Cost and Performance Summary Report
In Situ Thermal Desorption at Rocky Mountain Arsenal Hex Pit
Adams County, Colorado
November 2005

Summary Information [1, 2, 4, 5, 6, 7, 8, 9]

Rocky Mountain Arsenal (RMA) near Denver, Colorado, was established by the U.S. Army in 1942 as a chemical agent and munitions facility for use during World War II. From the early 1950s to the mid-1980s, several companies leased certain areas of the facility to manufacture agricultural and industrial chemicals, mainly pesticides. Industrial and waste disposal practices, including disposal of pesticides in drums that later corroded or ruptured, resulted in contamination of soil, surface water, and groundwater at the facility. Thirty-one contaminated areas of the facility that required remediation were identified, and in 1987, RMA was placed on the National Priorities List. This report addresses the full-scale application of in situ thermal desorption (ISTD) at the Hex Pit at RMA. The application also is the subject of an evaluation report prepared under the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) program.

The Hex Pit was an unlined, earthen disposal pit located near the northern edge of the South Plants Area of RMA. Figure 1 shows the location of the pit. The Hex Pit was used from 1947 to 1955 for disposal of distillation products and other residues that were primarily generated during the production of hexachlorocyclopentadiene (hex or C_5Cl_6), a chemical formerly used in pesticide manufacturing. In addition, other organochlorine pesticides such as aldrin, chlordane, dieldrin, endrin, and isodrin were disposed of in the pit. The volume of waste in the pit was approximately 3,200 cubic yards (cy), and the waste included solid and semisolid layers of tar-like material. The contaminated portion of the pit extended over an area of approximately 7,000 square feet (ft^2) and its depth varied from 8 to 10 ft. Figure 2 shows the locations of 117 soil borings and eight piezometers and monitoring wells that were used in predesign studies to delineate the limits of the Hex Pit, characterize the geology, evaluate the potential for lateral migration of contaminants, and determine the depth to groundwater in the contaminated area.

The 1996 record of decision (ROD) selected innovative thermal technology for remediation of the Hex Pit. The ROD required the application of specific criteria to evaluate the innovative thermal technology; if these criteria were not met, a contingency remedy such as solidification/stabilization would be required. The criteria included a greater than 90 percent destruction removal efficiency (DRE) for hex, dieldrin, and chlordane, and a cost lower than off-site incineration. Several thermal technologies were evaluated and ISTD was selected as the remedial technology because it could meet the criteria specified in the ROD. Bench-scale feasibility studies indicated that ISTD could heat the contaminated area to temperatures high enough to effectively treat and remove the tarry hex still bottoms that were present. A subsequent bench-scale treatability study conducted on the Hex Pit material showed that ISTD was capable of removing more than 99 percent of the contaminants of concern (COC) at the site. A pilot study of the ISTD application, however, was not conducted at the site.

This report contains a brief discussion of the bench-scale treatability study and a more detailed discussion of the full-scale application of ISTD at the Hex Pit from October 2001 to March 2002. It includes a description of the design and operation of the ISTD system and the lessons learned from its application.

CERCLIS ID Number:	C05210020769
Type of Action:	Remedial
Site Lead:	PRP Lead

Timeline [1, 6]

Key dates associated with the Hex Pit and the ISTD application are presented below.

June 1996	ROD signed for RMA Hex Pit site
1999	Bench-scale treatability study
October 9, 2001 to February 18, 2002	ISTD system installation
February 19 to March 2, 2002	System shakedown
March 3, 2002	Startup of ISTD system
March 15, 2002	System shutdown

Factors that Affected Cost or Performance of Treatment [1, 2, 4, 5, 6, 8]

The geology in the area of the Hex Pit includes a layer of silty sand that is approximately 25 ft thick and that is underlain by Denver Formation bedrock. The Denver Formation consists of weathered, clayey sandstone and sandy shale. The depth to the water table has been reported between 13 to 14 ft below ground surface (bgs) in the immediate vicinity of the Hex Pit and thus lies below the maximum depth of the pit (10 ft). The regional groundwater flow direction is to the north-northeast at a gradient of about 0.008 ft per ft (about 42 ft per mile).

FIGURE 1
LOCATION OF THE HEX PIT AT RMA [6]

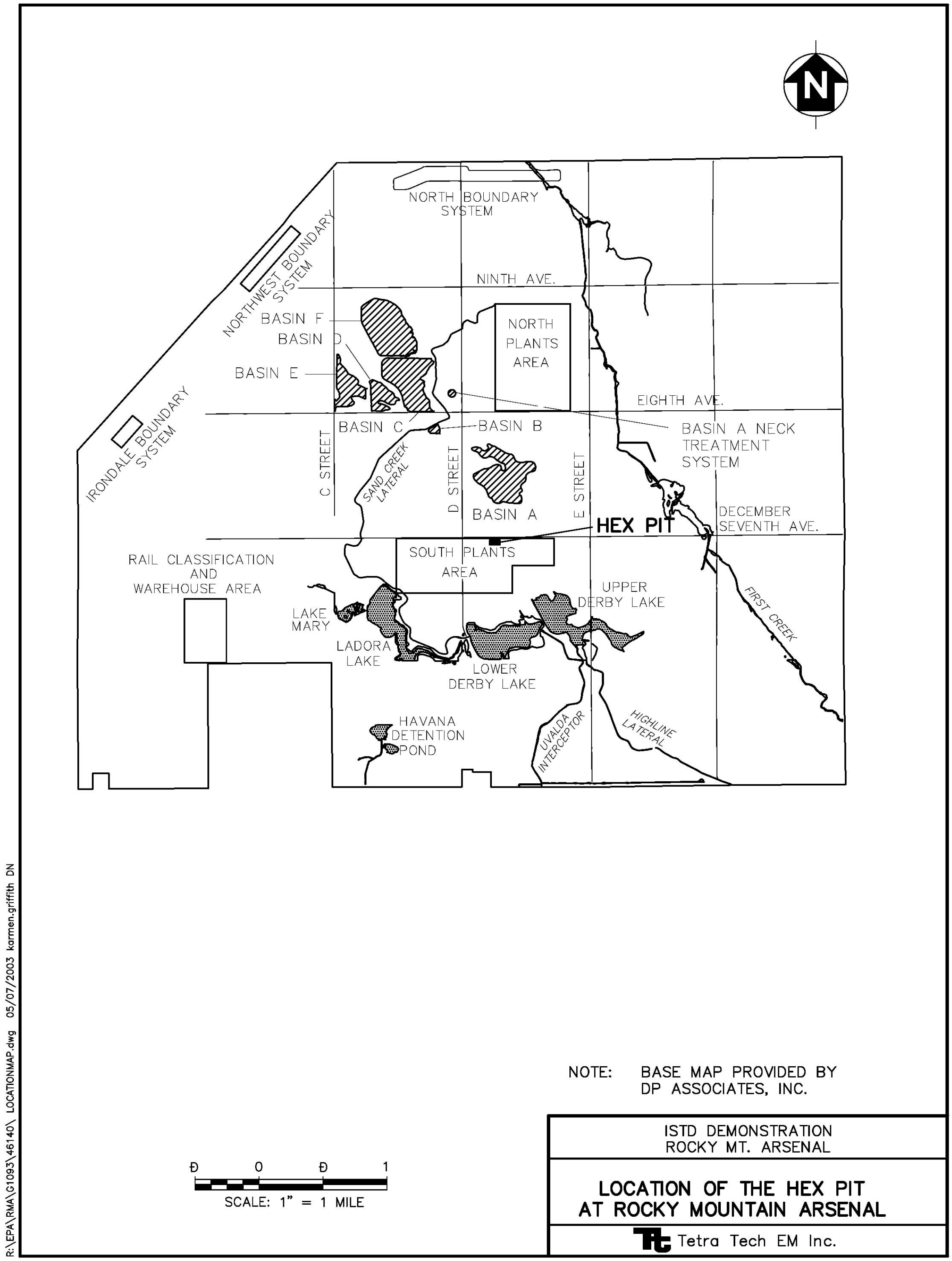
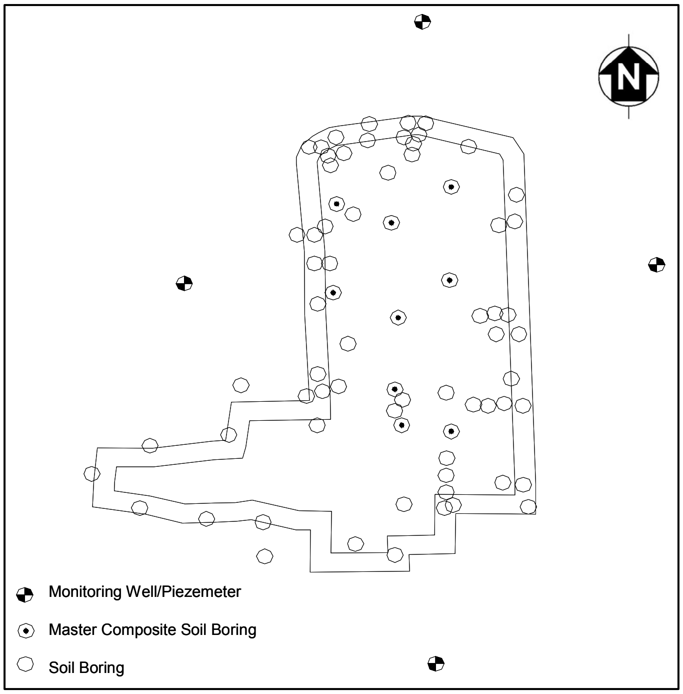


FIGURE 2
DELINEATION OF THE HEX PIT [6]



The material in the Hex Pit consisted of layers of soil and waste. The soil layers consisted of silty sand that was often stained dark brown, rust orange, or black, and that may have been mixed with granules or globules of waste. The waste layers included black, tarlike residue; rusted metal fragments (probably drum remains); black, orange, and occasionally white, crystalline substances; a light bluish-gray, pastelike material that was probably lime; and wood fragments. The layered nature of the soil-and-waste-material unit reflected historical disposal practices at the site where hex was disposed of in bulk or in drums. The hex-containing drums may have ruptured or later corroded. The hex was periodically covered with soil backfill and lime. These disposal practices resulted in layers of relatively pure waste material sandwiched between layers of soil and lime.

Listed below are the key matrix characteristics of the Hex Pit site.

Matrix Characteristics [1, 2, 7]

Parameter	Value
Soil Classification:	Silty sand
Clay Content or Particle Size Distribution:	Negligible; samples exhibited no plasticity
Moisture Content:	36.1 to 37.9 percent by weight (g/g) or 46.2 to 47.3 percent by volume (cm^3/cm^3)
Organic Content:	5 to 27 percent
Depth:	Soil and waste present from 2 to 10 ft bgs
Depth of Treatment:	12 ft bgs
Presence of NAPL:	Free-phase liquids were observed in some instances

Notes:
cm = centimeter
g = gram
NAPL = nonaqueous-phase liquid

Treatment Technology Description [1, 4, 6, 7, 8, 9]

The following sections describe the bench-scale treatability study, system design, and full-scale operation of the ISTD treatment process.

Treatability Study

The main objective of the bench-scale treatability study was to evaluate whether ISTD could achieve 90 percent DRE for each of the COCs at the Hex Pit, as per the ROD. Additional objectives included comparing post-treatment concentrations of the COCs to the site-specific soil evaluation criteria (human health exceedance [HHE] criteria) established in the ROD, and collecting data on off-gases produced during the ISTD treatment process for use in designing emission controls for a full-scale system.

In 1999, three composite soil samples were collected from the northern, middle, and southern portions of the Hex Pit, and one sample was collected beneath a concrete foundation slab of a building located in the southern part of the Hex Pit site. Test samples included a "master composite" that was representative of the entire contents of the Hex Pit and a "waste composite" that was representative of only visibly contaminated soil-and-waste material. The master composite sample was analyzed for hex, dieldrin, total chlordane, endrin, isodrin, aldrin, volatile organic compounds (VOC), dioxins, and furans. In addition, eight grab samples were collected from the pit at depths of approximately 5 ft bgs without consideration of whether the material was primarily waste or soil backfill. The grab samples were analyzed only for VOCs and were not subjected to bench-scale treatability testing.

The master composite sample contained the following mean pretreatment COC concentrations (expressed in milligrams/kilogram [mg/kg]): hex, 7,600; dieldrin, 3,100; total chlordane, 670; endrin, < 280; isodrin, <200; and aldrin, <170. The 90 percent DRE goals for the full-scale cleanup of the site with respect to hex, dieldrin, and chlordane were calculated based on the average COC concentrations in this sample. Because the concentrations of endrin, isodrin, and aldrin in the sample were below detection limits, 90 percent DRE goals were not set for these COCs.

During the treatability study, the test samples were thermally treated at temperatures of approximately 580 to 1,060°F under controlled conditions to simulate treatment of the material in the Hex Pit using ISTD.

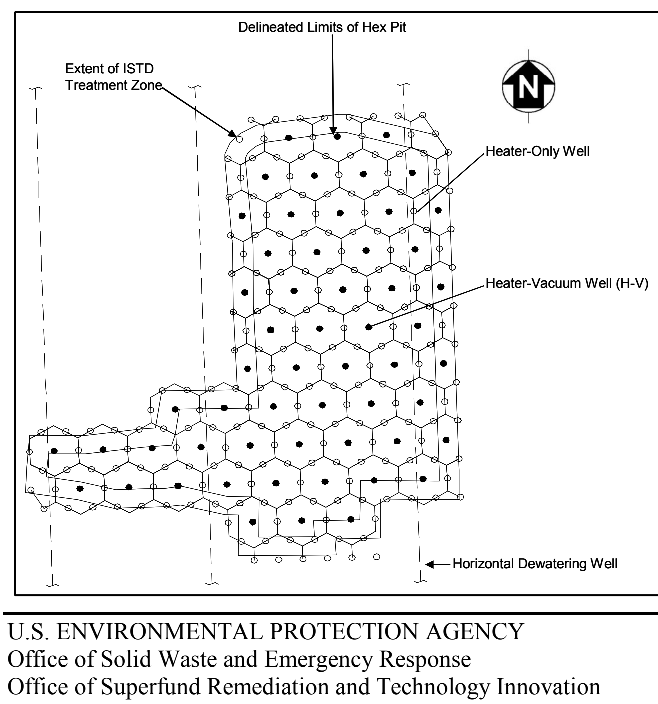
Post-treatment analytical results from the treatability study indicated that DREs of 99 percent were achieved and that site cleanup goals would be met. Dioxin and furan concentrations were reduced by more than 90 percent, and the results indicated that the ISTD treatment process did not create these compounds. Off-gas emissions indicated that a significant quantity of hydrochloric acid vapor or chlorine gas was generated. However, based on past experience with using ISTD at sites containing chlorinated compounds, it was expected that the hydrochloric acid generated from the in situ desorption of chlorinated compounds would be neutralized by the lime and calcareous material in the Hex Pit.

System Design

The system design involved a number of vertical, heater-only (H-O) wells and a number of combination heater-vacuum (H-V) extraction wells. Figure 3 shows the locations of the H-O, H-V, and horizontal dewatering wells for the ISTD application at the Hex Pit site. The dewatering wells were installed several feet below the ISTD thermal well field because of concern for potentially rising groundwater levels. The array of H-O and H-V wells used at the site was designed to heat the soil to 617°F, which is above the boiling points of all the COCs except dieldrin, which was expected to decompose at this temperature. The boiling points of the COCs at the Hex Pit site are listed in the following table.

COC	Boiling Point (^{o}F)
Hex	462
Aldrin	293
Chlordane	347
Dieldrin	725
Endrin	473

FIGURE 3
ISTD HEATER ONLY, HEATER-VACUUM, AND HORIZONTAL WELL LAYOUT [6]



Prior to ISTD system installation, a field trial was conducted at an uncontaminated site in Houston, Texas, to evaluate a new generation of H-V and H-O wells for potential use at the Hex Pit site. The design of ISTD wells used in previous applications had been relatively complex and expensive to construct and therefore, new well design was used in the field trial. The new well design specified readily available materials, which could result in substantial cost savings at the Hex Pit site. The field trial lasted 63 days, and the performance of the new well design was found to be acceptable; therefore, the new well design was incorporated into the ISTD system design for the Hex Pit.

Design considerations for the ISTD system incorporated treatment temperature and heating duration, well spacing, power input, in situ neutralization of acids (produced by heating of the organochlorine pesticides), treatment of extracted materials, and the results of the bench-scale treatability study.

System design parameters such as well spacing and heating duration were optimized to minimize well installation and operating costs, while attaining the required DREs. The design involved a treatment area that encompassed 3,198 cy of contaminated soil, which extended 5 ft beyond and 2 feet below the delineated surface boundaries of the Hex Pit. The H-O and H-V wells were positioned in a triangular grid spaced on 6-foot centers with a 3.75:1 ratio, respectively.

The grid included a total of 266 thermal wells installed to depths of 12.5 ft bgs in a hexagonal arrangement covering an area of 7,194 ft^2. Of the 266 thermal wells, 210 were H-O wells and 56 were H-V wells. Each H-V well was constructed using a Type 304 stainless-steel well screen that contained a stainless-steel "can" enclosing the heating element. The electrical heating element in each well was designed to reach maximum temperatures between 1,400 and 1,600°F, and a minimum temperature of 617°F was to be attained between wells within the delineated boundaries of the Hex Pit. Negative pressure was maintained along the boundaries of the treatment area to ensure that steam and contaminant vapors were captured and directed to an off-gas treatment system. Vapors extracted from the H-V wells were passed through an uninsulated, heat-resistant, flexible rubber steam hose to a vapor tee that was connected to a manifold tap. A vacuum equivalent to approximately 20 inches of water column was applied, which was expected to be adequate to capture all the vapors released during ISTD system operation. The collected off-gas was then conveyed to an off-gas treatment system that consisted of a cyclone separator, a flameless thermal oxidizer, a heat exchanger, a knock-out pot, two acid gas dry scrubbers, two activated carbon adsorption beds, and two main process blowers. The main process blowers were induced-draft fans designed to supply the vacuum needed to draw the vapors from the well field and through the off-gas treatment system. The off-gas was vented to the atmosphere after passing through the off-gas treatment system. Air emissions were monitored to ensure compliance with air discharge permit requirements.

ISTD of chlorinated compounds was expected to produce low concentrations of in situ hydrochloric acid vapors. The technology vendor calculated the site soil's buffering capacity based on the concentrations of calcium (Ca^{+2}) and iron (Fe^{+3}) in a pre-treatment master composite sample. The calculated buffering capacity was found to be 98,500 mg/kg for Ca^{+2} and 28,500 mg/kg for Fe^{+3}. The vendor had calculated that only 20 percent of this in situ buffering capacity was required to neutralize the hydrochloric acid vapors and consequently prevent corrosion of the ISTD system.

Installation of the ISTD system at the site began in October 2001 and was completed in February 2002. During the installation, it was determined that a potential rise in the groundwater level could adversely affect the system. Therefore, three horizontal dewatering wells were installed several feet below the completed ISTD well field prior to the beginning of heating.

Shakedown Period

Shakedown operations for the ISTD system were carried out for 2 weeks following system installation.

Full-Scale Operation

The system was started up on March 3, 2002, and was expected to run for 85 days until the end of May 2002. However, because portions of the aboveground piping had been corroded by hydrochloric acid that was generated during heating of the organochlorine contaminants, the system was shut down on March 15, 2002, 12 days after system startup. Following shutdown, the Hex Pit site was buried under approximately 3 ft of imported fill material, and the application was evaluated, and lessons learned noted.

Following system shutdown, a comprehensive assessment of the damage to the piping system and thermal well field was conducted. The assessment revealed that acidic corrosion of the subsurface components had occurred. Extensive corrosion had also occurred in the piping system and the thermal well field. The technology vendor believed that the chlorinated contaminants in the tarlike waste were hydrolyzed to hydrochloric acid and that the waste liquefied and flowed into the H-V wells before it could undergo in situ neutralization.

Soil and waste samples were collected before and after the ISTD application under the EPA SITE program from the northern portion of the Hex Pit. A comparison of pre- and post-treatment contaminant concentrations was performed to evaluate whether any contaminant desorption occurred during the brief operation of the ISTD system.

<u>Operating Parameters [1, 4, 7]</u>

Listed below are the key operating parameters for the ISTD system used at the Hex Pit site.

Operating Parameter	Value
Residence Time	3 days at target treatment temperature
Operating Pressure or Vacuum	Approximately 20 to 30 inches of water (approximately 1.5 to 2.2 inches of mercury at 0^oC)
Target Treatment Temperature	617^oF
Treatment Temperature Achieved	100 to 458^oF

<u>Performance Information [1, 2, 6, 7, 8]</u>

This section describes the performance goals for cleanup at the Hex Pit site as well as performance of the ISTD technology.

Performance Goals

Two specific remediation goals were set for RMA:

1. Remediation Goal I was to meet or exceed the ROD requirement of 90% DRE for the six COCs (hex, aldrin, dieldrin, endrin, isodrin, and chlordane).
2. Remediation Goal II was to reduce the mean concentration of the six COCs below the ROD HHE criteria. This goal was established to allow the treated soils to be left in place, rather than disposing them in an on-site landfill. For chlordane and dieldrin, this required a DRE of 92% and 98% respectively (see Table 1).

Concentrations for Remediation Goal I were determined by applying a 90 percent DRE to the mean concentrations of COCs in a composite sample collected during the bench-scale treatability study. The 90 percent DRE goals for hex, dieldrin, and chlordane were calculated based on the average COC concentrations in this sample. Because the concentrations of endrin, isodrin, and aldrin were below detection limits in pre-treatment samples, 90 percent DRE goals were not set for these COCs. Table 1 shows the pre-treatment concentrations and the cleanup goals for the COCs at the Hex Pit site.

TABLE 1
PRE-TREATMENT CONCENTRATIONS AND CLEANUP GOALS FOR COCS [1, 2, 4, 6, 8]

COC	Pre-Treatment Concentrations of COCs[1] (mg/kg)	Mean Pre-Treatment Concentrations of COCs (mg/kg)	Post-Treatment Concentrations of COCs (mg/kg)	HHE Criterion (mg/kg)	PRG (mg/kg) (90% DRE)
Hex	5,500 – 11,000	7,600	N/A[3]	1,100	760
Aldrin	3.8 – 1,400	<170	N/A[3]	71	N/A[3]
Chlordane (total)	NR[2]	670	N/A[3]	55	67
Dieldrin	23 – 1,500	3,100	N/A[3]	41	335
Endrin	< 3.9 – 63	<280	N/A[3]	230	N/A[3]
Isodrin	NR[2]	<200	N/A[3]	52	N/A[3]

Notes:

1 Concentrations based on EPA SITE program pre-treatment characterization data
2 Not reported
3 Information not able to be directly correlated to the pre-treatment concentrations

As noted in Remediation Goal II, if ISTD was successful in treating the Hex Pit waste such that the HHE criteria were met, the residual materials could remain in place. If ISTD was successful only in meeting Remediation Goal I, which had to be met to comply with the ROD and avoid a contingency remedy, treatment residuals would have to be excavated and disposed of in a hazardous waste landfill.

The EPA SITE program also evaluated the performance of the technology according to a number of secondary objectives that included:

- Determining the cost of treatment for contaminated material at the Hex Pit;
- Evaluating the air emissions from the treatment process;
- Evaluating changes in hex concentrations in soil and groundwater outside the boundaries of the treatment area;
- Evaluating changes in the concentrations of several VOCs at the site such as carbon tetrachloride, chloroform, and tetrachloroethene; and
- Evaluating the toxicity equivalent quotients for dioxins and furans to assess the potential for creation of these compounds by the ISTD system in soil and in the off-gas treatment system.

HACH chromium test kits were used in the field to verify the technology performance. Subsequently, EPA performed additional soil and groundwater sampling and laboratory analytical testing. All regulatory requirements were achieved in accordance with project specifications.

Pre-Treatment Sampling

Pre-treatment samples were collected to establish baseline conditions at the Hex Pit before construction and operation of the treatment system. This sampling was different from the bench-scale treatability study sampling, which was performed to determine the target DREs for the full-scale application.

Pre-treatment sampling was confined to the northern part of the Hex Pit because the southern portion of the pit had been disturbed during demolition and removal of a building foundation, and clean fill had been mixed with material originally disposed of in the Hex Pit. The pre-treatment samples included:

- Six composite samples, each consisting of materials collected from three separate boreholes at depths ranging from 2 to10 ft bgs. These samples were analyzed for COCs, VOCs, dioxins, and furans.
- Nine grab samples from soil cores collected 5 ft bgs before the core material was mixed for the composite samples. The grab samples were analyzed for VOCs only.

In addition, samples of soil and groundwater contiguous to the treated area were collected to evaluate migration of contaminants out of the treated area.

Post-Treatment Sampling

The original objective of the post-treatment sampling was to characterize the effects of the ISTD application. However following the system shutdown due to corrosion problems, the post-treatment sampling was modified to assess the soil and wastes that were located near the heater wells.

Post-treatment sampling of the Hex Pit was confined to the northern part of the pit. Boreholes were drilled through the soil cover that was placed on the site following the failure of the ISTD system. Soil-and-waste material samples were collected and analyzed to estimate the extent of any desorption and removal of COCs and VOCs and to determine whether the treatment process had generated any dioxins and furans. The post-treatment samples included:

- Six composite samples, each consisting of materials collected from three separate boreholes advanced about 0.5 ft from six H-V wells. The materials were collected at depths ranging from 2 to 10 ft below the Hex Pit cover material. The samples were analyzed for COCs, VOCs, dioxins, and furans. The composites were prepared by homogenizing core material obtained from single boreholes drilled through the soil-and-waste material. The post-treatment sampling procedure was different from the pre-treatment sampling procedure in that each post-treatment sample consisted of composited material from a single borehole rather than composited material from three separate boreholes.

- Six grab samples collected from a depth of 5 ft below the soil-and-waste material layer. These samples were analyzed for VOCs only.

Soil and groundwater contiguous to the treated area were not sampled as part of post-treatment sampling.

Performance Data

The ISTD system at the Hex Pit operated for 12 days. During operation and post-treatment monitoring, sampling and analysis of air emissions indicated that none of the hourly average air quality standards for off-gas emissions had been exceeded during system operation or during the extended well field cool-down period. Vapor-phase COC concentrations were not measured in the influent or effluent of the off-gas treatment system prior to ISTD system shutdown.

In general, the post-treatment core samples collected from the Hex Pit were similar to pre-treatment core samples. The soil-and-waste material did not appear to have undergone any physical changes as a result of the brief period of ISTD system operation.

Shutdown of the system prevented the evaluation of the effectiveness of the technology at this site. Therefore, post-treatment sample analyses are not presented in this report. More detailed information about the sampling and analyses is provided in the SITE evaluation report.

Cost Information [2, 3]

The total cost of design and construction of the ISTD system was approximately $1.9 million. An additional $0.37 million was spent to install the horizontal dewatering wells. The full-scale application of ISTD at the Hex Pit site was not completed because of extensive damage to the piping system and the well field; the ISTD system was shut down 12 days after treatment was initiated. Because of the short period of system operation, no operation and maintenance (O&M) costs are available.

The nature of the waste at the Hex Pit site contributed to the cost of the full-scale application. The waste contained contaminants with very high boiling points. In order to volatilize these contaminants, high operating temperatures along with robust equipment, closer well spacing (installation of 266 thermal wells on a 6-ft spacing to obtain a reasonable operating time as compared to 7.5 to 20-ft spacing in other ISTD applications), and longer operating times were required. Heater wells with a new well design also were required specifically for this application. In addition, the high chlorine content of the waste required the use of technologies operating at high temperatures (> 600°F). The cost for the ISTD system design and construction at the Hex Pit is competitive with the estimated cost for excavation and off-site incineration. In addition, the ISTD application avoids the risks associated with transporting highly contaminated waste through the community.

Observations and Lessons Learned [1, 8, 9]

A summary of the observations made and lessons learned at the Hex Pit site by the parties involved in the ISTD application is provided below.

Primary Lessons Learned

- A field pilot study should be conducted when contemplating applications of ISTD to treat wastes that are qualitatively different than those previously encountered. In situ neutralization of acids generated during treatment should not be assumed in situations in which the waste resides as a neat solid material that has not penetrated into a porous matrix. At the Hex Pit, the waste consisted of highly chlorinated compounds in pure form or as layers of tar that were not uniformly mixed with the soil matrix. The resulting high levels of hydrochloric acid produced by the ISTD system were not neutralized in situ as anticipated, probably because heating the solid tarry layers created preferential pathways along which the acid gas was able to discharge directly into the collection system.

- During drilling of the horizontal dewatering wells after the installation of the ISTD well field, a phenomenon called "frac-out" was observed. Frac-out is the emergence of a pool of fluid at the ground surface that is caused by fracturing of the subsurface formation by drilling fluids. The drilling fluids may have caused displacement of liquid wastes into the thermal wells, further contributing to the rapid corrosion. Careful consideration should be given to the potential effects of remedial activities that may impact the site in unexpected ways or mobilize contaminants. These activities include horizontal drilling in which overpressurization may lead to frac-outs.

Secondary Lessons Learned

- In situations where corrosion may occur, the temperature of the vapor in the system piping should be maintained at or above the temperature of the vapor in the subsurface where the initial "carrying capacity" of the vapor is established. Exposed sections of pipe should be insulated and heated. The system design should also provide for condensate collection at points of condensation. A design should consider worst-case outside temperature fluctuations.

- Lateral connections from the ISTD H-V well vapor tees to the piping manifold should be designed in such a way as to eliminate low points that may serve as liquid accumulation or flow obstruction points.

- Neutralization requirements and system construction materials should be identified by determining the amount of chloride that may be produced based on the results of extractable organic halide analyses or stoichiometric quantities calculated from the conversion of the site contaminants.

- The potential for corrosion should be evaluated in laboratory studies and material screening tests.

- System construction materials should be selected based on reasonable worst-case conditions and conservative assumptions. An alternative to stainless-steel, cold-worked well screens and use of single-piece wells without welds should be considered.

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