIS/CADD calculations	= (E) * (D) / 3 (to approximate a conical shaped plume)	= (F) * 0.30	= (G) * 28.32	= (G) * 7.481	= (H) * (A)	= (I) * 0.00000000221
MASS CALCULATIONS:										
2010										
210.00	21.77	6.82	14.94	138,939	692,047	207,614	5,879,629	1,553,160	1,234,722,040	2.7
2007										
84.64	19.62	6.53	13.09	127,853	557,925	167,378	4,740,135	1,252,152	401,218,531	0.9
1998										
150.38	23.53	8.22	15.31	421,922	2,152,647	645,794	18,288,887	4,831,185	2,750,343,769	6.1
1988										
593.67	26.03	6.07	19.96	1,714,644	11,409,050	3,422,715	96,931,292	25,605,332	57,544,877,104	126.9
1983										
1152.86	30.04	6.91	23.13	2,274,279	17,534,430	5,260,329	148,972,518	39,352,522	171,744,031,991	378.7

Note: The depth to water for the 1983 data was not available. An average depth to water from the four other sample sets shown was used.

TABLE H-3
Mass of Cadmium in Groundwater Calculations
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

(A) Avg Concentration (ppb)	(B) Avg Well Depth (ft)	(C) Avg Depth to Water (ft)	(D) Water Column Height (ft)	(E) Area of Impacted GW (ft^2)	(F) Volume of Impacted GW (ft^3)	(G) Assume 30% Porosity of Aquifer	(H) Conversion to Liters of GW	Conversion to Gallon of GW	(I) Conversion to total µg in GW	(J) Conversion to total lbs in GW
Average of all wells with detections	Average of all wells with detections	Average of all wells with detections	= (B) - (C)	Determined from GIS/CADD calculations	= (E) * (D) / 3 (to approximate a conical shaped plume)	= (F) * 0.30	= (G) * 28.32	= (G) * 7.481	= (H) * (A)	= (I) * 0.00000000221
MASS CALCULATIONS:										
2010										
59.20	28.90	7.57	21.33	742,913	5,280,871	1,584,261	44,866,283	11,851,860	2,656,083,939	5.9
2007										
60.64	25.78	5.04	20.75	731,652	5,060,244	1,518,073	42,991,832	11,356,705	2,606,840,418	5.8
1998										
118.55	27.36	8.16	19.20	833,702	5,336,011	1,600,803	45,334,751	11,975,610	5,374,260,335	11.9
1988										
342.2	31.00	6.35	24.65	1,231,268	10,118,561	3,035,568	85,967,298	22,709,087	29,418,009,287	65.0



N

0 200 400
SCALE IN FEET

Legend

- Property Line
- Stream
- 11 Existing Well

Areas with Pb concetrations greater than the NJGWQC

- 1983 (Area = 2,274,279.10 sq ft)
- 1988 (Area = 1,714,643.96 sq ft)
- 1998 (Area = 421,922.14 sq ft)
- 2007 (Area = 127,852.84 sq ft)
- 2010 (Area = 138,938.63 sq ft)

CSI Environmental, LLC
918 Chesapeake Ave.
Annapolis, MD 21403
410-268-2765

Drafter: M. Hickey

Approved By: J.D. Ferris

Prepared: 2/10/2011

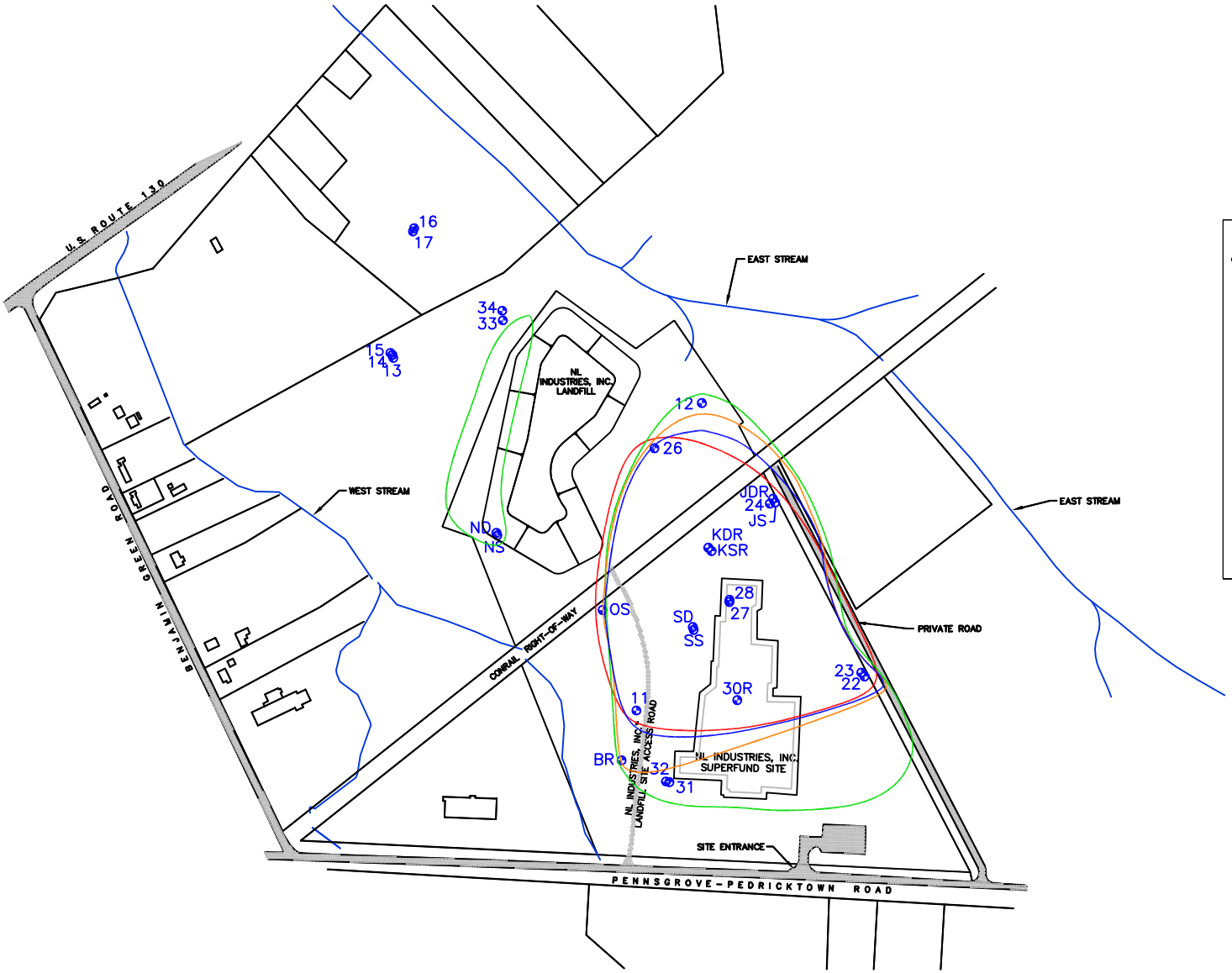
AREA OF LEAD IMPACTS

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE

H-1

500357



0 200 400
SCALE IN FEET

Legend

- Property Line
- Stream
- 11 Existing Well

Areas with Cd concetrations greater than the NJGWQC

- 1988 (Area = 1,231,268.12 sq ft)
- 1998 (Area = 833,701.64 sq ft)
- 2007 (Area = 731,651.89 sq ft)
- 2010 (Area = 742,912.73 sq ft)

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Approved By: J.D. Ferris

Prepared: 2/10/2011

AREA OF CADMIUM IMPACTS

NL Industries, Inc. Superfund Site
Pedricktown, NJ

FIGURE
H-2
500358

APPENDIX I

New Jersey Groundwater Quality Standards

TABLE I-1
New Jersey Groundwater Quality Standards
N.J.A.C 7:9C, Appendix Table 1

Last Revision: July 22, 2010

Constituent	CASRN	Ground Water Quality Criterion	Practical Quantitation Level (PQL)*	Higher of PQL and Ground Water Quality Criterion (ug/L)*
Acenaphthene	83-32-9	400	10	400
Acetone	67-64-1	6,000	10	6,000
Acetophenone	98-86-2	700	10	700
Acrolein	107-02-8	4	5	5
Acrylamide	79-06-1	0.008	0.2	0.2
Acrylonitrile	107-13-1	0.06	2	2
Adipates (Di(2-ethylhexyl)adipate) (DEHA)	103-23-1	30	3	30
Alachlor	15972-60-8	0.4	0.1	0.4
Aldicarb sulfone	1646-88-4	7	0.3	7
Aldrin	309-00-2	0.002	0.04	0.04
Aluminum	7429-90-5	200	30	200
Ammonia (Total)	7664-41-7	3,000	200	3,000
Aniline	62-53-3	6	2	6
Anthracene	120-12-7	2,000	10	2,000
Antimony (Total)	7440-36-0	6	3	6
Arsenic (Total)	7440-38-2	0.02	3	3
Asbestos	1332-21-4	$7X10^6$f/L>10um[a]	10^6f/L>10um[a]	$7X10^6$f/L>10um[a]
Atrazine	1912-24-9	3	0.1	3
Barium **	7440-39-3	6,000	200	6,000
Benz(a)anthracene	56-55-3	0.05	0.1	0.1
Benzene	71-43-2	0.2	1	1
Benzidine	92-87-5	0.0002	20	20
Benzo(a)pyrene (BaP)	50-32-8	0.005	0.1	0.1
Benzo(b)fluoranthene (3,4-Benzofluoranthene)	205-99-2	0.05	0.2	0.2
Benzo(k)fluoranthene	207-08-9	0.5	0.3	0.5
Benzoic acid	65-85-0	30,000	50	30,000
Benzyl alcohol	100-51-6	2,000	20	2,000
Beryllium	7440-41-7	1	1	1
alpha-BHC- (alpha-HCH)	319-84-6	0.006	0.02	0.02
beta-BHC (beta-HCH)	319-85-7	0.02	0.04	0.04
gamma-BHC (gamma-HCH/Lindane)	58-89-9	0.03	0.02	0.03
1,1-Biphenyl	92-52-4	400	10	400
Bis(2-chloroethyl) ether	111-44-4	0.03	7	7
Bis(2-chloroisopropyl) ether	108-60-1	300	10	300
Bis(2-ethylhexyl) phthalate (DEHP)	117-81-7	2	3	3
Bromodichloromethane (Dichlorobromomethane)	75-27-4	0.6	1	1
Bromoform	75-25-2	4	0.8	4
n-Butanol (n-Butyl alcohol)	71-36-3	700	20	700
tertiary-Butyl alcohol (TBA)	75-65-0	100	2	100
Butylbenzyl phthalate	85-68-7	100	1	100
Cadmium	7440-43-9	4	0.5	4
Camphor	76-22-2	1,000	0.5	1,000
Carbofuran	1563-66-2	40	0.5	40
Carbon disulfide	75-15-0	700	1	700
Carbon tetrachloride	56-23-5	0.4	1	1
Chlordane	57-74-9	0.01	0.5	0.5
Chloride	16887-00-6	250,000	2,000	250,000
4-Chloroaniline (p-Chloroaniline)	106-47-8	30	10	30
Chlorobenzene (Monochlorobenzene)	108-90-7	50	1	50
Chloroform	67-66-3	70	1	70
2-Chloronaphthalene	91-58-7	600	10	600
2-Chlorophenol	95-57-8	40	20	40
Chlorpyrifos	2921-88-2	20	0.1	20
Chromium (Total)	7440-47-3	70	1	70
Chrysene	218-01-9	5	0.2	5
Color		10 CU	5 CU	10 CU
Copper	7440-50-8	1,300	4	1,300
Cumene (Isopropyl benzene)	98-82-8	700	1	700

TABLE I-1
New Jersey Groundwater Quality Standards
N.J.A.C 7:9C, Appendix Table 1

Last Revision: July 22, 2010

Constituent	CASRN	Ground Water Quality Criterion	Practical Quantitation Level (PQL)*	Higher of PQL and Ground Water Quality Criterion (ug/L)*
Cyanide (free Cyanide)	57-12-5	100	6	100
2,4-D (2,4-Dichlorophenoxyacetic acid)	94-75-7	70	2	70
Dalapon (2,2-Dichloropropionic acid)	75-99-0	200	0.1	200
4,4'-DDD (p,p'-TDE)	72-54-8	0.1	0.02	0.1
4,4'-DDE	72-55-9	0.1	0.01	0.1
4,4'-DDT	50-29-3	0.1	0.1	0.1
Demeton	8065-48-3	0.3	1	1
Dibenz(a,h)anthracene	53-70-3	0.005	0.3	0.3
Dibromochloromethane (Chlorodibromomethane)	124-48-1	0.4	1	1
1,2-Dibromo-3-chloropropane (DBCP)	96-12-8	0.02	0.02	0.02
Di-n-butyl phthalate	84-74-2	700	1	700
1,2-Dichlorobenzene (ortho)	95-50-1	600	5	600
1,3-Dichlorobenzene (meta)	541-73-1	600	5	600
1,4-Dichlorobenzene (para)	106-46-7	75	5	75
3,3-Dichlorobenzidine	91-94-1	0.08	30	30
Dichlorodifluoromethane (Freon 12)	75-71-8	1,000	2	1,000
1,1-Dichloroethane (1,1-DCA)	75-34-3	50	1	50
1,2-Dichloroethane	107-06-2	0.3	2	2
1,1-Dichloroethylene (1,1-DCE)	75-35-4	1	1	1
cis-1,2-Dichloroethylene	156-59-2	70	1	70
trans-1,2-Dichloroethylene	156-60-5	100	1	100
2,4-Dichlorophenol (DCP)	120-83-2	20	10	20
1,2-Dichloropropane	78-87-5	0.5	1	1
1,3-Dichloropropene (cis and trans)	542-75-6	0.4	1	1
Dieldrin	60-57-1	0.002	0.03	0.03
Diethyl phthalate	84-66-2	6,000	1	6,000
Diisodecyl phthalate (DIDP)	26761-40-0	100	3	100
Diisopropyl ether (DIPE)	108-20-3	20,000	5	20,000
2,4-Dimethyl phenol	105-67-9	100	20	100
2,4-Dinitrophenol	51-28-5	10	40	40
2,4-Dinitrotoluene/2,6-Dinitrotoluene Mix	25321-14-6	0.05	10	10
Di-n-octyl phthalate	117-84-0	100	10	100
Dinoseb	88-85-7	7	2	7
Diphenylamine	122-39-4	200	20	200
1,2-Diphenylhydrazine	122-66-7	0.04	20	20
Diquat	85-00-7	20	2	20
Endosulfan (alpha and beta)	115-29-7	40	0.1	40
alpha-Endosulfan (Endosulfan I)	959-98-8	40	0.02	40
beta-Endosulfan (Endosulfan II)	33213-65-9	40	0.04	40
Endosulfan sulfate	1031-07-8	40	0.02	40
Endothall	145-73-3	100	60	100
Endrin	72-20-8	2	0.03	2
Epichlorohydrin	106-89-8	4	5	5
Ethion	563-12-2	4	0.5	4
Ethyl acetate	141-78-6	6,000	10	6,000
Ethylbenzene	100-41-4	700	2	700
Ethylene dibromide (1,2-Dibromoethane)	106-93-4	0.0004	0.03	0.03
Ethylene glycol	107-21-1	300	200	300
Ethylene glycol monomethyl ether	109-86-4	7	20,000	20,000
Ethyl ether	60-29-7	1,000	50	1,000
Fluoranthene	206-44-0	300	10	300
Fluorene	86-73-7	300	1	300

TABLE I-1
New Jersey Groundwater Quality Standards
N.J.A.C 7:9C, Appendix Table 1

Last Revision: July 22, 2010

Constituent	CASRN	Ground Water Quality Criterion	Practical Quantitation Level (PQL)*	Higher of PQL and Ground Water Quality Criterion (ug/L)*
Fluoride	7782-41-4	2,000	500	2,000
Foaming agents (ABS/LAS)		500	0.5	500
Formaldehyde	50-00-0	100	30	100
Glyphosate	1071-83-6	700	30	700
Hardness (as CaCO3)		250,000	10,000	250,000
Heptachlor	76-44-8	0.008	0.05	0.05
Heptachlor epoxide	1024-57-3	0.004	0.2	0.2
Hexachlorobenzene	118-74-1	0.02	0.02	0.02
Hexachlorobutadiene	87-68-3	0.4	1	1
Hexachlorocyclopentadiene	77-47-4	40	0.5	40
Hexachloroethane	67-72-1	2	7	7
Hexane (n-Hexane)	110-54-3	30	5	30
Indeno (1,2,3-cd)pyrene	193-39-5	0.05	0.2	0.2
Iron	7439-89-6	300	20	300
Isophorone	78-59-1	40	10	40
Lead (Total)	7439-92-1	5	5	5
Malathion	121-75-5	100	0.6	100
Manganese	7439-96-5	50	0.4	50
Mercury (Total)	7439-97-6	2	0.05	2
Methanol	67-56-1	4,000	70	4,000
Methoxychlor	72-43-5	40	0.1	40
Methyl acetate	79-20-9	7,000	0.5	7,000
Methyl bromide (Bromomethane)	74-83-9	10	1	10
Methylene chloride	75-09-2	3	1	3
Methyl ethyl ketone (2-Butanone) (MEK)	78-93-3	300	2	300
Methyl Salicylate	119-36-8	4,000	50	4,000
Methyl tertiary butyl ether (MTBE)	1634-04-4	70	1	70
Mirex	2385-85-5	0.1	0.08	0.1
Molybdenum	7439-98-7	40	2	40
Naphthalene	91-20-3	300	2	300
Nickel (Soluble salts)	7440-02-0	100	4	100
Nitrate	14797-55-8	10,000	100	10,000
Nitrite	14797-65-0	1,000	10	1,000
Nitrate and Nitrite		10,000	10	10,000
Nitrobenzene	98-95-3	4	6	6
N-Nitrosodimethylamine	62-75-9	0.0007	0.8	0.8
N-Nitrosodiphenylamine	86-30-6	7	10	10
N-Nitrosodi-n-propylamine (Di-n-propylnitrosamine)	621-64-7	0.005	10	10
Odor		3b	NA	3b
Oil & Grease & Petroleum Hydrocarbons		None Noticeable	NA	None Noticeable
Oxamyl	23135-22-0	200	1	200
Parathion	56-38-2	4	0.08	4
PBBs (Polybrominated biphenyls)	67774-32-7	0.004	0.001	0.004
PCBs (Polychlorinated biphenyls)	1336-36-3	0.02	0.5	0.5
Pentachlorophenol	87-86-5	0.3	0.1	0.3
pH		6.5-8.5	NA	6.5-8.5
Phenol	108-95-2	2,000	10	2,000
Picloram	2/1/1918	500	1	500
Pyrene	129-00-0	200	0.1	200
Salicylic acid	69-72-7	80	30	80
Selenium (Total)	7782-49-2	40	4	40
Silver	7440-22-4	40	1	40
Simazine	122-34-9	0.3	0.8	0.8
Sodium	7440-23-5	50,000	400	50,000
Styrene	100-42-5	100	2	100

TABLE I-1
New Jersey Groundwater Quality Standards
N.J.A.C 7:9C, Appendix Table 1

Last Revision: July 22, 2010

Constituent	CASRN	Ground Water Quality Criterion	Practical Quantitation Level (PQL)*	Higher of PQL and Ground Water Quality Criterion (ug/L)*
Sulfate	14808-79-8	250,000	5,000	250,000
Taste		None Objectionable	NA	None Objectionable
TDS (Total dissolved solids)		500,000	10,000	500,000
2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD)	1746-01-6	0.0000002	0.00001	0.00001
1,1,1,2-Tetrachloroethane	630-20-6	1	1	1
1,1,2,2-Tetrachloroethane	79-34-5	1	1	1
Tetrachloroethylene (PCE)	127-18-4	0.4	1	1
2,3,4,6-Tetrachlorophenol	58-90-2	200	3	200
Tetrahydrofuran	109-99-9	10	10	10
Thallium	7440-28-0	0.5	2	2
Toluene **	108-88-3	600	1	600
Toxaphene	8001-35-2	0.03	2	2
2,4,5-TP (2-(2,4,5-Trichlorophenoxy)propionic acid)	93-72-1	60	0.6	60
1,2,4-Trichlorobenzene	120-82-1	9	1	9
1,1,1-Trichloroethane (TCA)	71-55-6	30	1	30
1,1,2-Trichloroethane	79-00-5	3	2	3
Trichloroethene (TCE)	79-01-6	1	1	1
Trichlorofluoromethane (Freon 11)	75-69-4	2,000	1	2,000
2,4,5-Trichlorophenol	95-95-4	700	10	700
2,4,6-Trichlorophenol	88-06-2	1	20	20
1,2,3-Trichloropropane	96-18-4	0.005	0.03	0.03
Vanadium pentoxide	1314-62-1	60	1	60
Vinyl acetate	108-05-4	7,000	5	7,000
Vinyl chloride	75-01-4	0.08	1	1
Xylenes (Total)	1330-20-7	1,000	2	1,000
Zinc	7440-66-6	2,000	10	2,000
Microbiological criteria[m],	Standards promulgated in the Safe Drinking Water Act Regulations (N.J.A.C. 7:10-1 et seq.)			
Radionuclides &				
Turbidity				

Notes:

* Ground Water Quality Criteria and PQLs are expressed as ug/L unless otherwise noted. Table 1 criteria are all maximum values unless clearly indicated as a range for which the minimum value is to the left and the maximum value is to the right.
** Revised via administrative change (see 39 N.J.R. 3538(a)).
PQL = Practical Quantitation Level as defined in N.J.A.C. 7:9C-1.4
CASRN = Chemical Abstracts System Registration Number
NA = Not available for this constituent.
a = Asbestos criterion is measured in terms of fibers/L longer than 10 micrometers (f/L > 10 um)
b = Odor Threshold Number
L = Liter
f = Fibers
CU = Standard Cobalt Units
ug = micrograms
mg = milligrams
H = Hardness
(Total) = means the concentration of metal in an unfiltered sample following treatment with hot dilute mineral acid (as defined in "Methods for Chemical Analysis of Water & Wastes", EPA-600/4-79-020, March 1979) or other digestion defined by the analytical method. However samples that contain less than 1 nephlometric turbidity unit (NTU) and are properly preserved, may be directly analyzed without digestion.

m = Pursuant to prevailing Safe Drinking Water Act Regulations any positive result for fecal coliform is in violation of the MCL and is therefore an exceedance of the ground water quality standards.

APPENDIX J

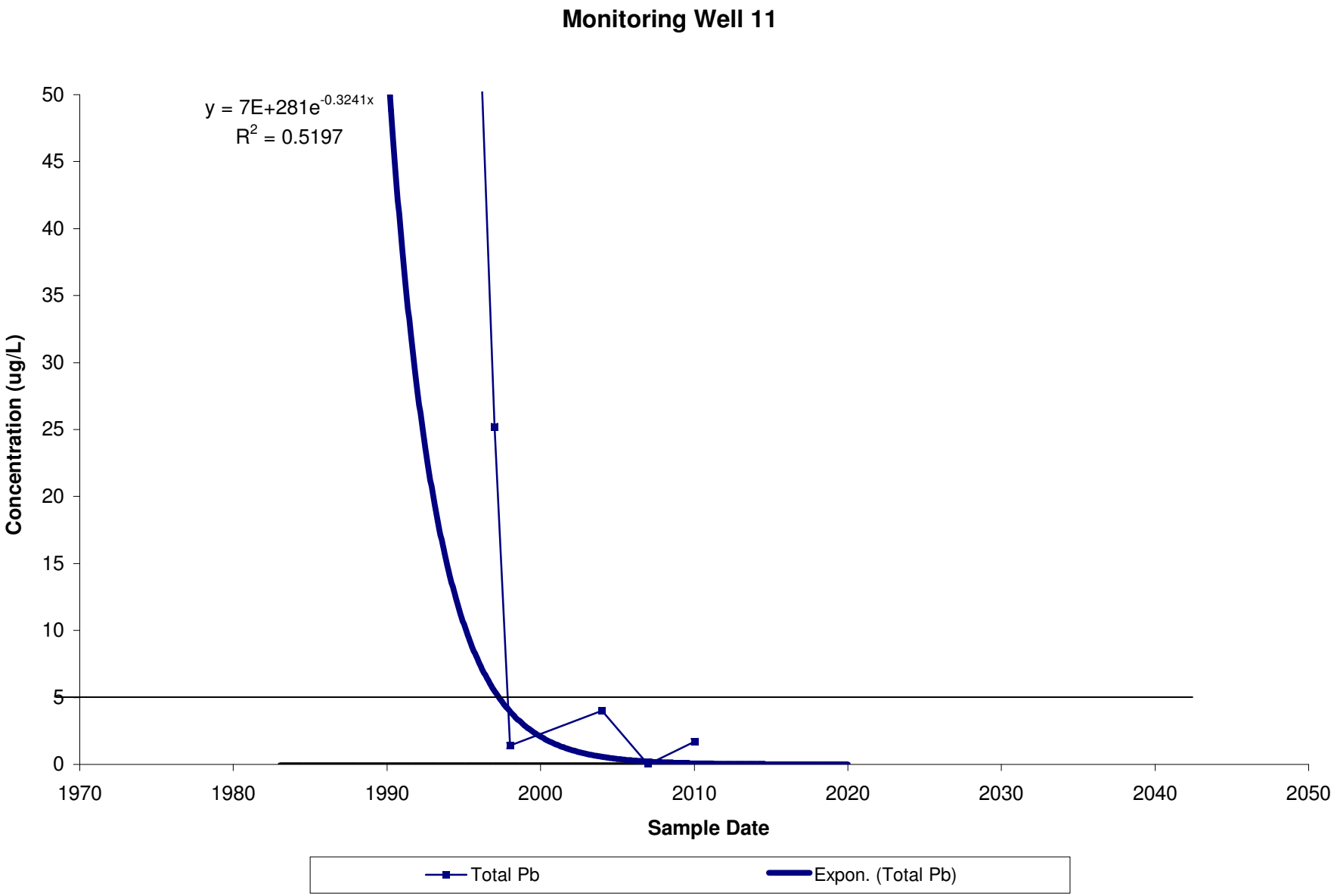
Lead and Cadmium Trend Charts and Attenuation Calculation

TABLE J-1
Cadmium and Lead Rate of Attenuation Calculation
NL Industries, Inc. Superfund Site
Pedricktown, New Jersey

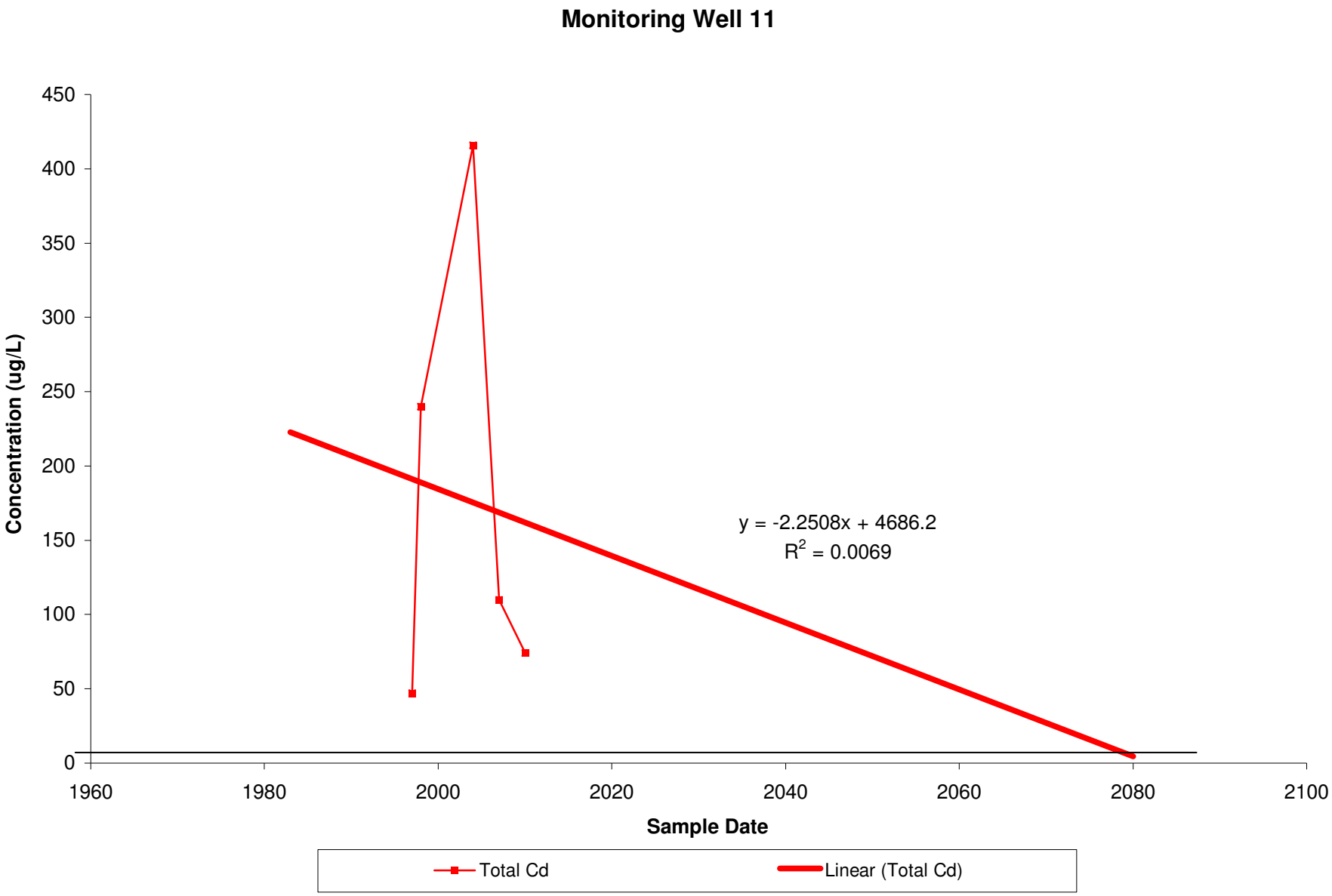
AVERAGE TOTAL PB RATE OF ATTENUATION	**-8.2**	**ug/L per year**
AVERAGE TOTAL CD RATE OF ATTENUATION	**-2.6**	**ug/L per year**

Total Pb (ug/L)														
Year	11	12	13	14	15	16	17	22	23	24	26	27	28	30R
2010	1.7	0	0	3.5	0	0	0	0	0	0	0	20	0	0
YEARS TO RAO	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**1.8**	**NA**	**NA**
Total Cd (ug/L)														
Year	11	12	13	14	15	16	17	22	23	24	26	27	28	30R
2010	74	0	0	0	0	0	0	3.7	16	0	42	7.7	110	63
YEARS TO RAO	**26.9**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**4.6**	**NA**	**14.6**	**1.4**	**40.8**	**22.7**

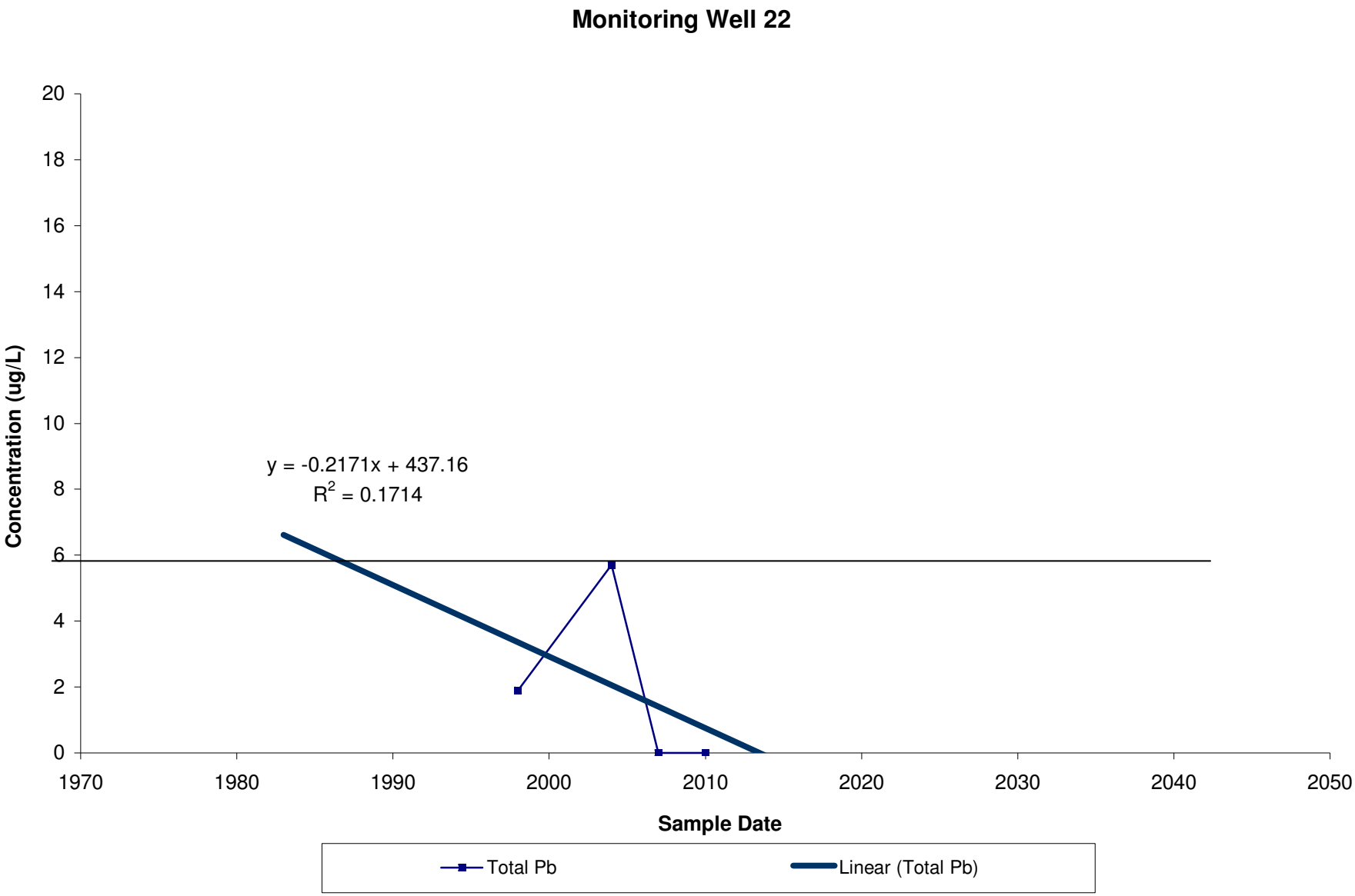
Total Pb (ug/L)														
Year	31	32	33	34	JS	JDR	KSR	KDR	SS	SD	NS	ND	OS	BR
2010	150	0	0	2.2	0	0	0	0	68	73	48	3.4	1100	11
YEARS TO RAO	**17.7**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**7.7**	**NA**	**5.2**	**NA**	**133.5**	**0.7**
Total Cd (ug/L)														
Year	31	32	33	34	JS	JDR	KSR	KDR	SS	SD	NS	ND	OS	BR
2010	0	0	2	0	2.5	18	0	76	2.8	180	0	0	5.3	0
YEARS TO RAO	**NA**	**NA**	**NA**	**NA**	**NA**	**5.4**	**NA**	**27.7**	**NA**	**67.7**	**NA**	**NA**	**0.5**	**NA**


Monitoring Well 11
y = 7E+281e^-0.3241x
R^2 = 0.5197
Concentration (ug/L)
50
45
40
35
30
25
20
15
10
5
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Expon. (Total Pb)

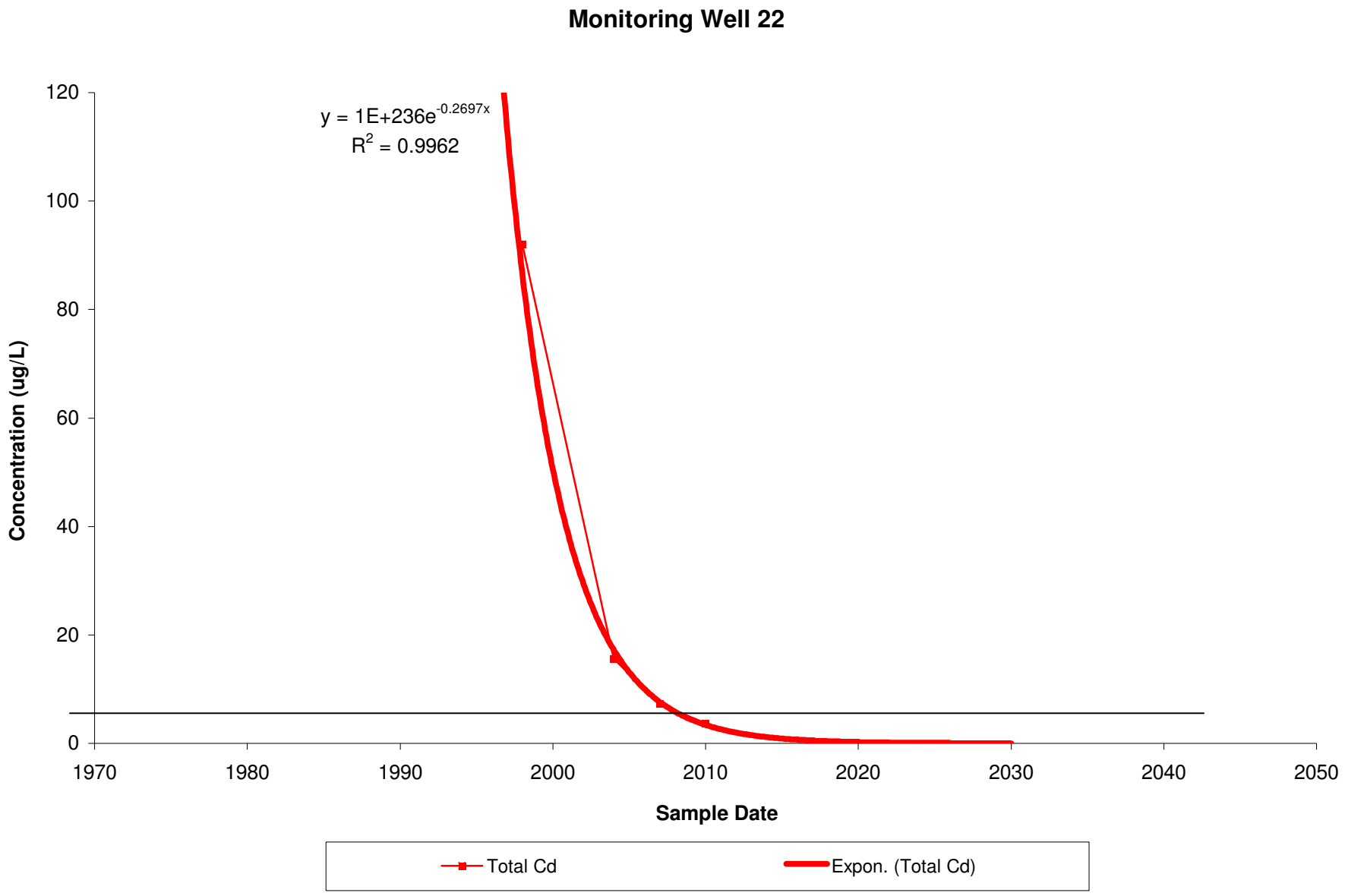
500366


Monitoring Well 11
Concentration (ug/L)
450
400
350
300
250
200
150
100
50
0
1960
1980
2000
2020
2040
2060
2080
2100
Sample Date
y = -2.2508x + 4686.2
R2 = 0.0069
Total Cd
Linear (Total Cd)

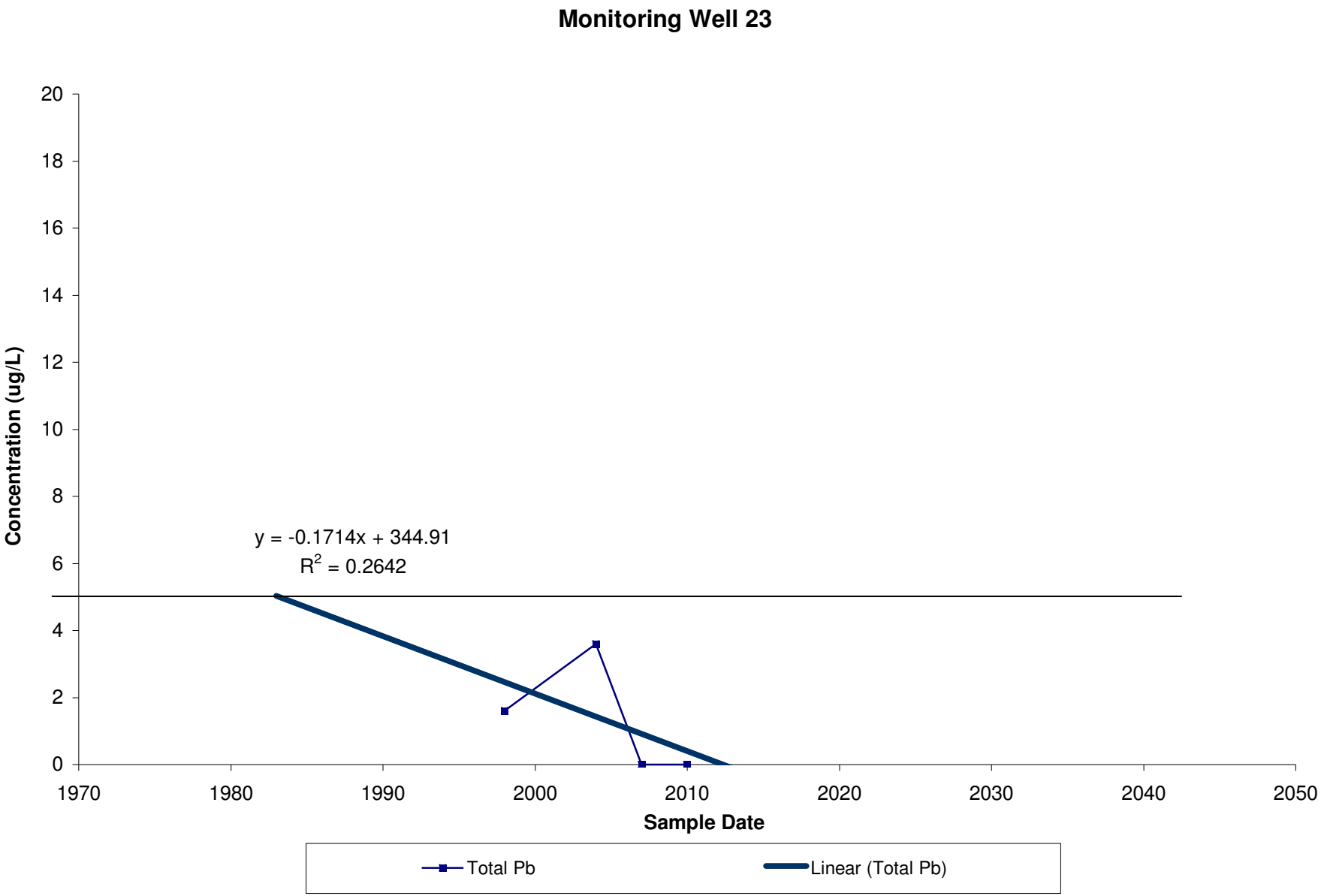
500367


Monitoring Well 22
Concentration (ug/L)
20
18
16
14
12
10
8
6
4
2
0
y = -0.2171x + 437.16
R2 = 0.1714
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

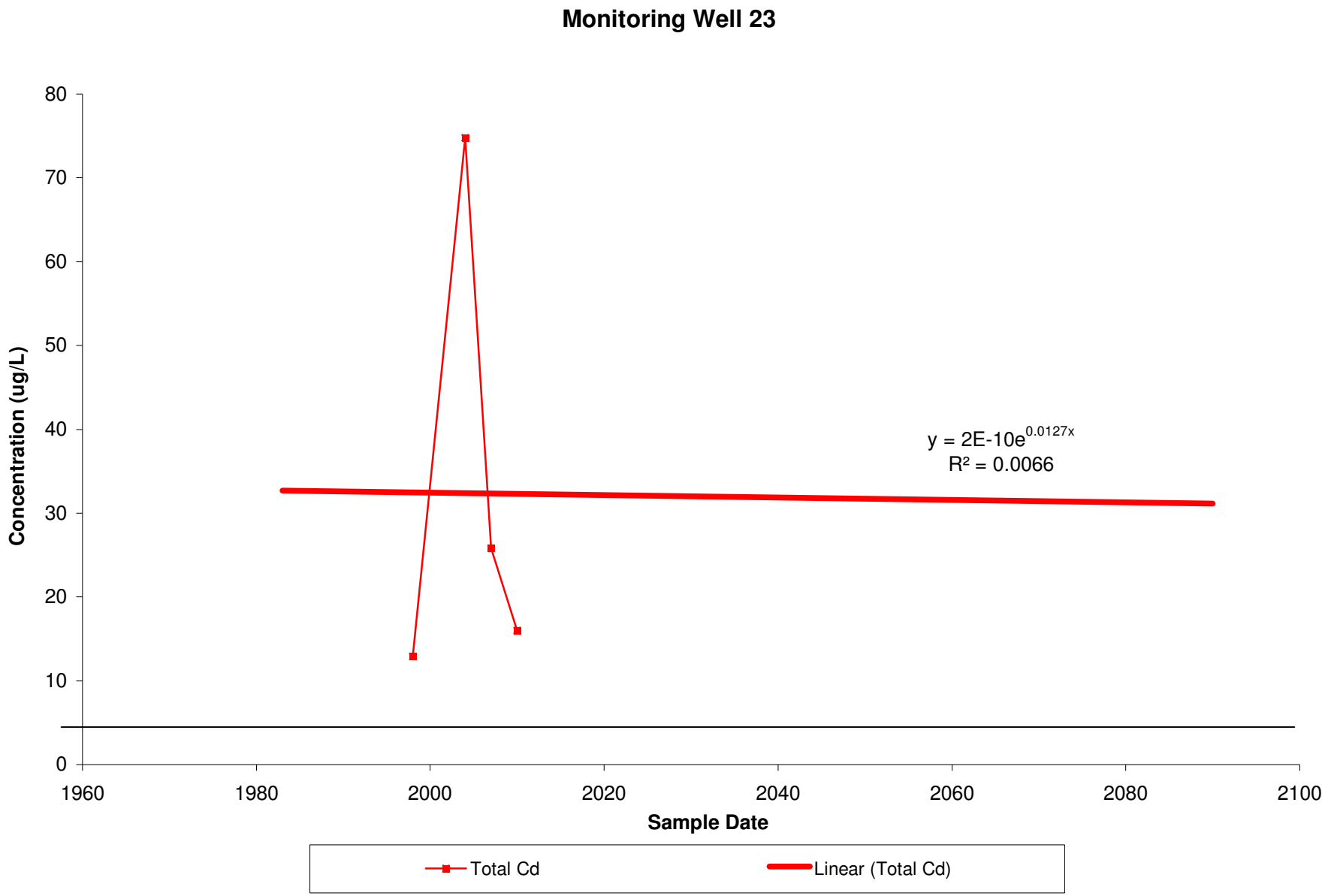
500368


Monitoring Well 22
y = 1E+236e^-0.2697x
R^2 = 0.9962
120
100
80
60
40
20
0
Concentration (ug/L)
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Expon. (Total Cd)

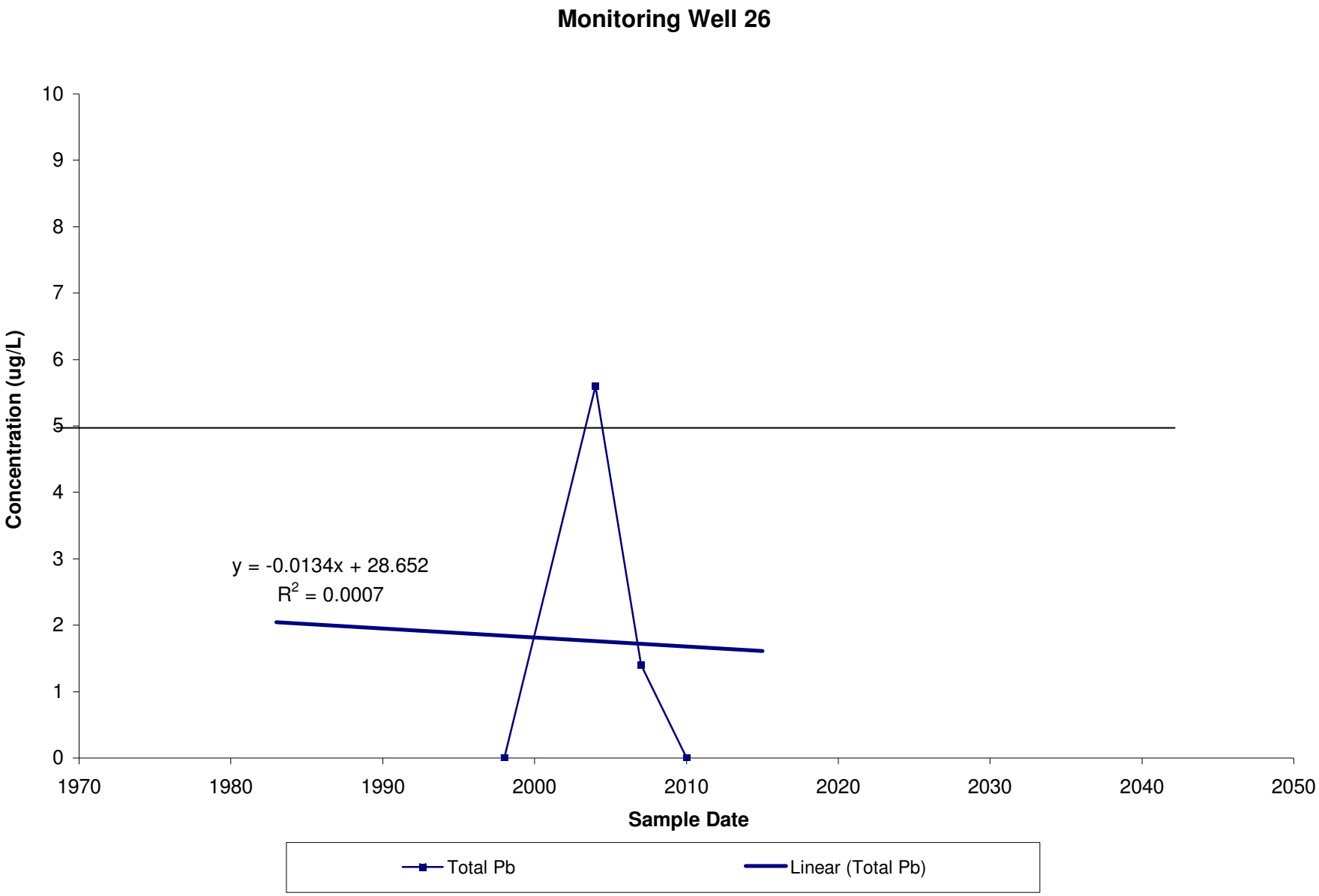
500369


Monitoring Well 23
Concentration (ug/L)
20
18
16
14
12
10
8
6
4
2
0
y = -0.1714x + 344.91
R2 = 0.2642
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

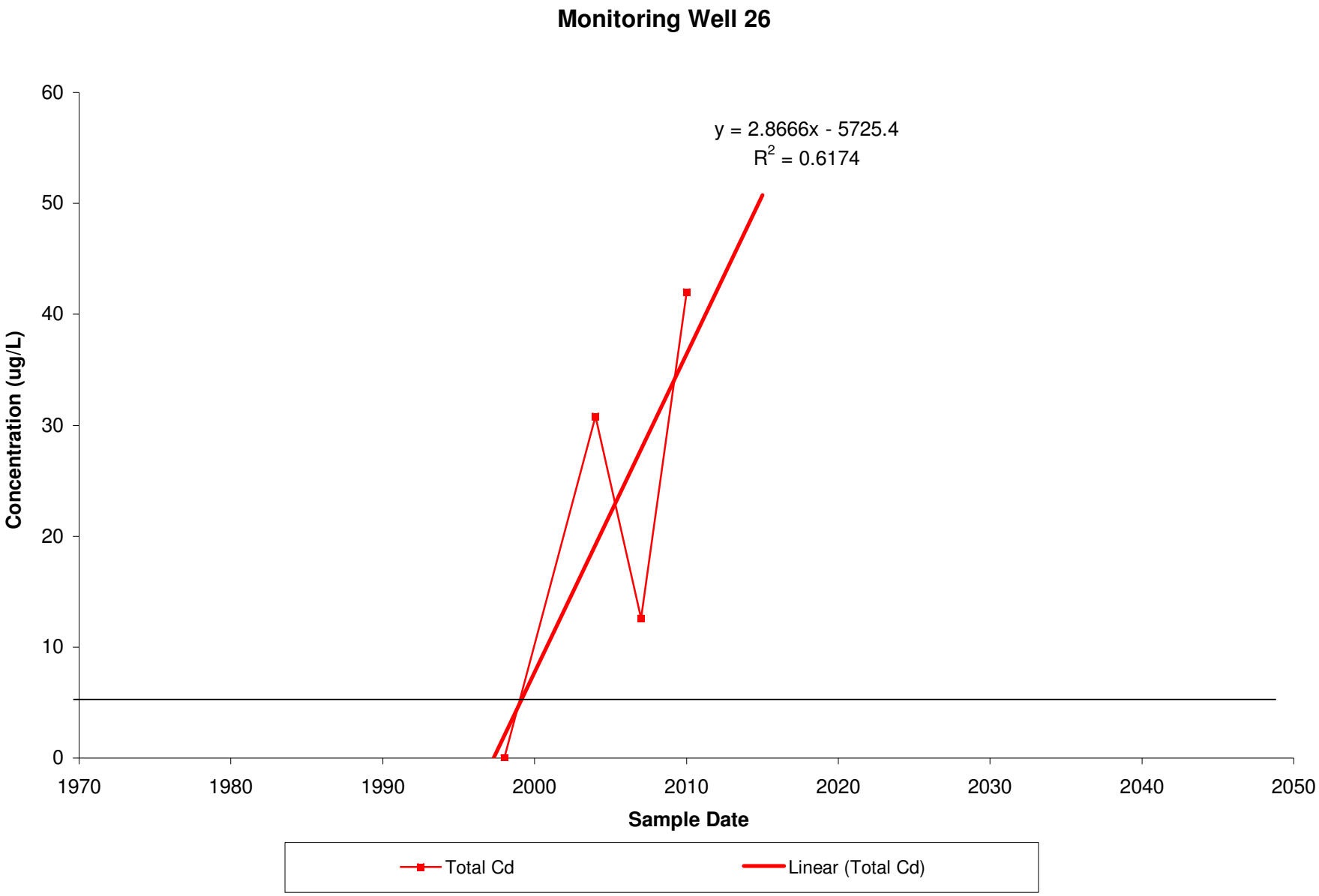
500370


Monitoring Well 23
Concentration (ug/L)
80
70
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
2060
2080
2100
Sample Date
y = 2E-10e^0.0127x
R² = 0.0066
Total Cd
Linear (Total Cd)

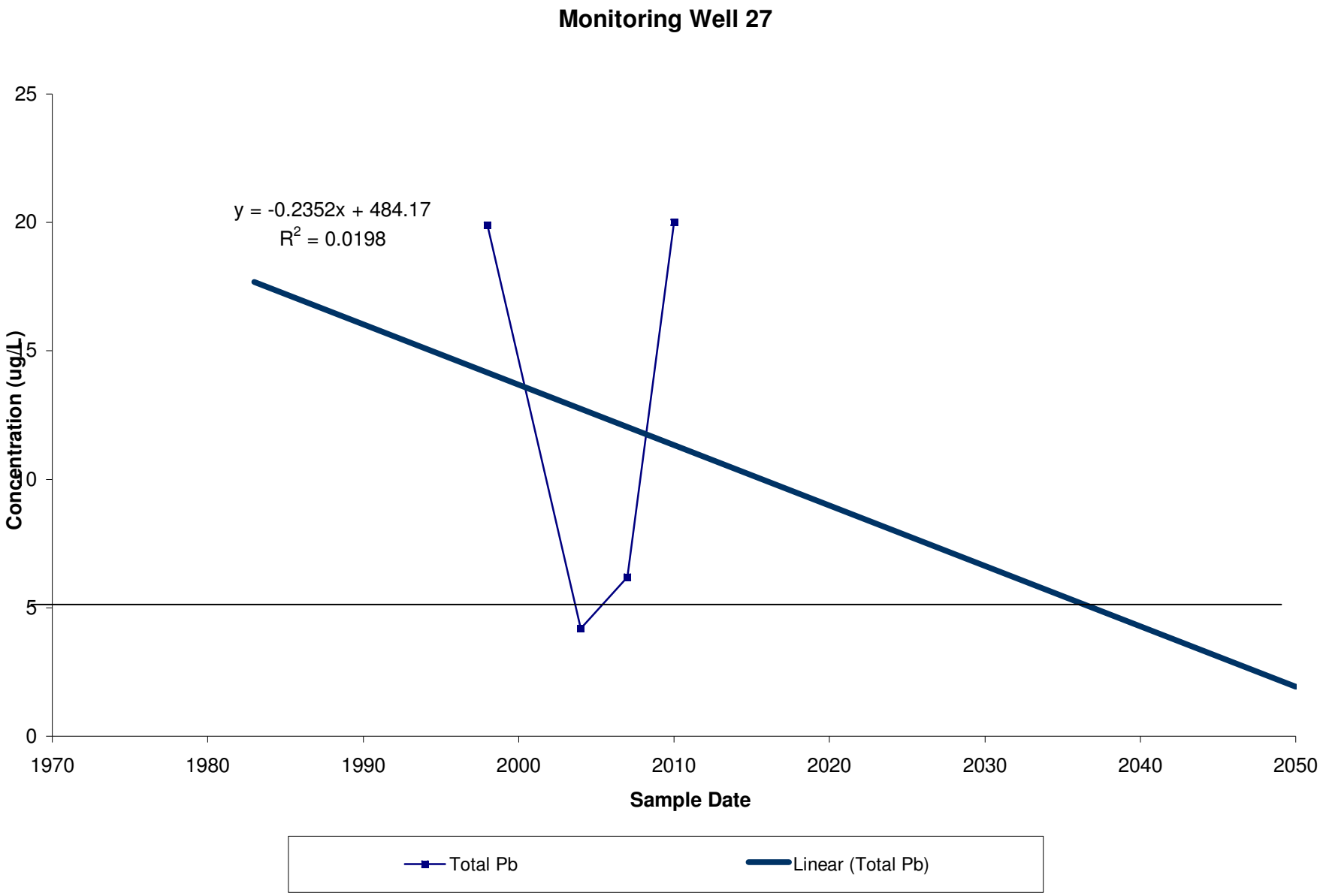
500371


Monitoring Well 26
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -0.0134x + 28.652
R2 = 0.0007
Total Pb
Linear (Total Pb)

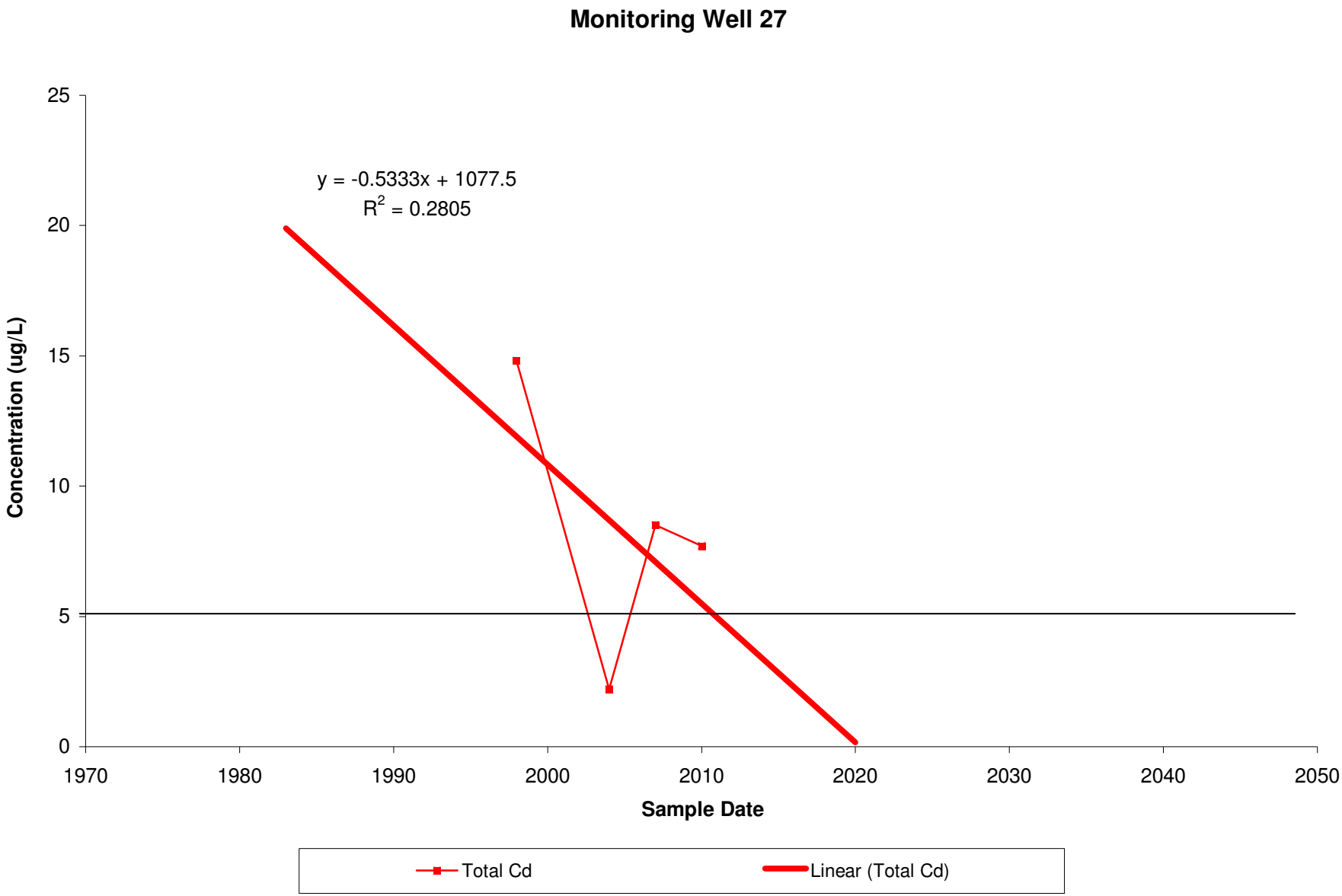
500372


Monitoring Well 26
y = 2.8666x - 5725.4
R2 = 0.6174
Concentration (ug/L)
60
50
40
30
20
10
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

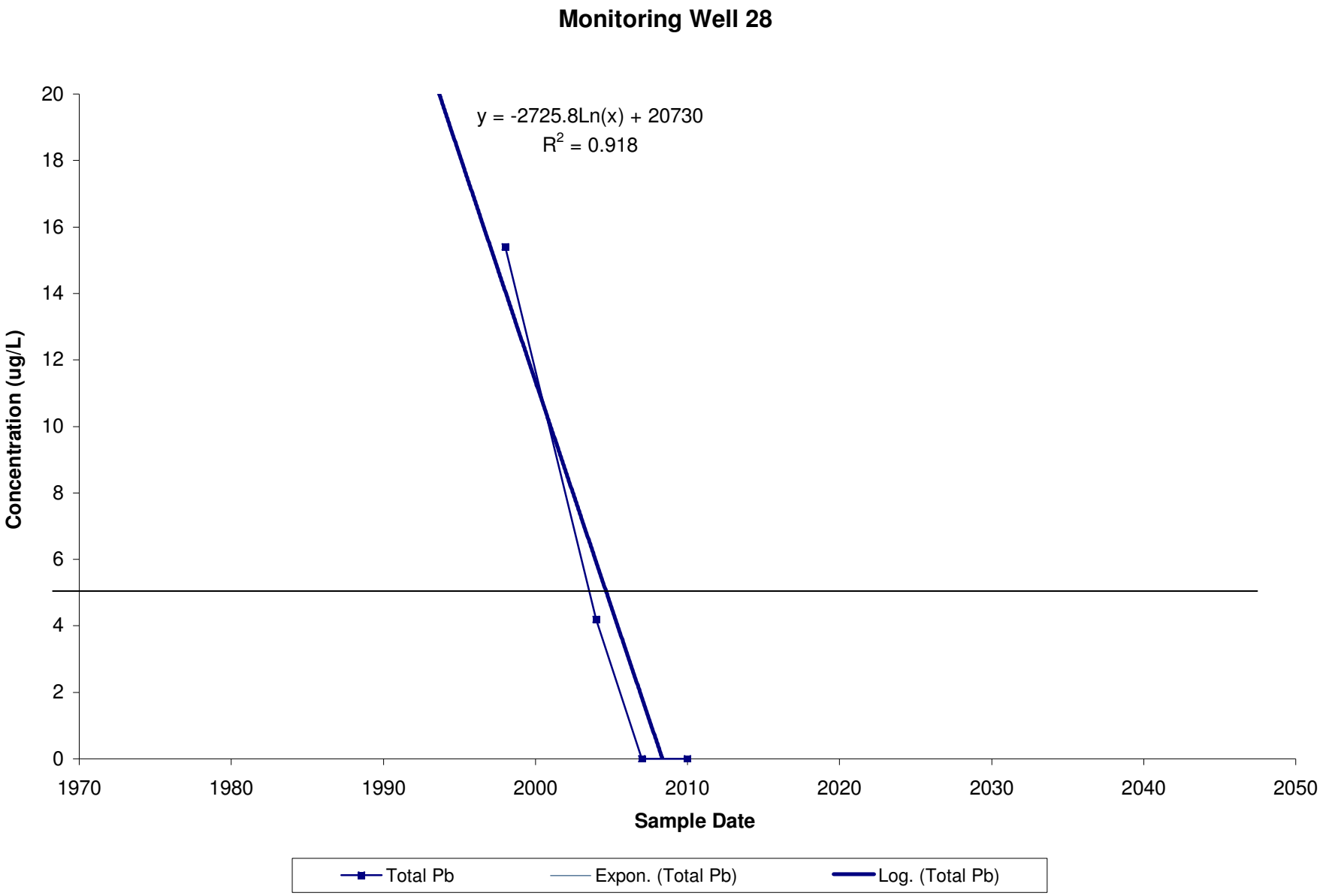
500373


Monitoring Well 27
y = -0.2352x + 484.17
R2 = 0.0198
Concentration (ug/L)
25
20
15
10
5
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

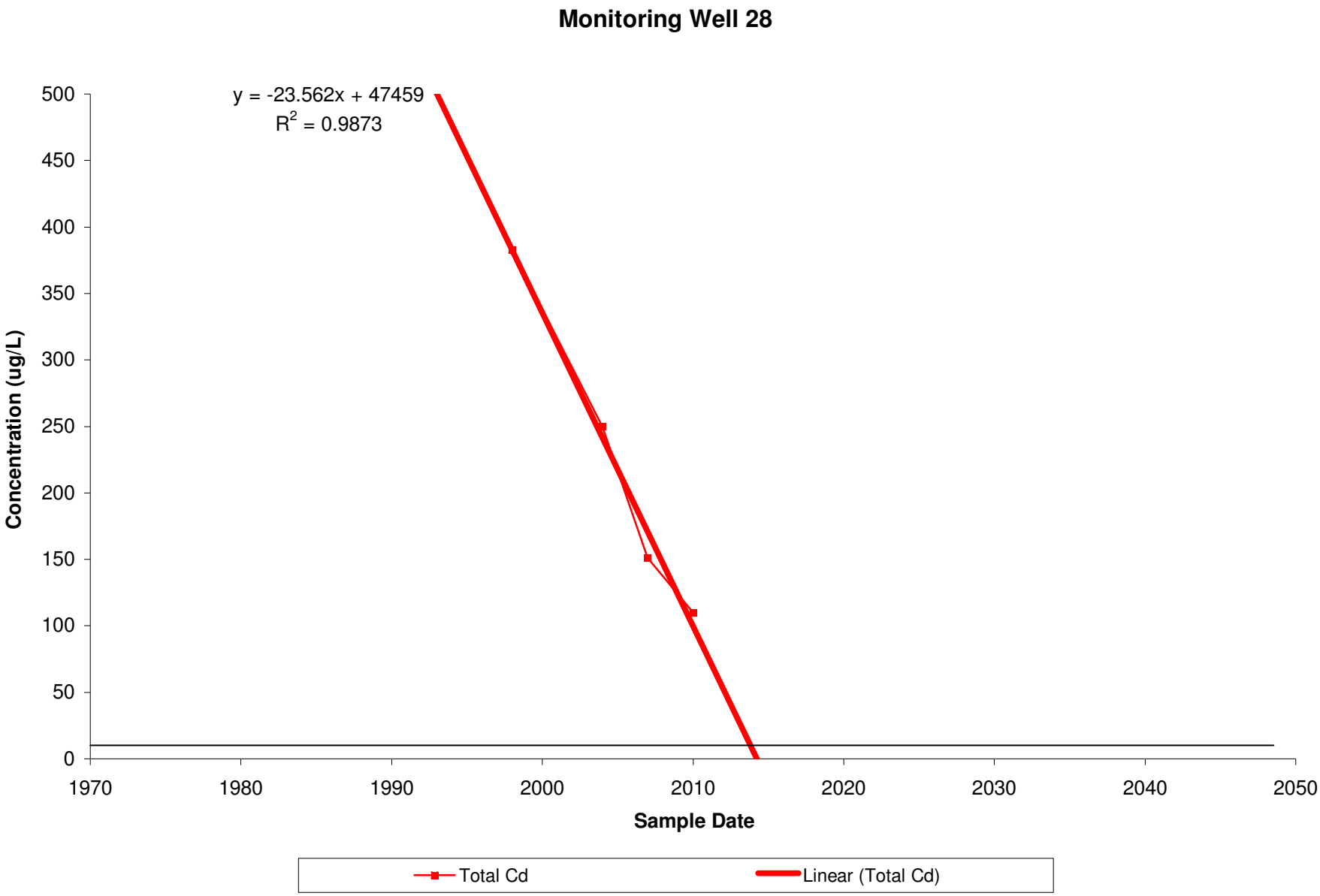
500374

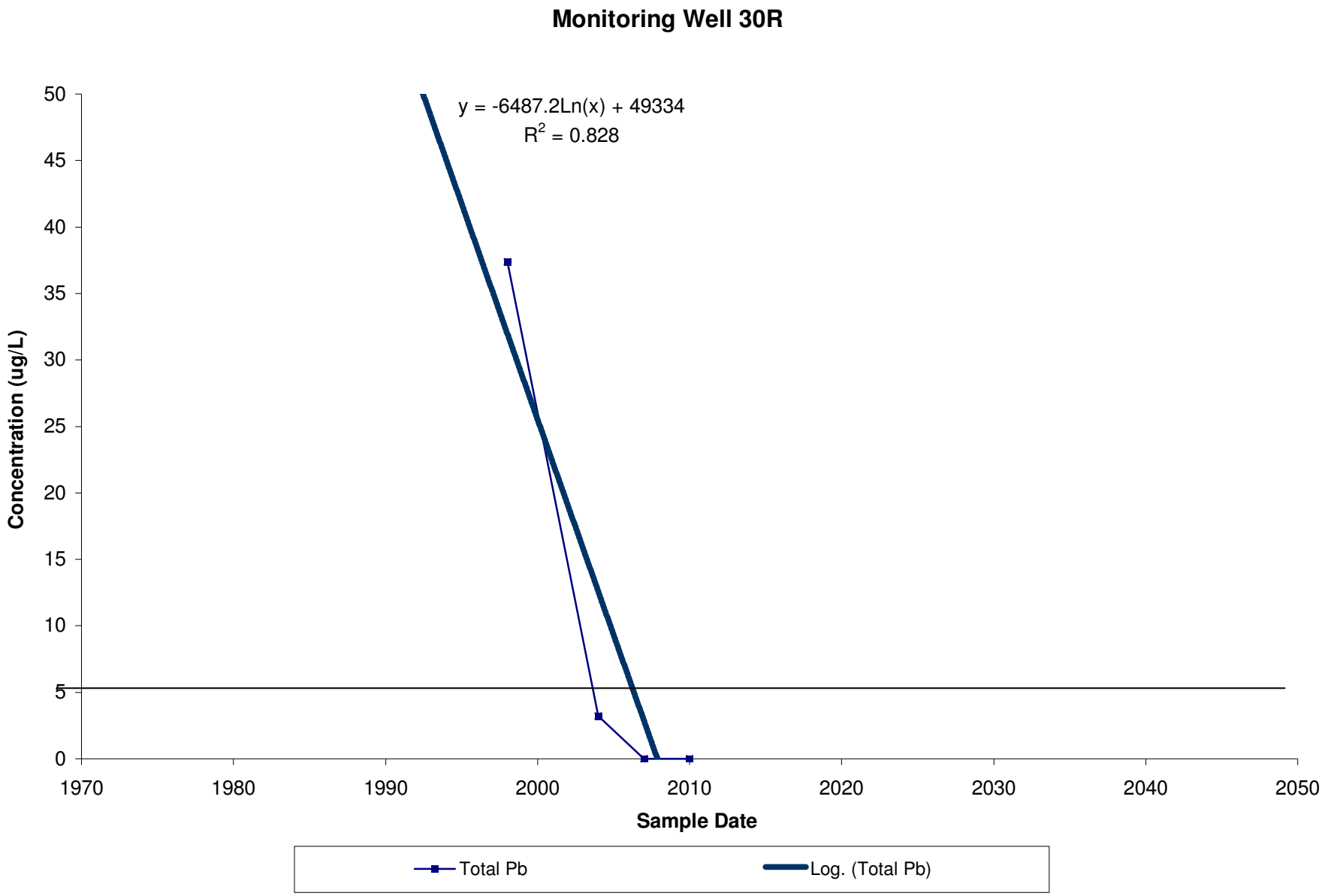

Monitoring Well 27
y = -0.5333x + 1077.5
R2 = 0.2805
Concentration (ug/L)
25
20
15
10
5
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

500375

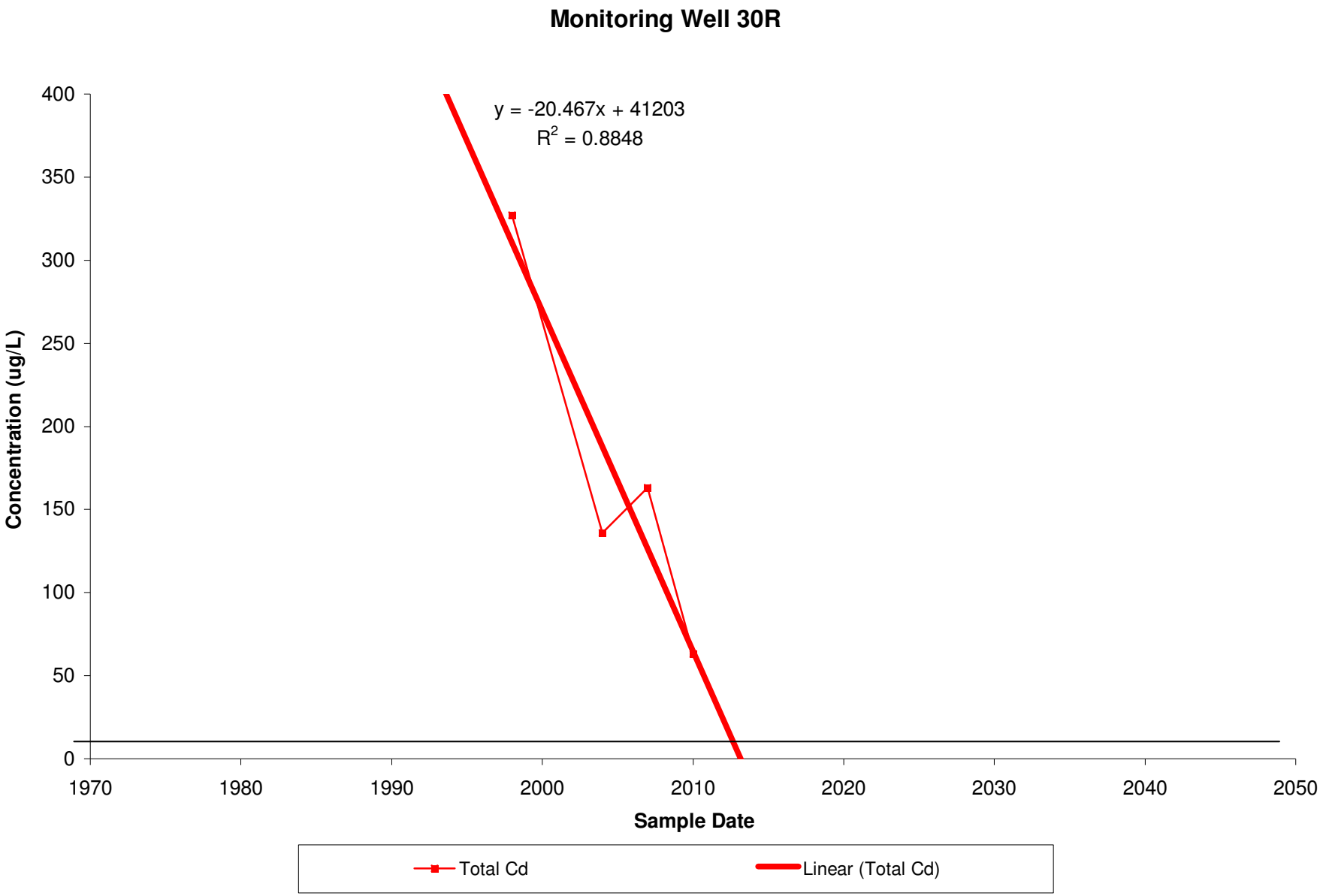

Monitoring Well 28
y = -2725.8Ln(x) + 20730
R2 = 0.918
Concentration (ug/L)
20
18
16
14
12
10
8
6
4
2
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Expon. (Total Pb)
Log. (Total Pb)

500376

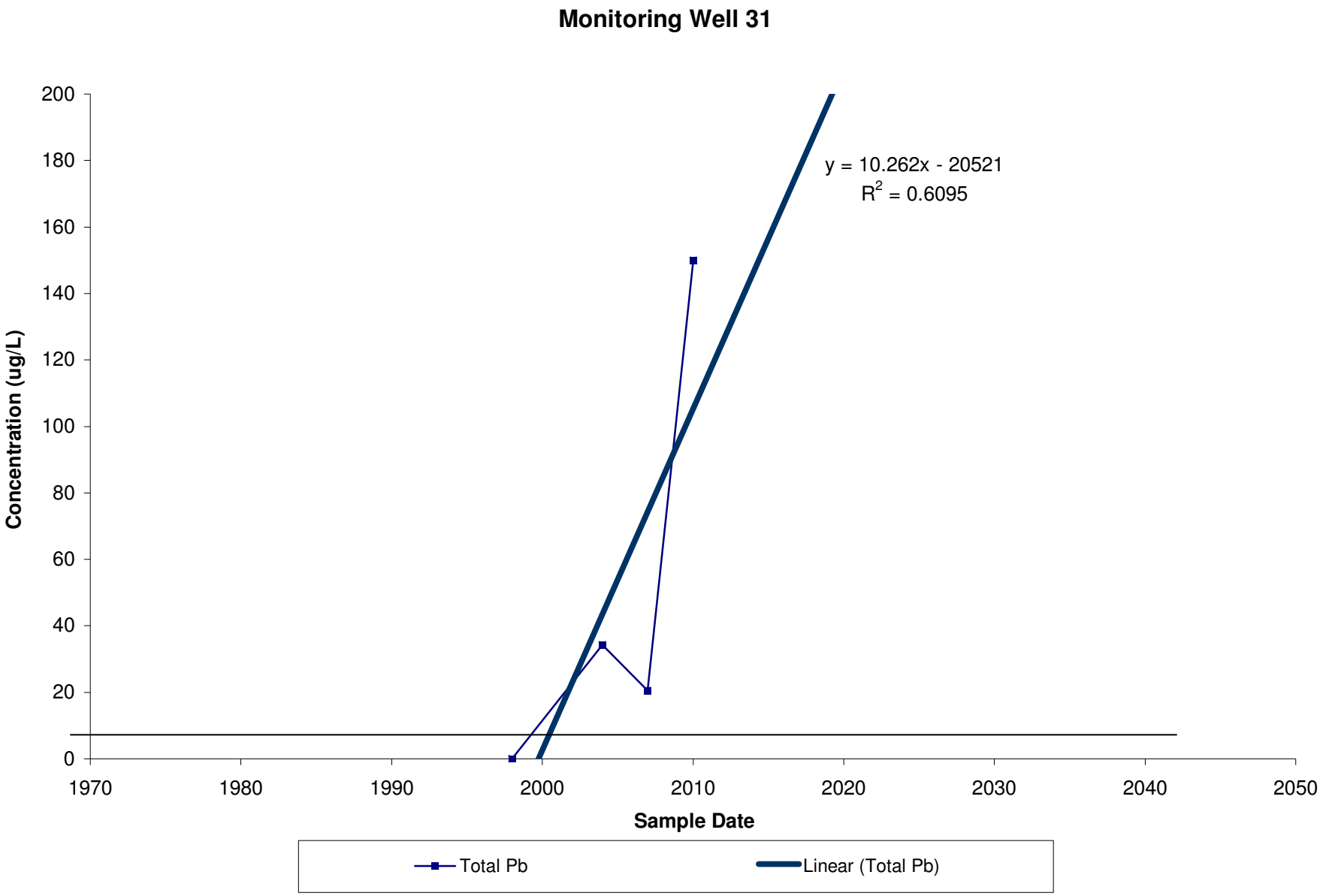

Monitoring Well 28
y = -23.562x + 47459
R2 = 0.9873
500
450
400
350
300
250
200
150
100
50
0
Concentration (ug/L)
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)


Monitoring Well 30R
y = -6487.2Ln(x) + 49334
R2 = 0.828
Concentration (ug/L)
50
45
40
35
30
25
20
15
10
5
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Log. (Total Pb)

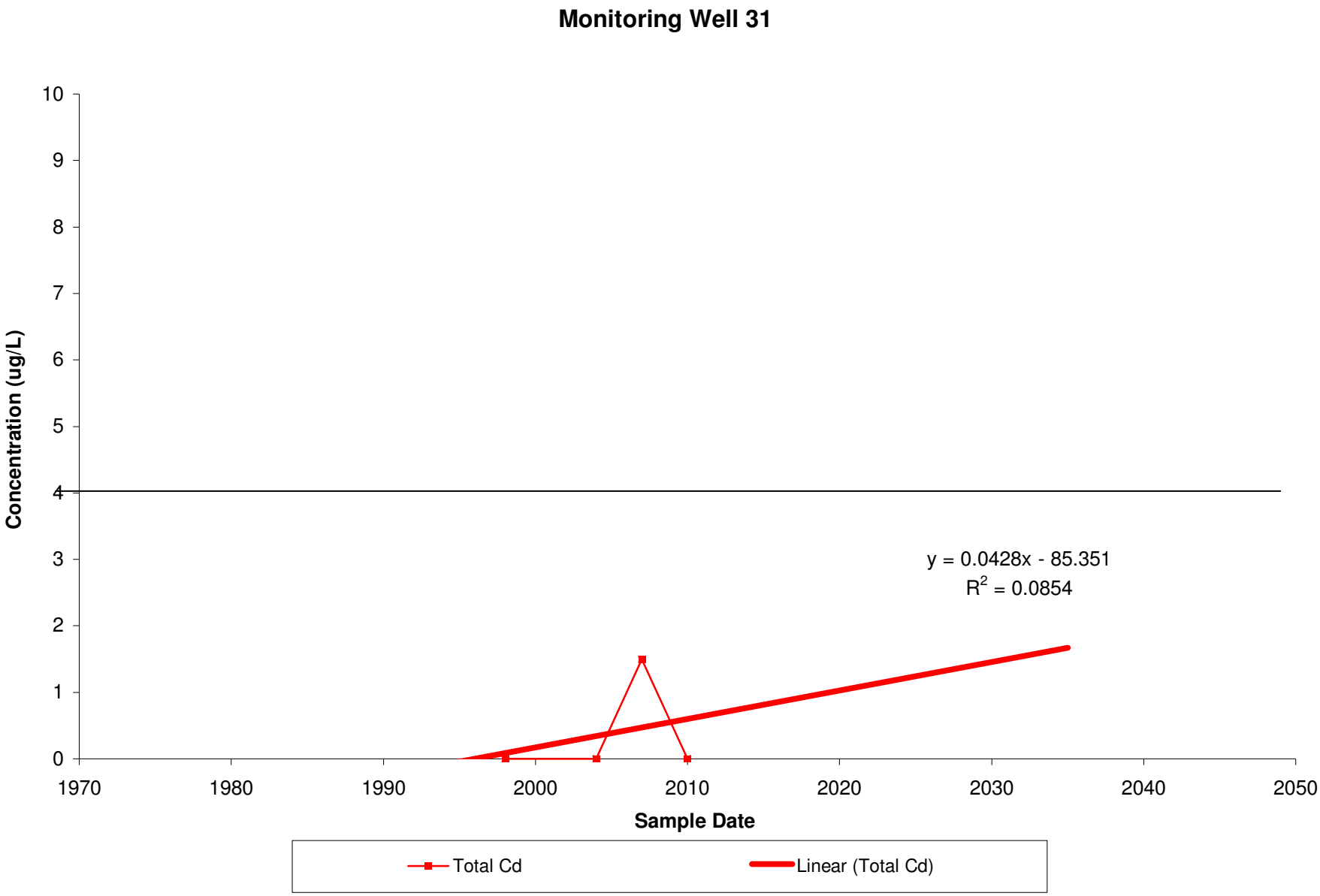
500378


Monitoring Well 30R
y = -20.467x + 41203
R2 = 0.8848
Concentration (ug/L)
400
350
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

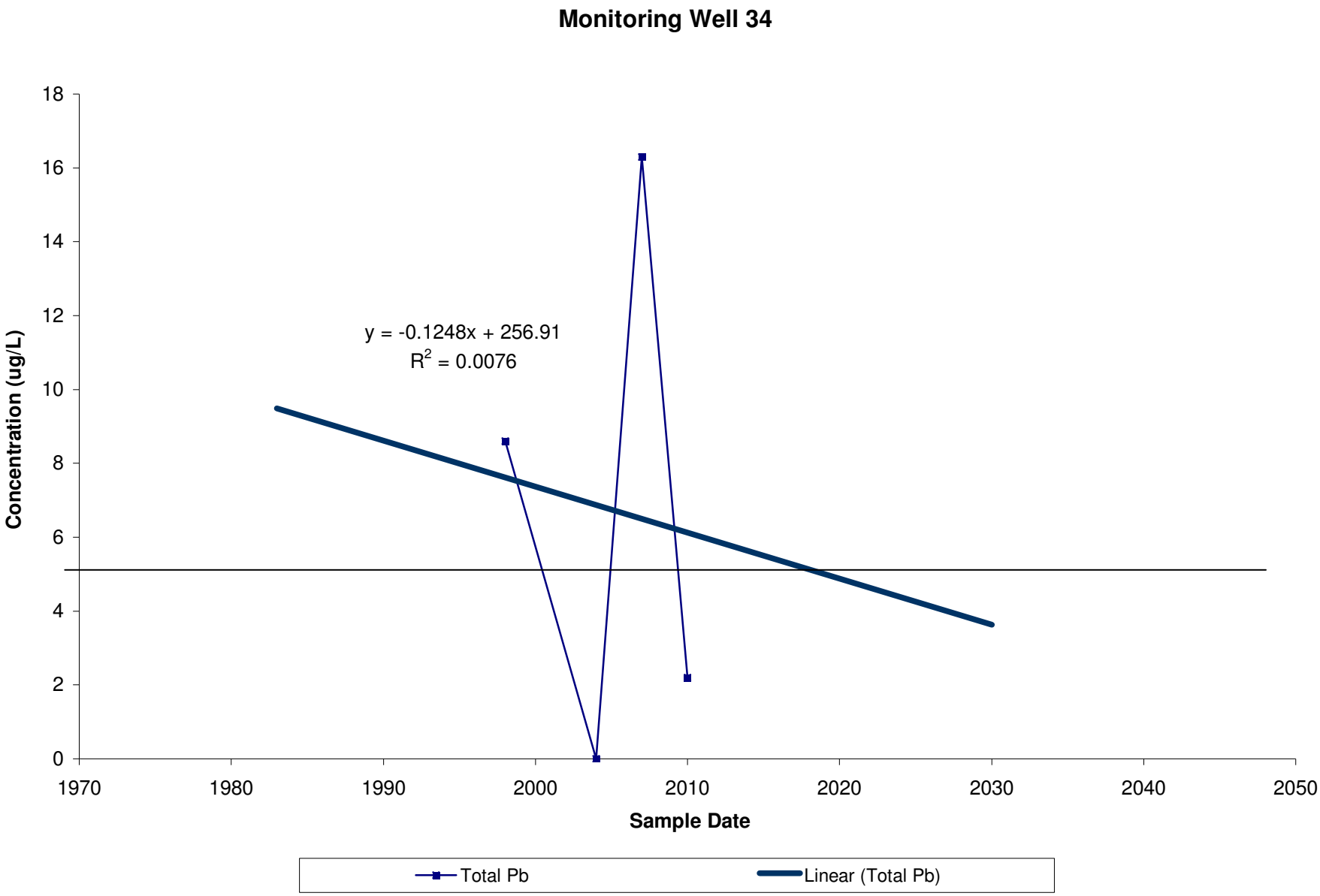
500379


Monitoring Well 31
y = 10.262x - 20521
R2 = 0.6095
Concentration (ug/L)
200
180
160
140
120
100
80
60
40
20
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

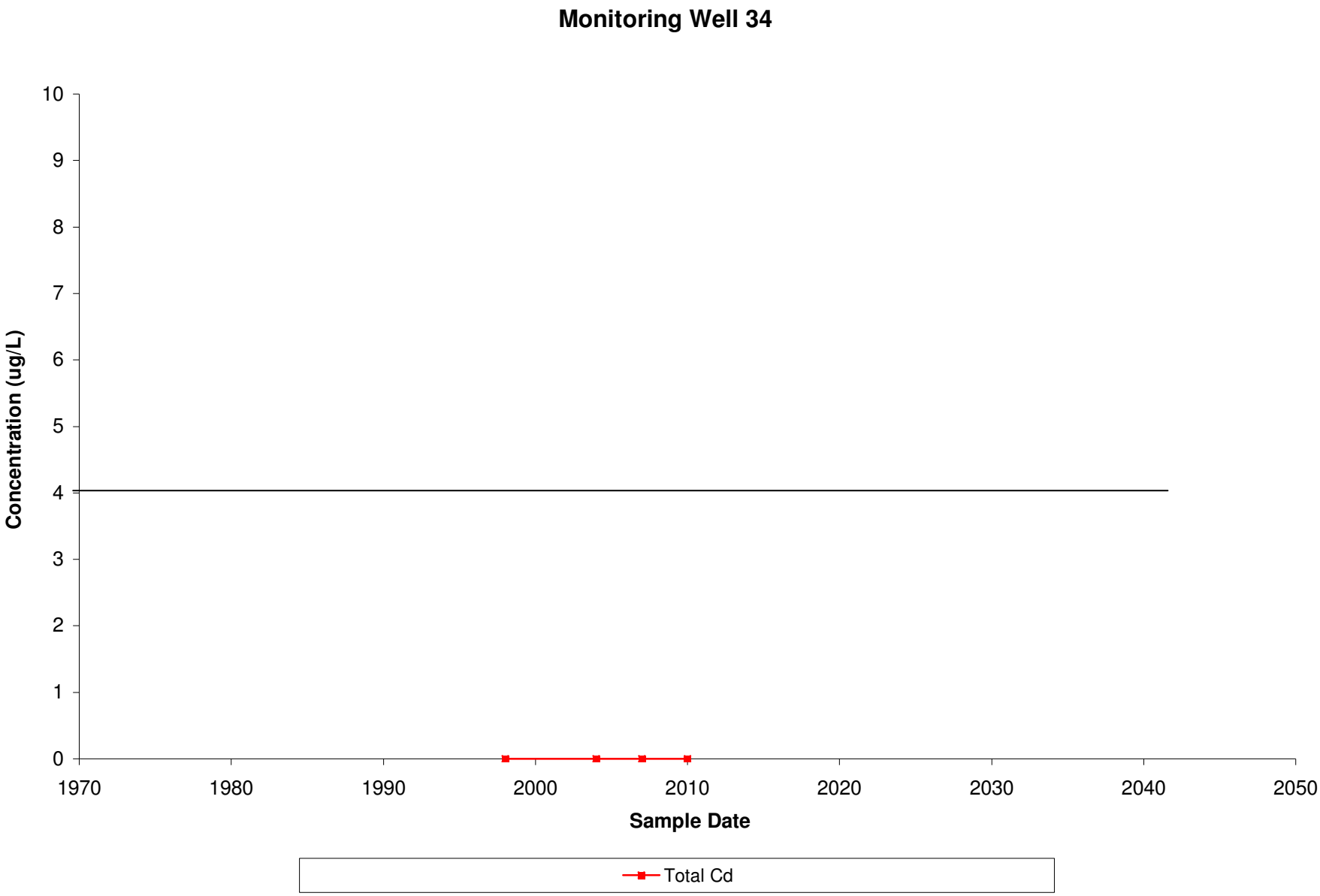
500380


Monitoring Well 31
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = 0.0428x - 85.351
R2 = 0.0854
Total Cd
Linear (Total Cd)

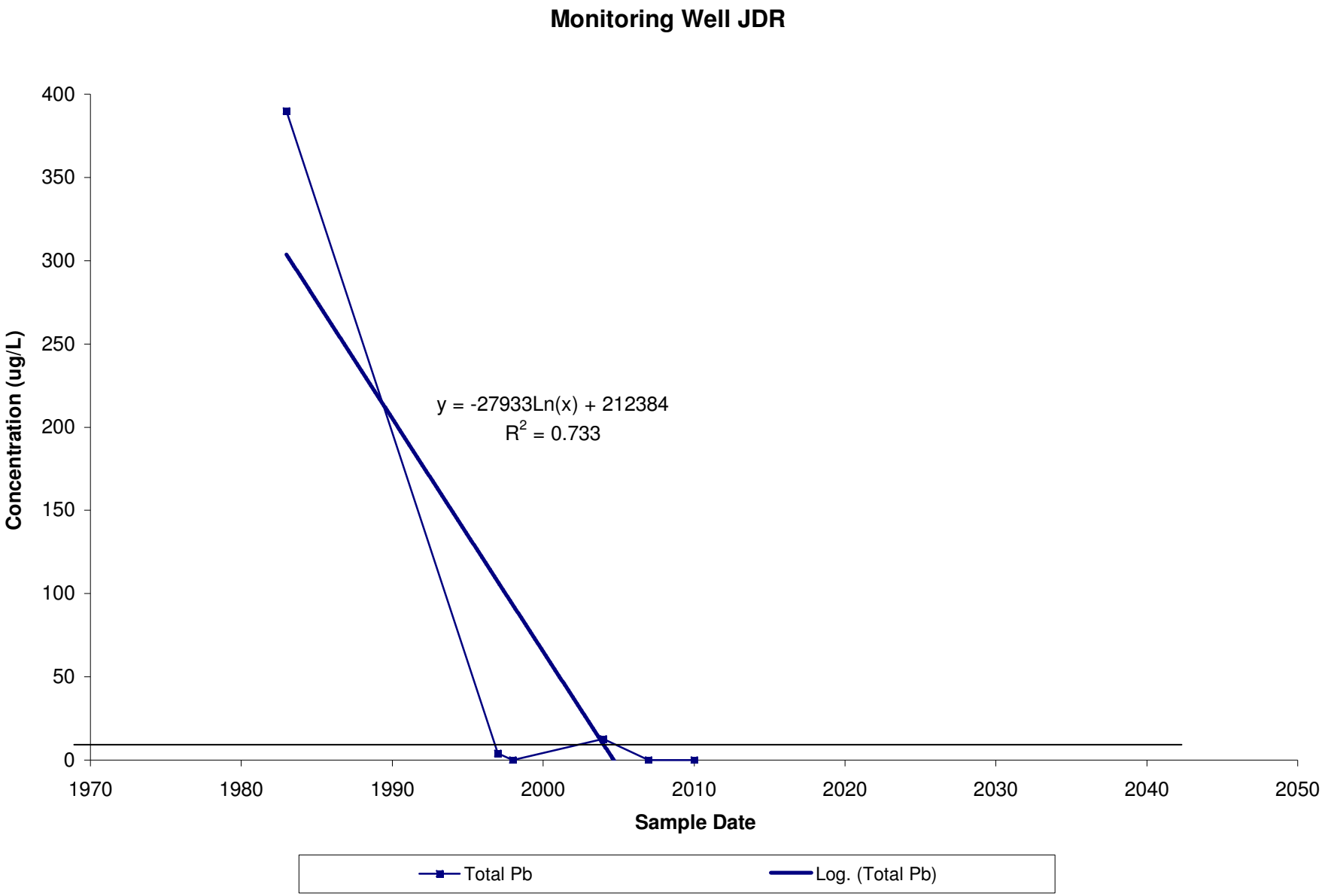
500381


Monitoring Well 34
Concentration (ug/L)
18
16
14
12
10
8
6
4
2
0
y = -0.1248x + 256.91
R2 = 0.0076
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

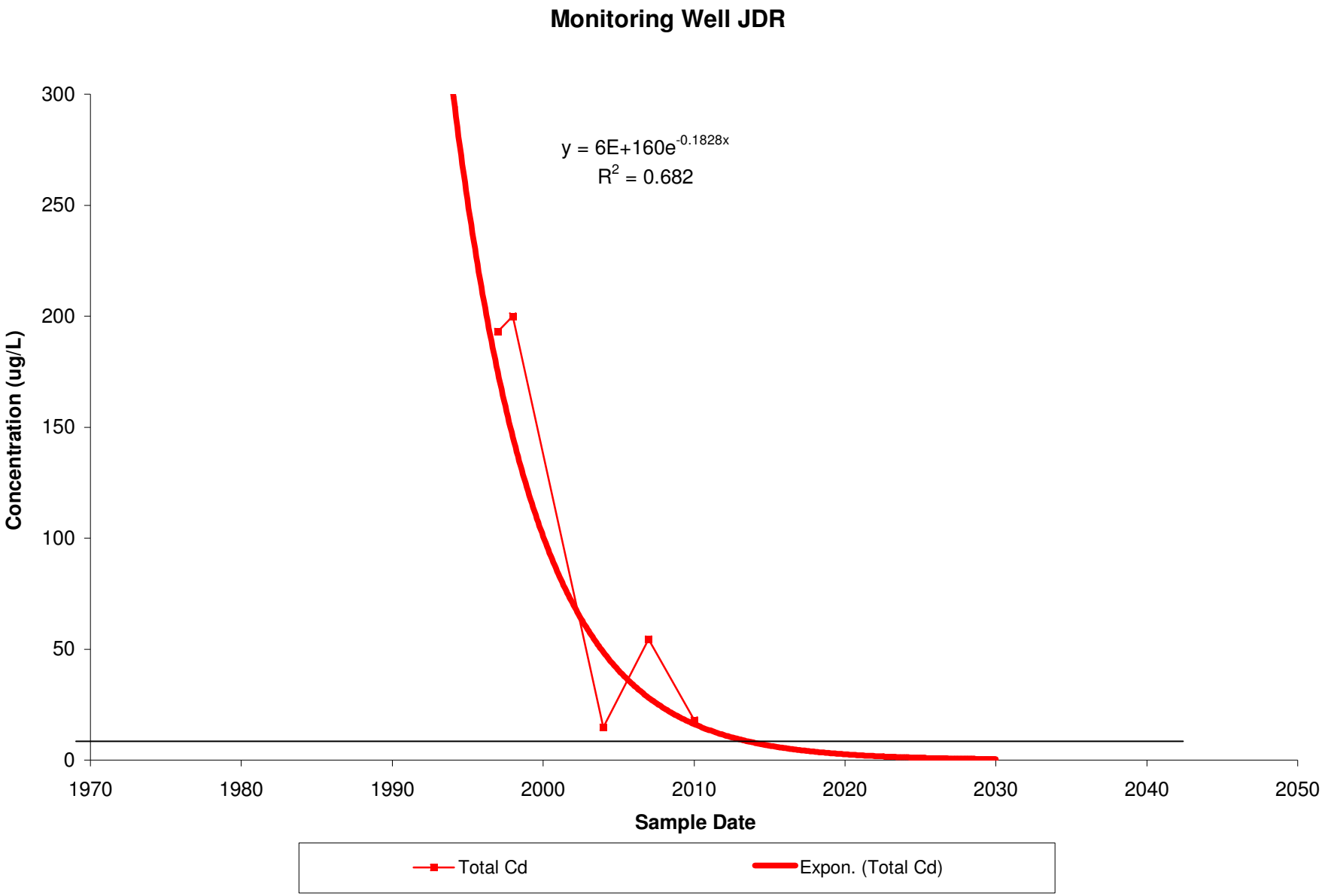
500382


Monitoring Well 34
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd

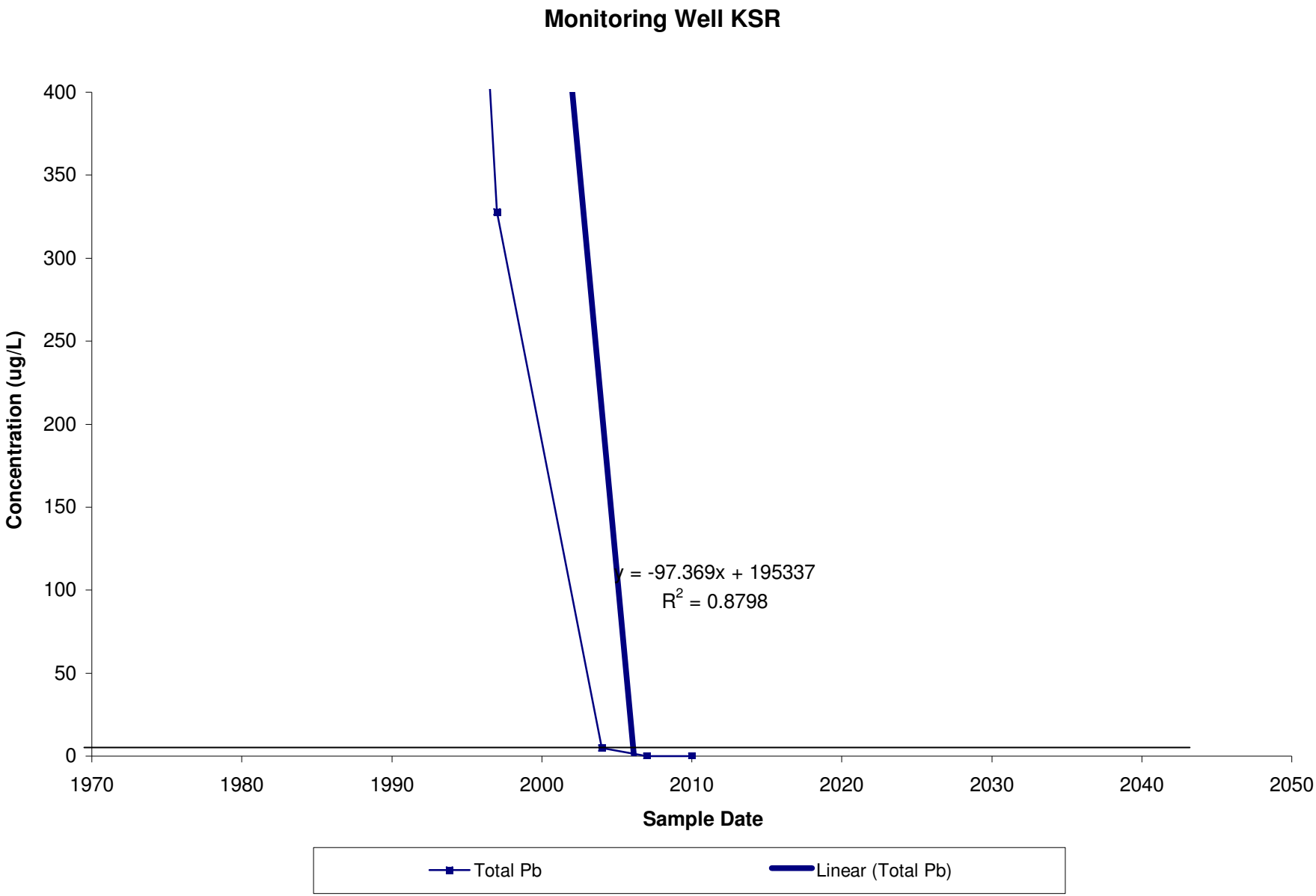
500383


Monitoring Well JDR
Concentration (ug/L)
400
350
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -27933Ln(x) + 212384
R2 = 0.733
Total Pb
Log. (Total Pb)

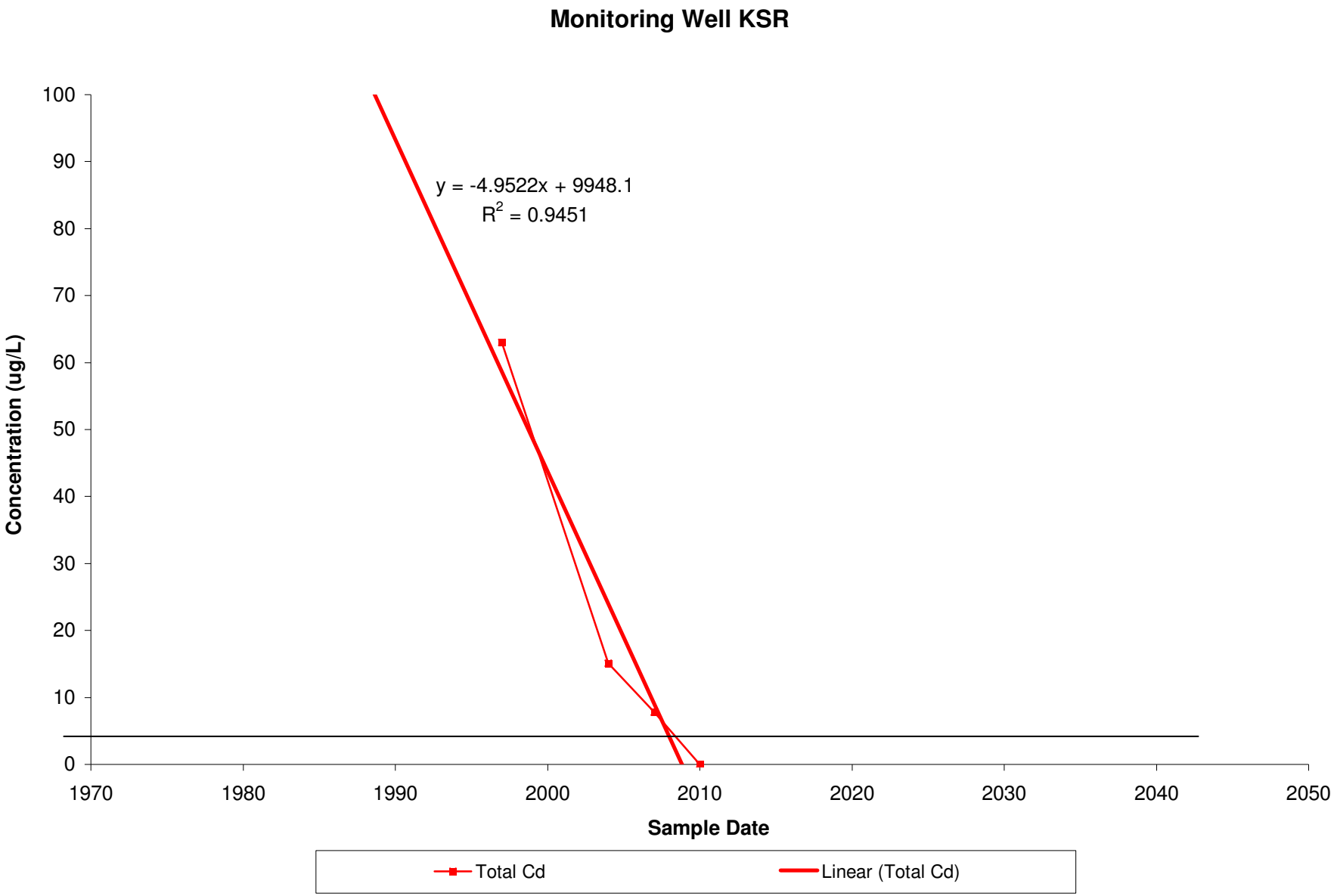
500384


Monitoring Well JDR
y = 6E+160e^-0.1828x
R^2 = 0.682
Concentration (ug/L)
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Expon. (Total Cd)

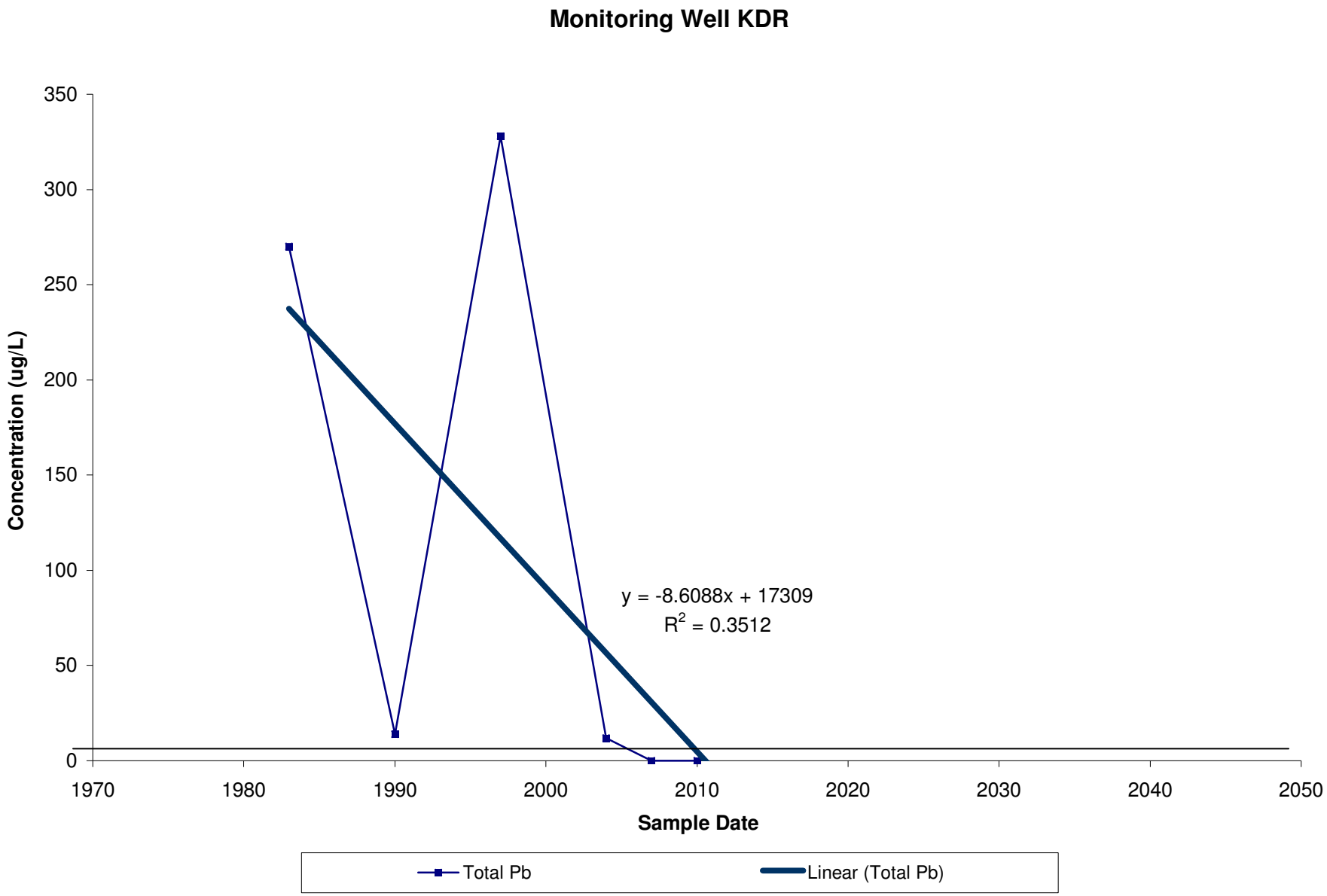
500385


Monitoring Well KSR
Concentration (ug/L)
400
350
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -97.369x + 195337
R2 = 0.8798
Total Pb
Linear (Total Pb)

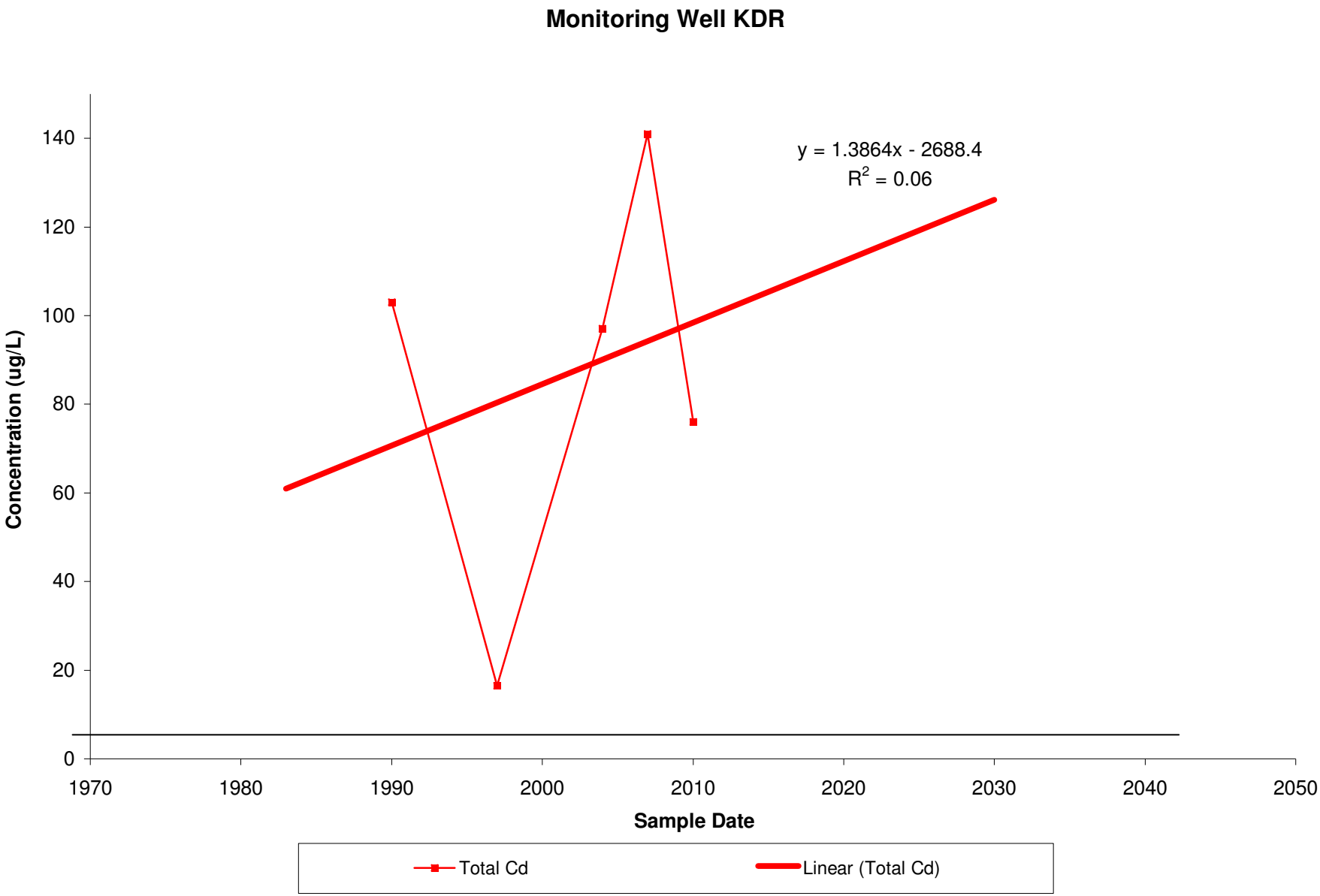
500386


Monitoring Well KSR
y = -4.9522x + 9948.1
R2 = 0.9451
Concentration (ug/L)
100
90
80
70
60
50
40
30
20
10
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

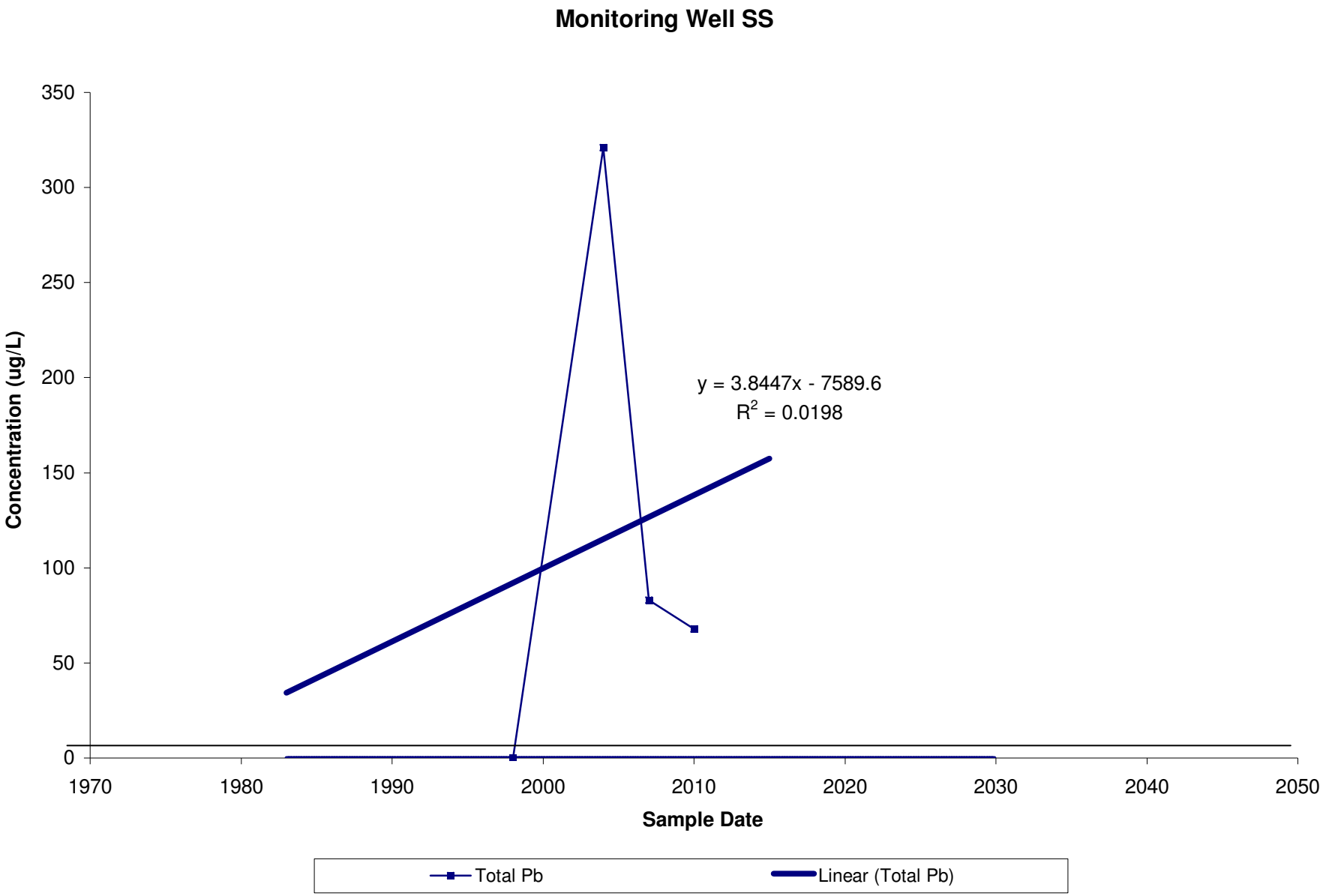
500387


Monitoring Well KDR
Concentration (ug/L)
350
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -8.6088x + 17309
R2 = 0.3512
Total Pb
Linear (Total Pb)

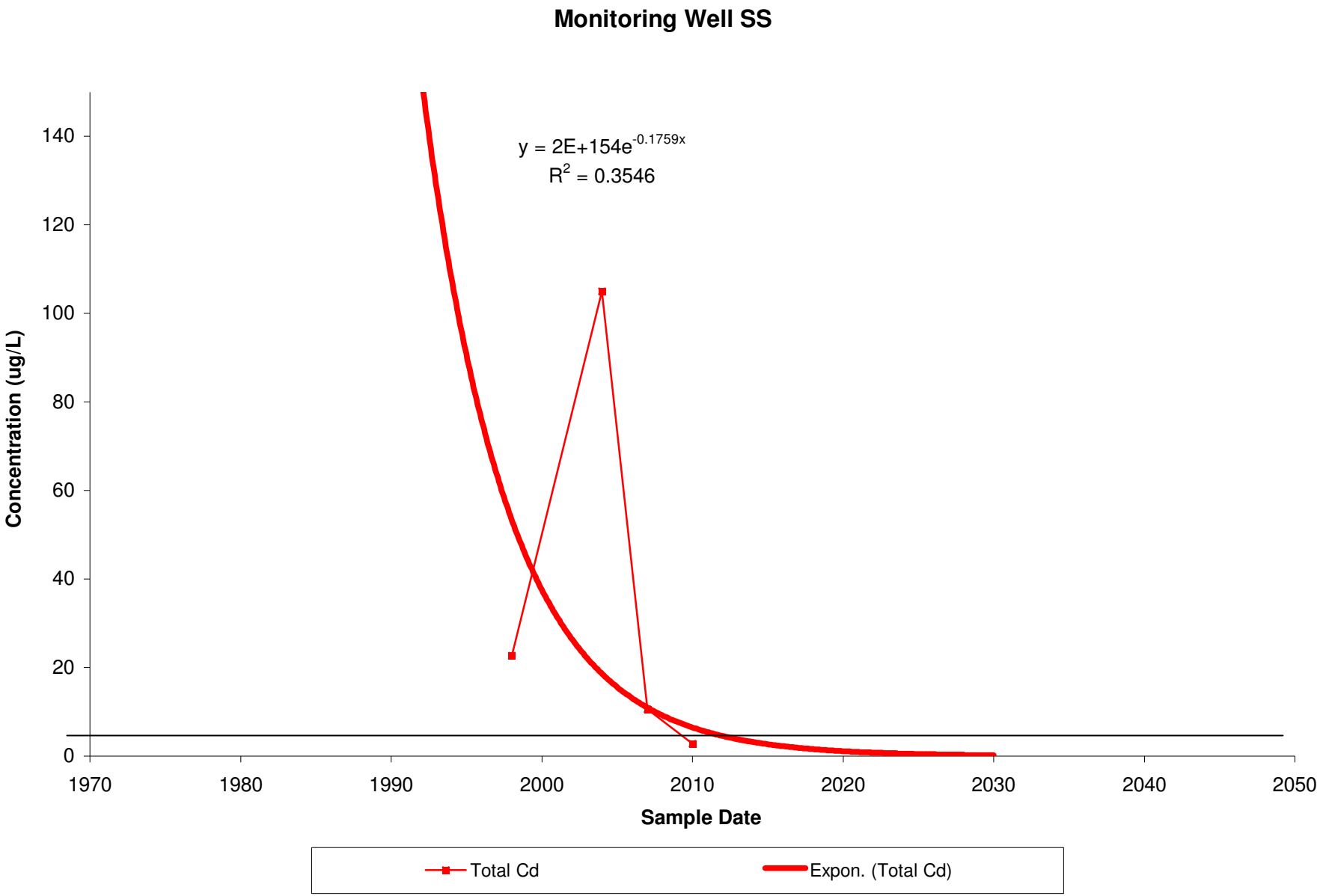
500388


Monitoring Well KDR
y = 1.3864x - 2688.4
R2 = 0.06
Concentration (ug/L)
0
20
40
60
80
100
120
140
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

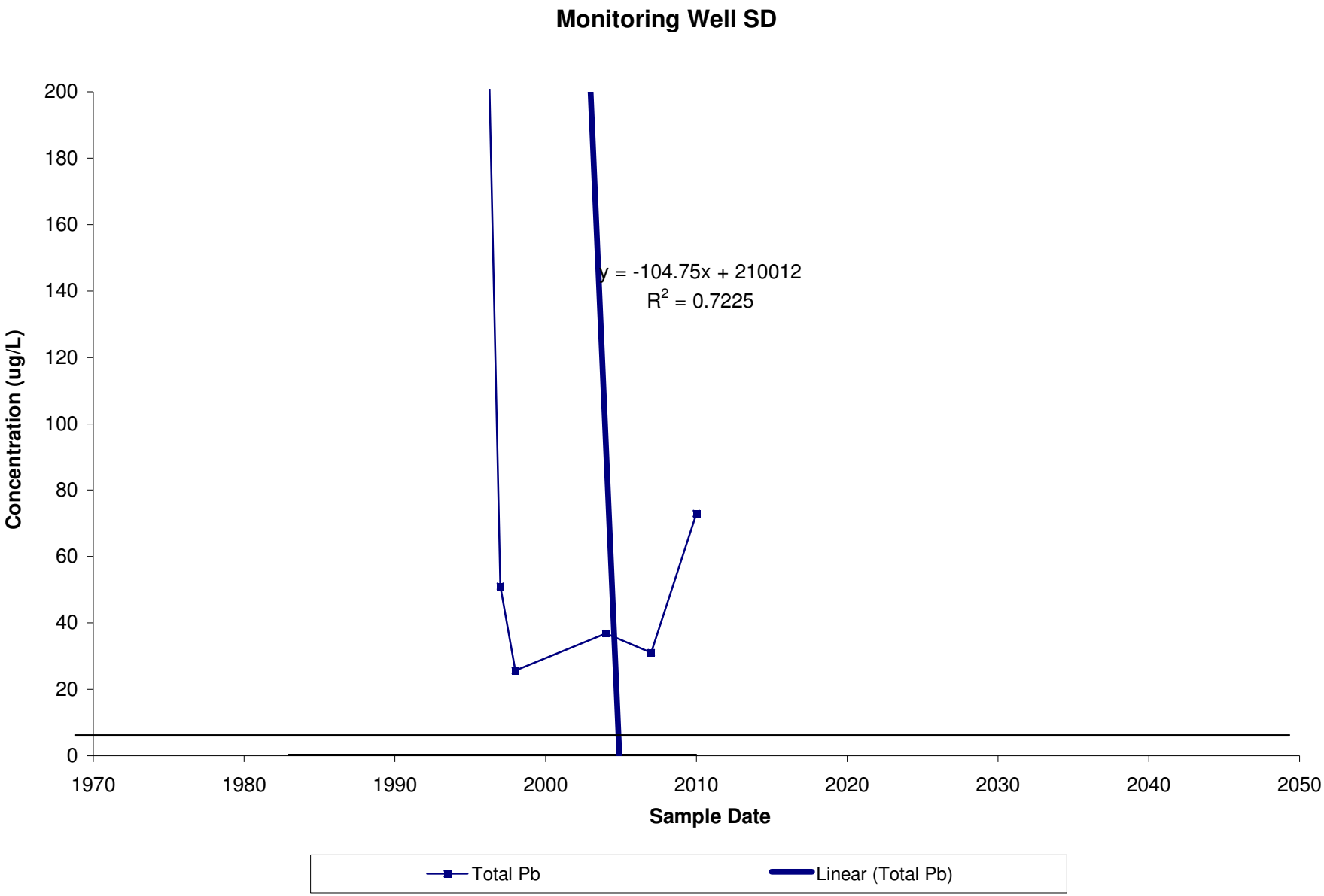
500389


Monitoring Well SS
350
300
250
200
150
100
50
0
Concentration (ug/L)
y = 3.8447x - 7589.6
R2 = 0.0198
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

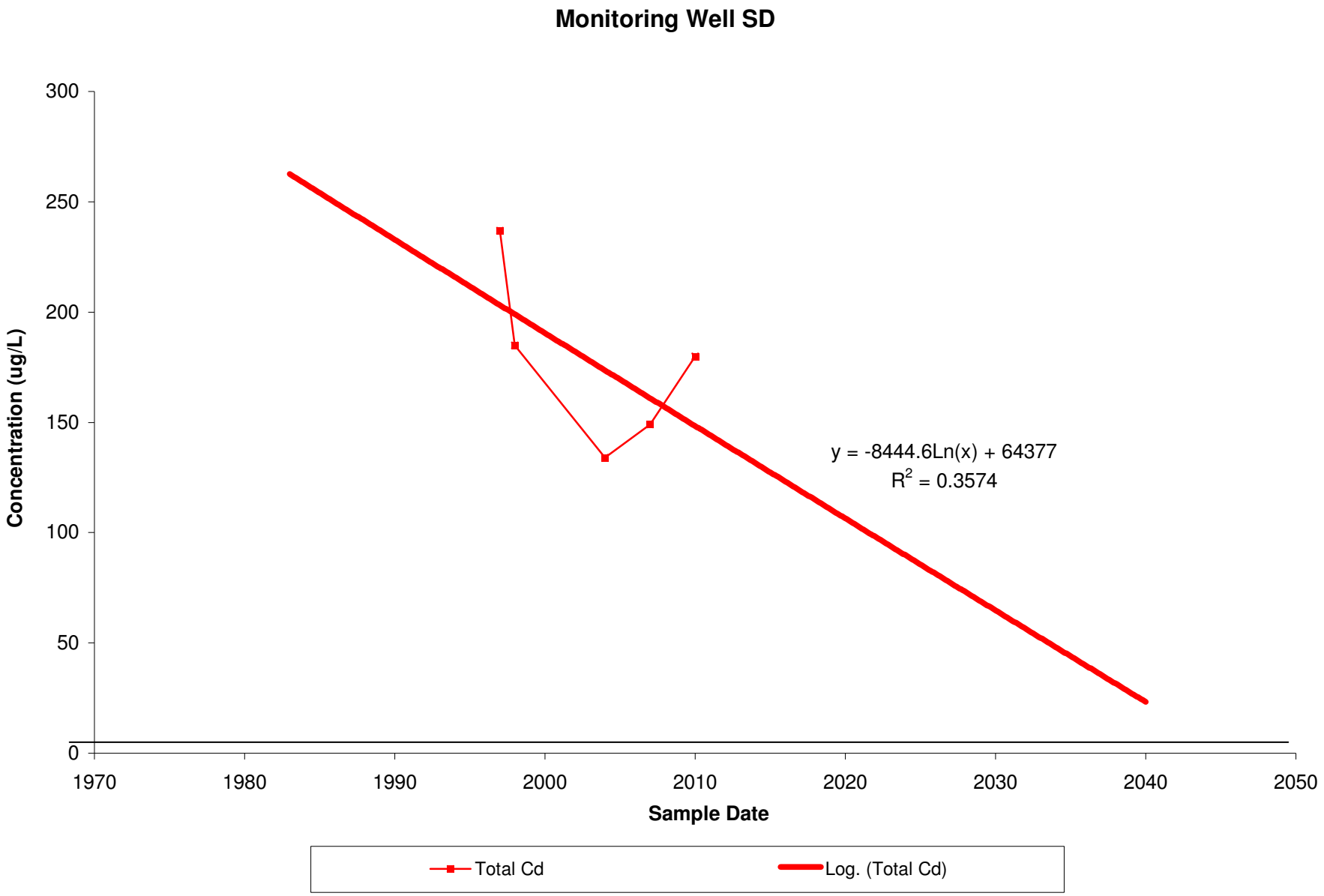
500390


Monitoring Well SS
y = 2E+154e^-0.1759x
R^2 = 0.3546
Concentration (ug/L)
140
120
100
80
60
40
20
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Expon. (Total Cd)

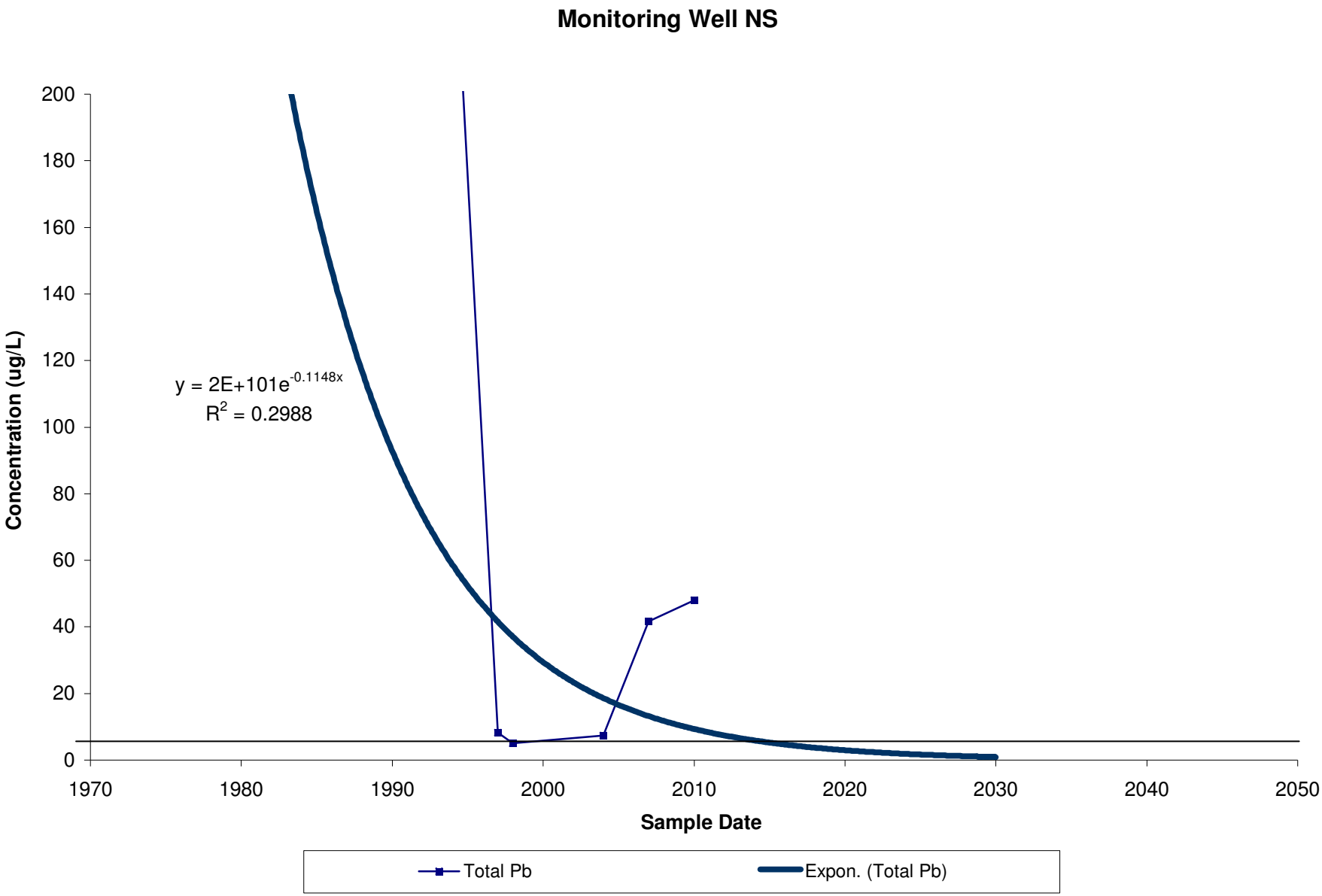
500391


Monitoring Well SD
Concentration (ug/L)
200
180
160
140
120
100
80
60
40
20
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -104.75x + 210012
R2 = 0.7225
Total Pb
Linear (Total Pb)

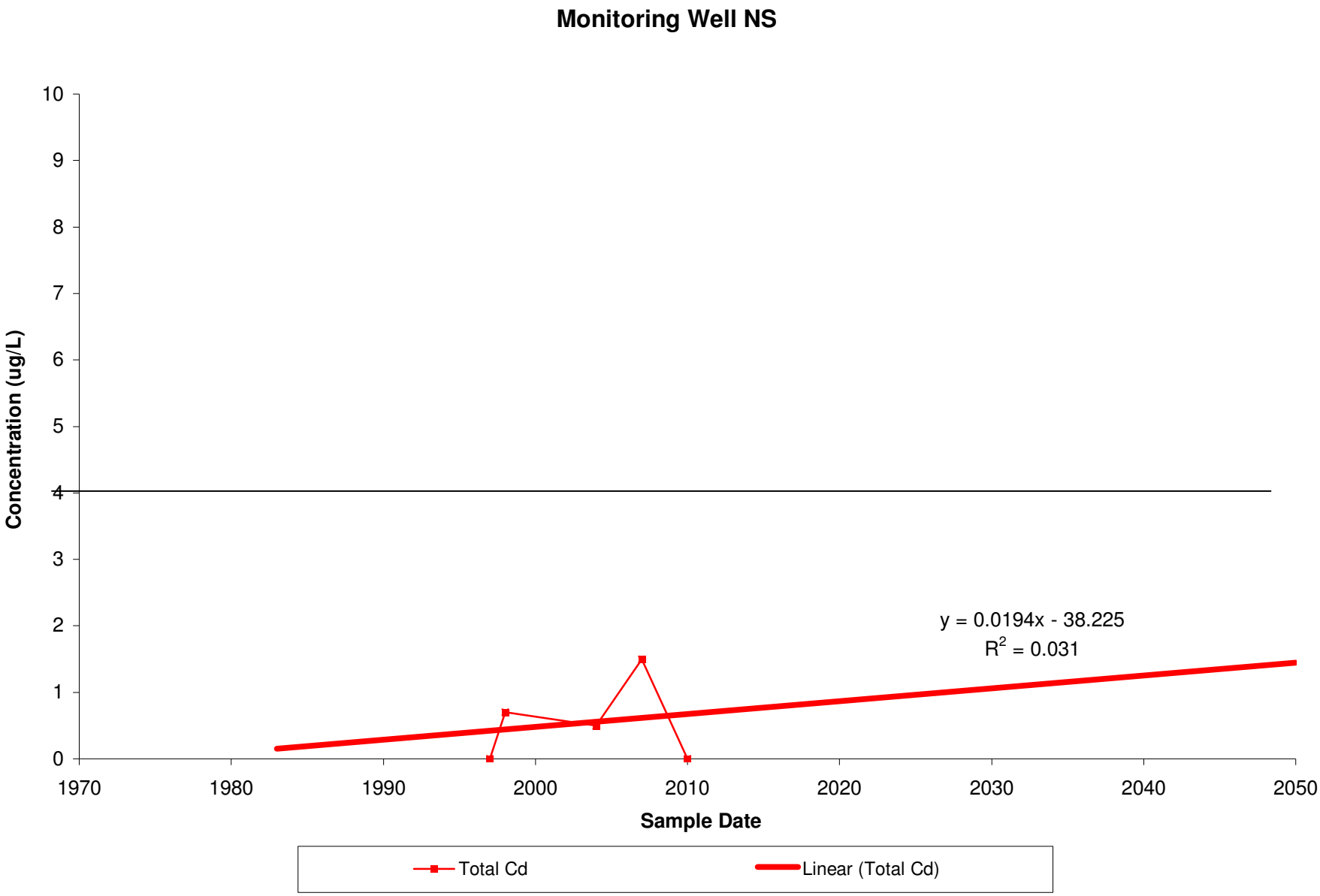
500392


Monitoring Well SD
300
250
200
150
100
50
0
Concentration (ug/L)
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -8444.6Ln(x) + 64377
R2 = 0.3574
Total Cd
Log. (Total Cd)

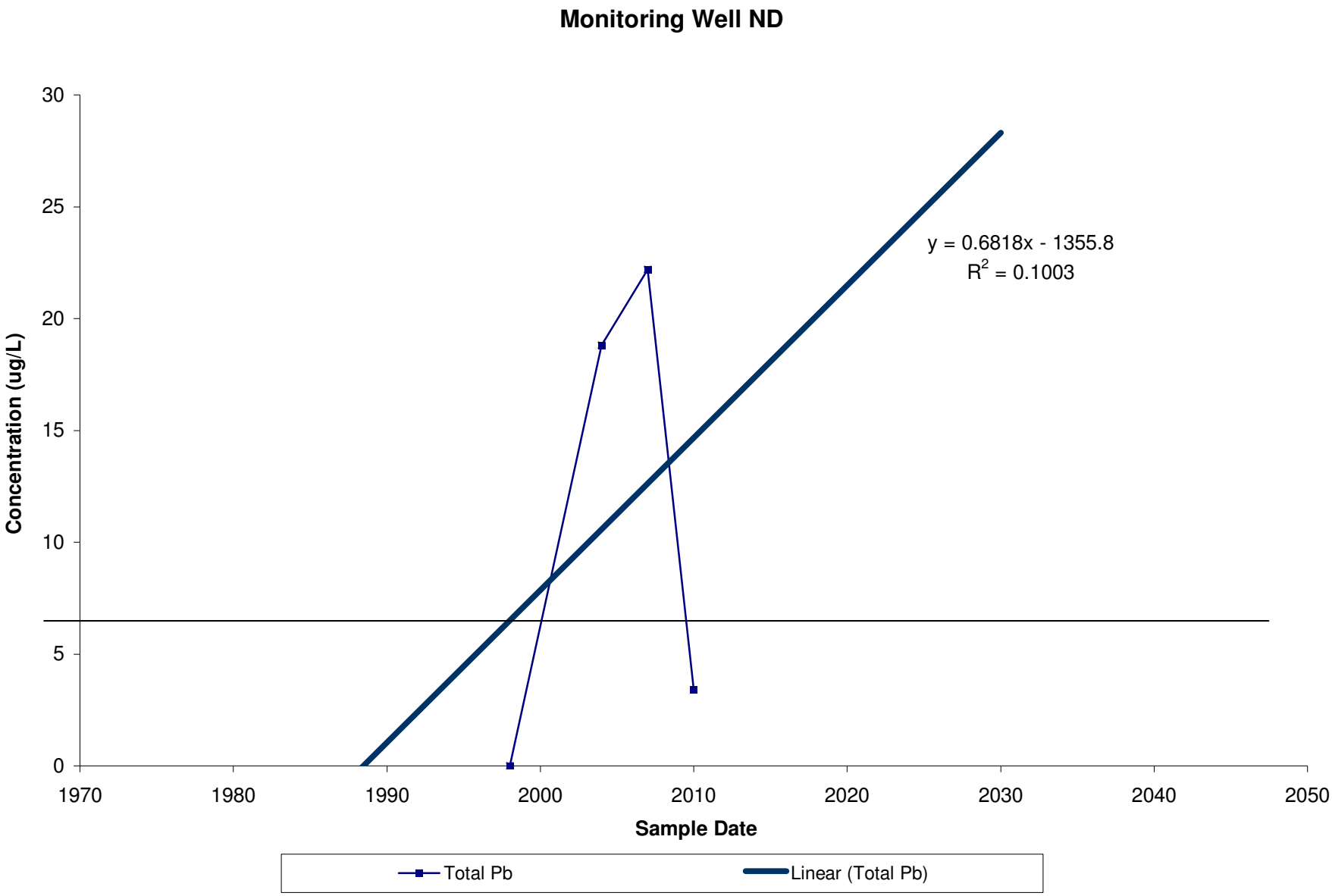
500393


Monitoring Well NS
Concentration (ug/L)
200
180
160
140
120
100
80
60
40
20
0
y = 2E+101e^-0.1148x
R^2 = 0.2988
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Expon. (Total Pb)

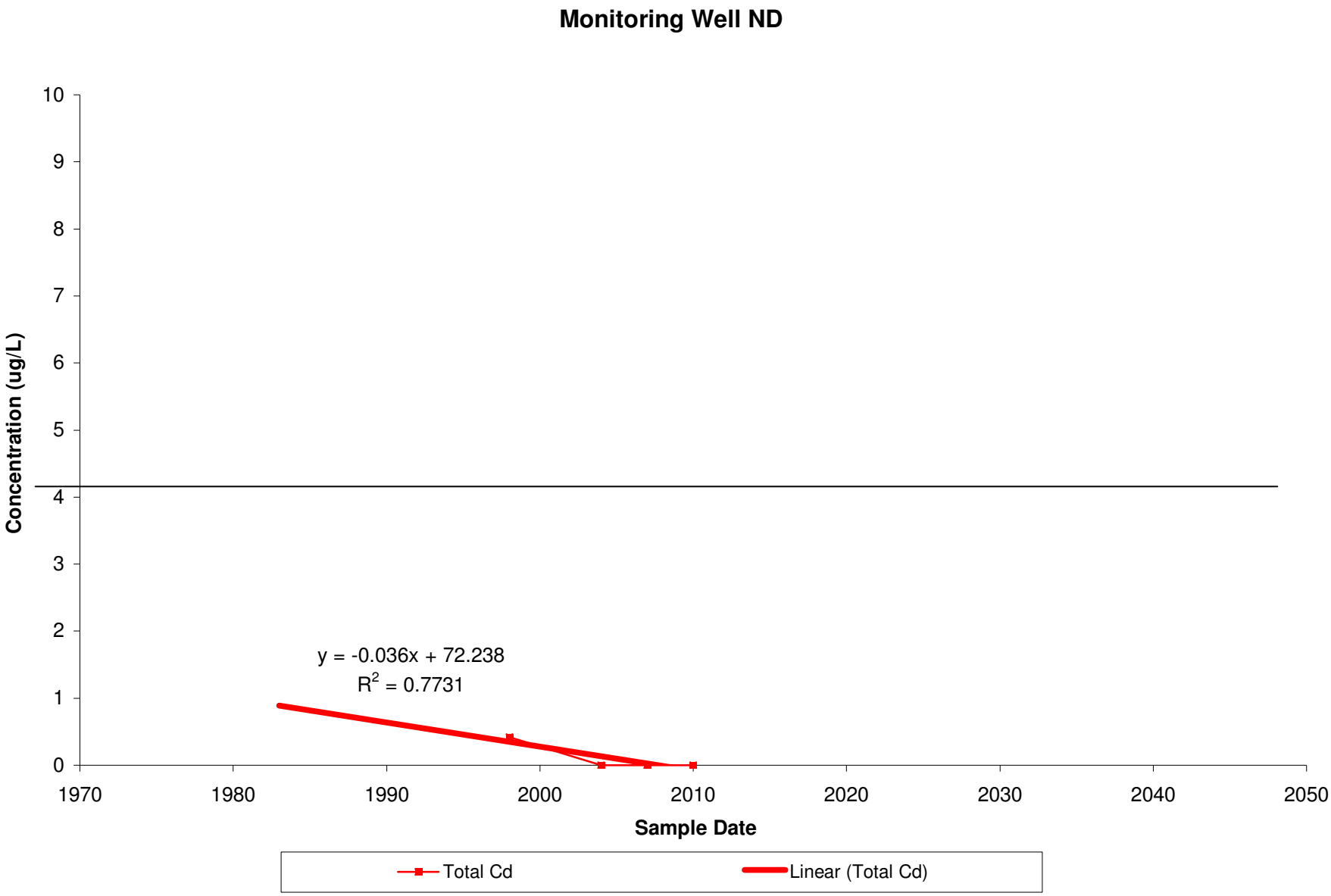
500394


Monitoring Well NS
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = 0.0194x - 38.225
R2 = 0.031
Total Cd
Linear (Total Cd)

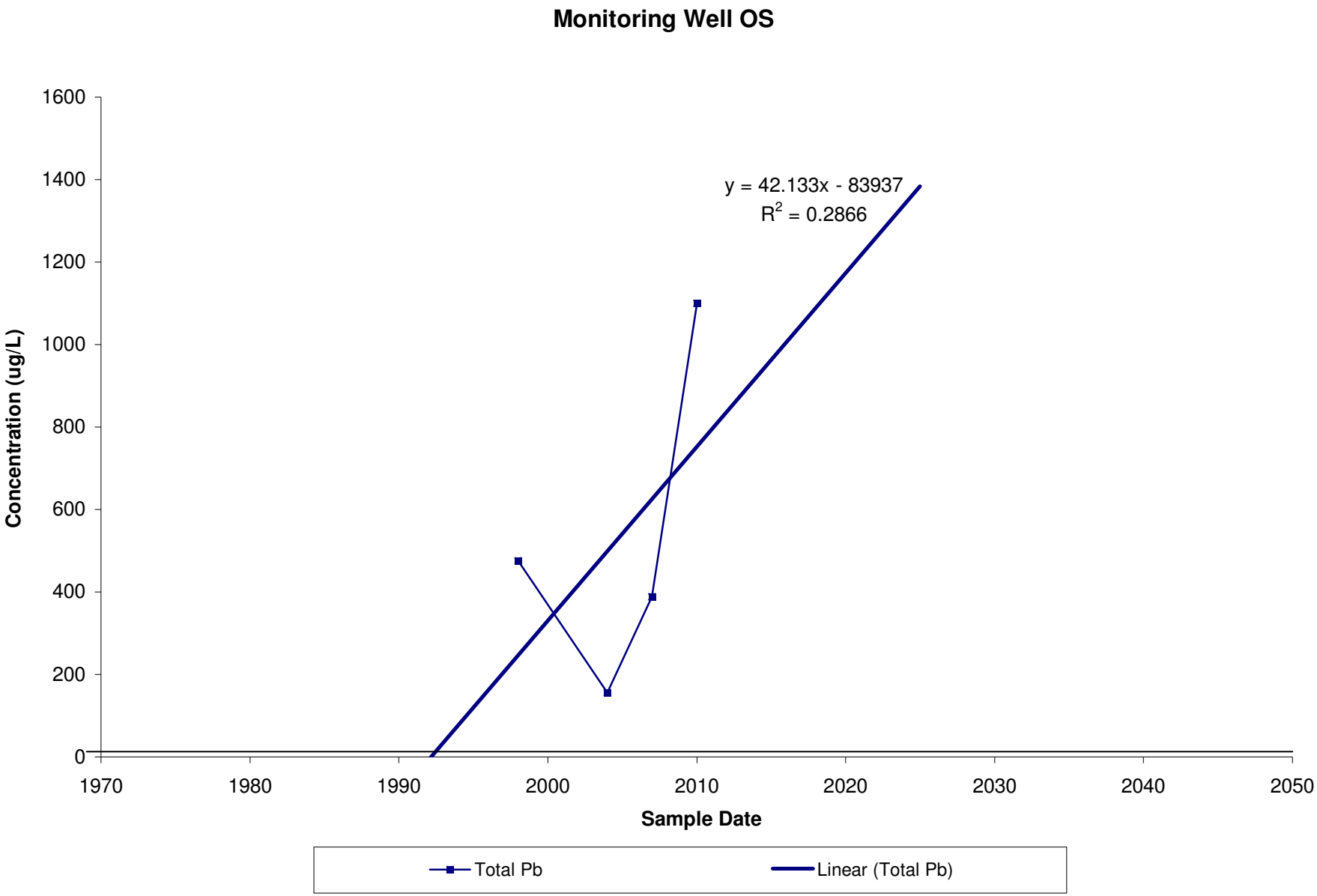
500395


Monitoring Well ND
Concentration (ug/L)
30
25
20
15
10
5
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = 0.6818x - 1355.8
R2 = 0.1003
Total Pb
Linear (Total Pb)

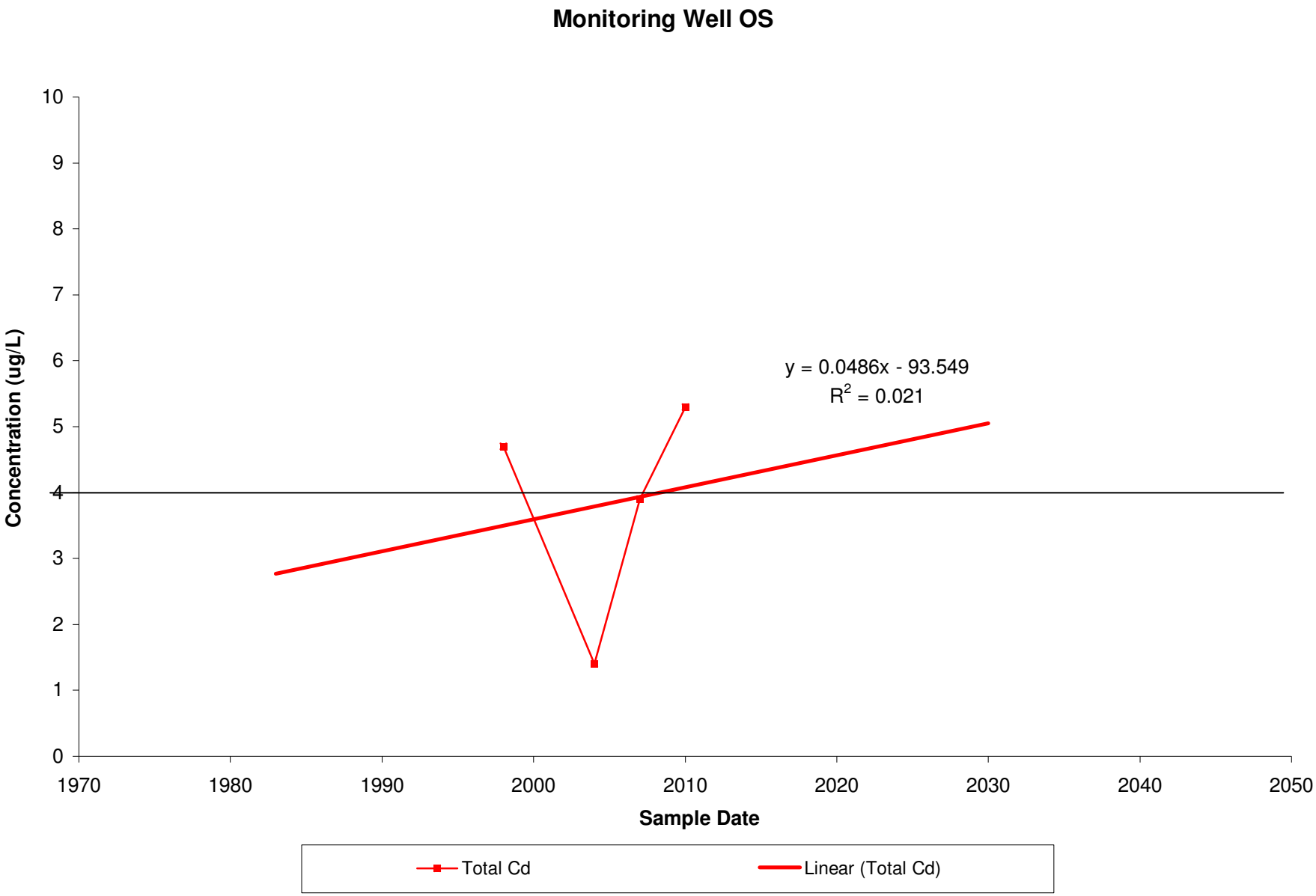
500396


Monitoring Well ND
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = -0.036x + 72.238
R2 = 0.7731
Total Cd
Linear (Total Cd)

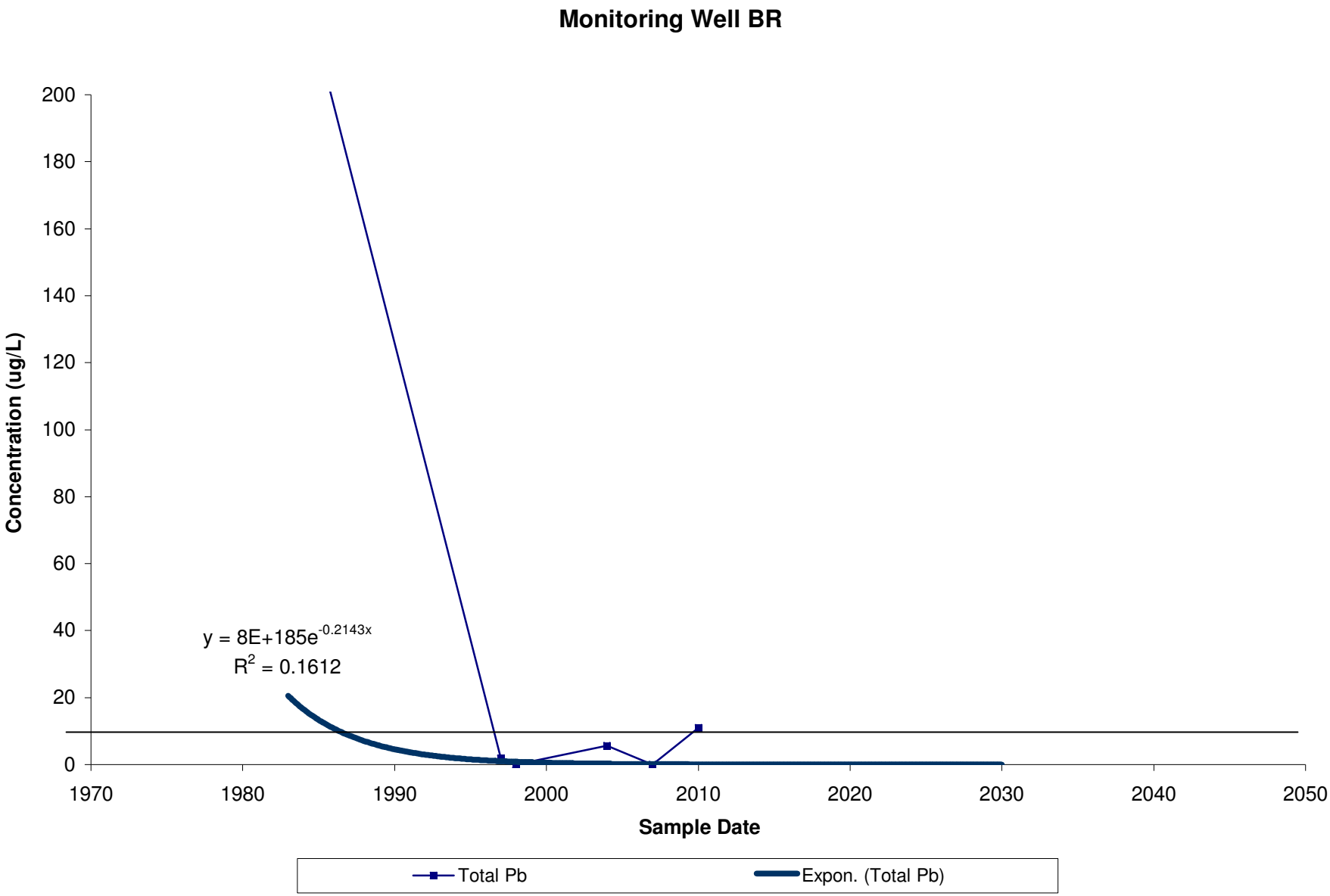
500397


Monitoring Well OS
y = 42.133x - 83937
R2 = 0.2866
Concentration (ug/L)
1600
1400
1200
1000
800
600
400
200
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Pb
Linear (Total Pb)

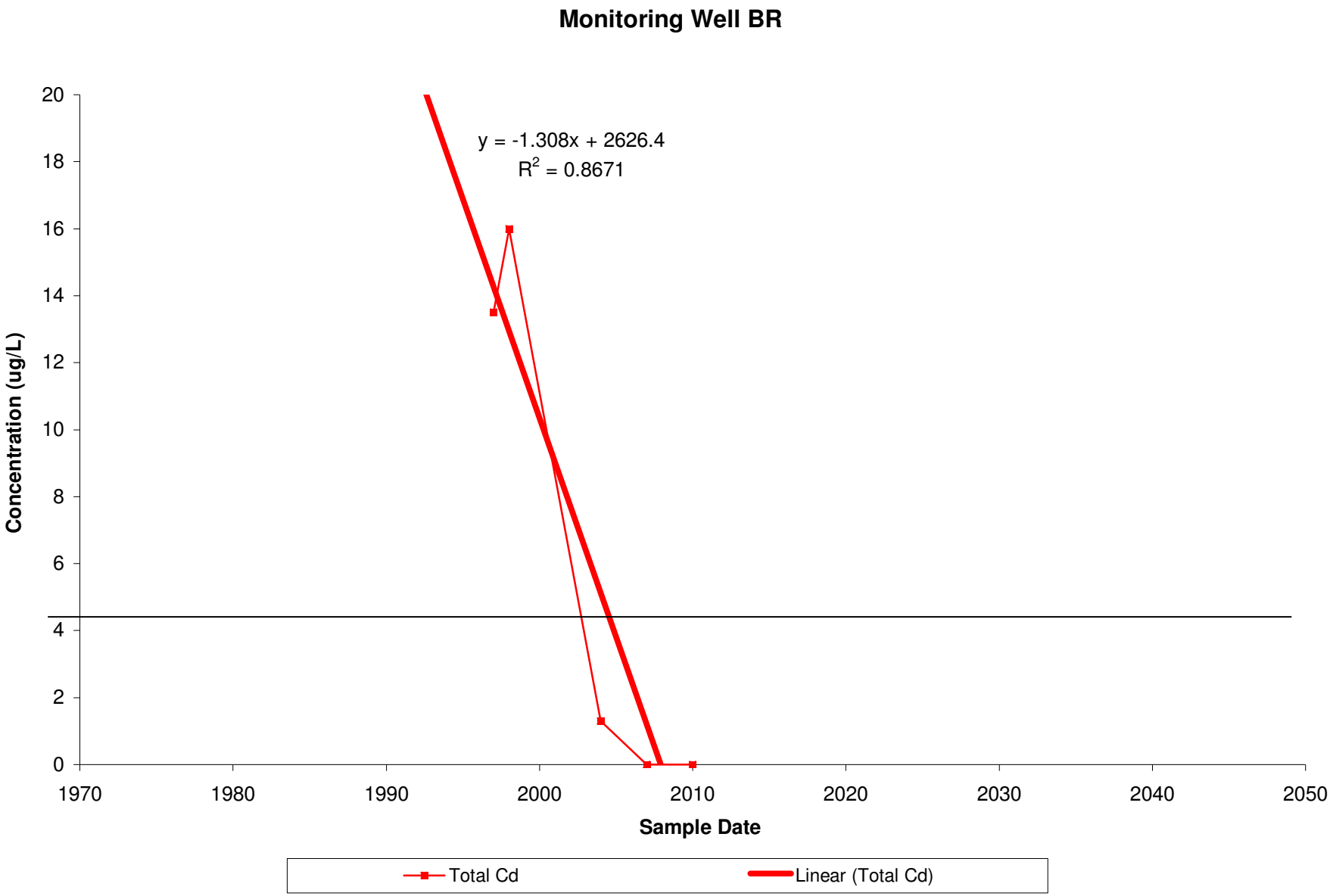
500398


Monitoring Well OS
Concentration (ug/L)
10
9
8
7
6
5
4
3
2
1
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = 0.0486x - 93.549
R2 = 0.021
Total Cd
Linear (Total Cd)

500399


Monitoring Well BR
Concentration (ug/L)
200
180
160
140
120
100
80
60
40
20
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
y = 8E+185e^-0.2143x
R^2 = 0.1612
Total Pb
Expon. (Total Pb)

500400


Monitoring Well BR
y = -1.308x + 2626.4
R2 = 0.8671
Concentration (ug/L)
20
18
16
14
12
10
8
6
4
2
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Sample Date
Total Cd
Linear (Total Cd)

500401