DOE–LM/1457–2007

Final Report
Northeast Site Area B
NAPL Remediation Project
at the Young - Rainey STAR Center
Largo, Pinellas County, Florida

April 2007

U.S. Department of Energy

Office of Legacy Management

Work Performed Under DOE Contract No. DE–AC01–02GJ79491
for the U.S. Department of Energy Office of Legacy Management.
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Work Performed by S.M. Stoller Corporation under DOE Contract No. DE–AC01–02GJ79491
for the U.S. Department of Energy Office of Legacy Management, Grand Junction, Colorado

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Acronyms

bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and total xylenes
BTU/hr	British Thermal Unit per hour
°C	degrees Celsius
cDCE	cis-1,2-dichloroethene
COCs	contaminants of concern
CPVC	Chlorinated polyvinyl chloride
digiPAM™	digital pressure acquisition module
digiTAM™	digital temperature acquisition module
digiT/Cs™	digital thermocouples
DOE	U.S. Department of Energy
DNAPL	dense non-aqueous phase liquid
DPT	direct push technology
EPA	U.S. Environmental Protection Agency
ET-DSP™	Electro-Thermal Dynamic Stripping Process
°F	degrees Fahrenheit
F.A.C.	Florida Administrative Code
FDEP	Florida Department of Environmental Protection
FID	flame ionization detector
FL-PRO	Florida Petroleum Range Organics
ft	foot (feet)
ft/day	foot (feet) per day
ft^2	square feet
ft^3	cubic feet
g	gram
gpm	gallons per minute
GAC	Granular Activated Carbon
Hawthorn	Hawthorn Group
HDPE	High-Density Polyethylene
IPS	inter-phase synchronization
kVA	kilovolt amperes
kW-Hr	kilowatt-Hour
kW-Hr/yd^3	kilowatt-Hour per cubic yard
lbs	pounds
lbs/gal	pounds per gallon
lbs/hr	pounds per hour
LM	Office of Legacy Management
LNAPL	light non-aqueous phase liquid
Mc^2	McMillan-McGee Corporation
µg/kg	micrograms per kilogram
µg/L	micrograms per liter
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/m^3	milligrams per cubic meter
NAPL	non-aqueous phase liquid
OVA	organic vapor analyzer

PDS	power delivery system
PPM	PPM Consultants
QC	Quality Control
scfm	standard cubic feet per minute
STAR	Science, Technology, and Research
Stoller	S.M. Stoller Corporation
TCE	trichloroethene
TDC/IPS	Time-Distributed Control/Inter-Phase Synchronization
TPH	Total Petroleum Hydrocarbons
TSS	total suspended solids
VOC	volatile organic compound
WRS	WRS Infrastructure & Environment, Inc.
yd^3	cubic yards

Executive Summary

The S.M. Stoller Corporation (Stoller), under contract to the Department of Energy (DOE), Office of Legacy Management (LM), completed a full-scale remediation of non-aqueous phase liquid (NAPL) at a site designated as Area B. Area B is located on the Northeast Site of the Young - Rainey Science, Technology, and Research Center (STAR Center), Largo, Florida. The site is owned by Pinellas County, but DOE-LM is responsible for environmental cleanup activities at the site.

Stoller's subcontracted remediation team consisted of three companies: WRS Infrastructure and Environment, Inc. (WRS), McMillan-McGee Corporation (Mc^2), and PPM Consultants (PPM). The approach used to remediate the site was to heat the subsurface using Electro-Thermal Dynamic Stripping Process (ET-DSP™) along with injection of ex situ generated steam and then extract and treat the volatilized contaminants. The ET-DSP™ process heats the subsurface through electrical resistive heating, convective heat transfer, conductive heating, and in situ steam generation. Convective heat transfer and in situ steam generation are accomplished by injecting water to the electrodes, a patented ET-DSP™ process.

WRS was the prime contractor; they provided overall project management, construction management, health and safety support and oversight, and regulatory support. Mc^2 provided the overall technical approach, the ET-DSP™ equipment, and equipment for ex situ generation of steam. PPM provided the dual-phase ground water and vapor extraction equipment, treatment equipment for the extracted ground water and vapors, engineering support, and operation and maintenance of the treatment system and dual-phase extraction system.

Scope

The Area B remediation covered an area of approximately 36,400 square feet and a remediation volume of 54,000 cubic yards. The depth of remediation extended from ground surface to 40 feet (ft) below ground surface (bgs). This included approximately 10 ft of the Hawthorn Group (Hawthorn) at a depth of 30 to 40 ft bgs. The Hawthorn is an underlying, weathered clay layer of low permeability. A particularly challenging aspect of the project was to remove NAPLs from the area underneath a building, Building 1400, located adjacent to the remediation area. This building was continuously occupied by tenants during the remediation.

The remediation was to continue until levels that indicate the absence of NAPLs were observed in the subsurface for trichloroethene (TCE), cis-1,2-dichloroethene (cDCE), methylene chloride, and toluene. In addition to the NAPL compounds, the remediation was required to achieve reduced levels of total petroleum hydrocarbons (TPH). The cleanup levels required for the contaminants are listed below.

Contaminant	Ground Water Goal	Soil Goal
TCE	11,000 µg/L	20,400 µg/kg
cDCE	50,000 µg/L	71,000 µg/kg
Methylene chloride	20,000 µg//L	227,000 µg/kg
Toluene	5,500 µg/L	15,000 µg/kg
TPH	50,000 µg/L	2,500,000 µg/kg

µg/L = micrograms per liter
µg/kg = micrograms per kilogram

The remediation also was required to meet several other criteria, including reaching and maintaining a minimum temperature of 85 degrees Celsius (°C) in the subsurface, limiting temperatures to not more than 40 °C within 6 ft of Building 1400 (i.e., under and adjacent to the building) and meeting all regulatory requirements.

Remediation Components

The components used for remediation of Area B include:

- One hundred eighty-five ET-DSP electrodes placed in 95 wells. Two electrodes were placed in each well, except for the slant electrodes that were placed under Building 1400 with one electrode each. The electrodes were placed at depths varying from 10 ft bgs to near the top of the Hawthorn.
- Twenty-nine shallow steam injection wells in electrode borings.
- Six stand-alone steam injection wells.
- Approximately 2,000 temperature sensors in 70 locations that were monitored over the internet.
- Pressure sensors in 30 wells used to monitor ground water elevations. These were also monitored over the internet.
- Twelve monitoring wells (in six well pairs) installed outside Area B.
- Nine power delivery systems to provide power to the electrodes.
- A hot water heater used to pre-heat the water injected into the electrodes.
- A steam generator, rated at ~1 million British thermal units per hour (BTU/hr) used to regenerate the vapor phase activated carbon. This unit was supplemented with the 3.3 million BTU/hr steam generator used with the shallow steam injectors, also called steam spears.
- A steam generator, rated at 3.3 million BTU/hr used to inject steam into the steam spears.
- Twenty three vertical dual-phase extraction wells and three horizontal dual-phase extraction wells located under Building 1400 used to maintain hydraulic control.
- Ten contingency vapor extraction wells installed within the Area B treatment area.
- An asphalt cap over the remediation area of approximately 12 inches in thickness.
- A treatment system for the extracted vapors and liquid. The vapors were extracted with a 100-horsepower vacuum pump. Contaminants were recondensed in NAPL form via steam regeneration of the carbon and also in cooled tanks. Then the remaining vapors were treated with granular activated carbon (GAC). Liquids were extracted with pneumatic-driven pumps. The extracted liquid was treated with an air stripper and then with GAC before being discharged to a publicly owned treatment works or re-injected into the electrodes.

- Several additional remediation components were installed in areas that had unexpectedly low vapor and ground water flow in the later stages of the operations phase. These included
    - Two additional dual phase extraction wells,
    - Six additional vapor extraction wells,
    - Conversion of two monitoring wells to extraction wells,
    - Twelve additional steam injection wells, and
    - Five temperature monitoring points.

Timeline

The project began with an initial kick-off meeting in February 2004 and demobilization was completed in December 2006. The design phase began after the kick-off meeting, and was completed prior to the start of construction in June 2004. Because of budget constraints, construction was extended across federal fiscal years 2004 and 2005 and was not complete until August 2005. Operations began in August 2005 and continued until May 2006, which was the end of the cool-down period. The operations period also included approximately 5 weeks of extended operations intended to maximize contaminant removal to levels below the cleanup goals.

After operations ended, confirmatory sampling was conducted to verify whether or not cleanup levels had been achieved. Confirmatory sampling consisted of three ground water sampling events and one soil sampling event that occurred from July 2006 to September 2006. The first confirmatory ground water sampling event showed that allowable levels for toluene were exceeded in one small area. This area had the highest levels of contamination and such a low permeability that almost no ground water or vapor could be extracted. Four weeks of additional heating and extraction operations were conducted in this area after the first confirmatory ground water sampling event. The second and third confirmatory ground water sampling events showed that the required cleanup levels were met across the entire remediation area.

Demobilization activities began in November 2006 and were completed in December 2006. All equipment, concrete pads, and asphalt associated with the vapor cap were removed from the site during the demobilization.

Operational Strategy

The operational strategy used a phased approach to focus on certain aspects of the remediation. The operational phases are listed below.

Hydraulic and pneumatic control. The focus of this phase was to establish ground water flow and vapor flow into the remediation area; these activities continued throughout the remediation.

Preheat. This phase focused on heating the low permeability upper 10 ft of the Hawthorn and on the outer edges of the remediation area. This was done to control downward and lateral migration of contaminants.

Ramp-up. This phase involved increasing temperatures throughout the entire remediation area to the target temperature of 85 °C.

Maintenance. The focus of this phase was to maintain the target temperature and maximize removal of the contaminants. During this phase the target temperature of 85 ºC was reached and efforts were focused on vapor and ground water extraction.

Cool Down. This phase was initiated after cleanup levels had been achieved. The focus of this phase was to reduce subsurface temperatures to below 100 ºC so that confirmatory sampling could take place safely.

Results

All remediation goals and performance standards were met during the remediation. In addition, there were no accidents and no regulatory or environmental violations. In summary, the remediation was successful.

During operations, approximately 17,867 pounds (lbs) of volatile organic compounds were removed from the subsurface. This compares favorably with the pre-remediation estimate of 15,200 lbs of contaminants in place. The majority of this mass (16,754 lbs) was from removal of the NAPL compounds (i.e., TCE, methylene chloride, cDCE, and toluene). Removal efficiency was estimated at 99.1 percent. Approximately 10,690 lbs of TCE were removed with a removal efficiency of 99.8 percent. The removal efficiency likely would have been higher except for one particularly recalcitrant zone where a significant amount of the mass remaining in the subsurface was located. Additional energy and additional extraction wells (vapor and ground water) were installed in this area to facilitate mass removal.

Total energy input to the subsurface during the remediation was 15,345,000 kilowatt-hours (kW-Hr) or 285 kilowatt-Hour per cubic yard (kW-Hr/yd^3). The predicted energy usage was 11,545,000 kW-Hr or 214 kW-Hr/yd^3.

1.0 Introduction

This report describes the thermal remediation of non-aqueous phase liquid (NAPL) Area B at the Northeast Site located on the Young - Rainey Science, Technology, and Research Center (STAR Center). The location of the Northeast Site is shown on Figure 1. Figure 2 shows the location of Area B at the Northeast Site.

The remediation was conducted for the U.S. Department of Energy (DOE) Office of Legacy Management (LM). Under contract to DOE-LM's technical assistance contractor, S.M. Stoller (Stoller), a team lead by WRS Infrastructure & Environment, Inc. (WRS) completed a full-scale remediation of NAPL at Area B on the STAR Center. The STAR Center is located in Largo, Florida. The site is owned by Pinellas County, but DOE-LM has responsibility for environmental cleanup activities at the site.

The contract was awarded to WRS in February 2004. Design started immediately and was completed in June 2004. Construction began in July 2004 and was completed in July 2005. Operations began in August 2005 and were completed in June 2006. DOE conducted the confirmatory sampling from July 2006 to September 2006, and WRS completed demobilization in December 2006. A more detailed project timeline is presented in Section 3.

The WRS team consisted of three companies: WRS, McMillan-McGee Corporation (Mc^2), and PPM Consultants (PPM). The approach used to remediate the site was to heat the subsurface using Electro-Thermal Dynamic Stripping Process (ET-DSP™) along with injection of ex situ generated steam to temperatures that would volatilize the contaminants and then extract and treat the volatilized contaminants.

The report is organized into four main sections. Section 1 provides background information and the management approach to the remediation. Section 2 describes the remediation approach and includes descriptions of the technologies used. Section 3 presents the results of the remediation, a project timeline, and discusses the operational phases and adjustments made during this phase. Section 4 evaluates the effectiveness of the remediation and presents lessons learned. The report also includes references and appendices.

1.1 Project Scope

The project scope included planning, design, construction, and operation and maintenance of a system that removed NAPLs and reduced total petroleum hydrocarbons (TPH) to specified levels from the subsurface at Area B of the Northeast Site. At the end of the remediation, the WRS team removed all remediation components and infrastructure at the site and returned the surface to its pre-remediation condition. Additional scope provided by the team included monitoring during operations, health and safety oversight during all field activities, waste management, environmental compliance, and disposal of remediation-generated wastes.

The WRS team completed this scope using ET-DSP™ technology to heat the subsurface with electrical resistive heating, convective heat transfer, and in situ steam generation; injection of ex situ generated steam in select areas; vapor extraction of volatilized contaminants and to maintain pneumatic control; ground water extraction to remove contamination and maintain

hydraulic control; and treatment and environmentally compliant discharge of the extracted vapor and ground water.

1.2 Remediation Goals and Performance Standards

The goals and performance standards for execution of the project, as specified by the Statement of Work (DOE 2003), were applied to the entire area and depth of the remediation. The Area B remediation area covered approximately 36,400 square feet (ft^2). The vertical extent of Area B was from ground surface to 10 feet (ft) below the top of the Hawthorn Group sediments (Hawthorn), a distance of about 40 ft, resulting in a remediation volume of 54,000 cubic yards (yd^3). In addition, remediation was required under a portion of Building 1400, located adjacent to the southern end of the remediation area.

The remediation goals and performance standards, as written in the Statement of Work (DOE 2003), are shown in the following text, Items 1 through 8.

1. NAPLs and dissolved and sorbed organic compounds shall be removed from the subsurface, within the remediation area, so that the ground water and soil concentrations are less than the cleanup goal concentrations listed in Table 1. Also, the treatment process shall be applied over the entire volume of the remediation area, even areas shown to not exceed the cleanup goals. To meet the cleanup goals, the water concentrations and soil concentrations of all four NAPL compounds (trichloroethene [TCE], cis-1,2-dichloroethene [cDCE], methylene chloride, and toluene) and TPH shall be at or below the cleanup goals. Within this report, these contaminants are also referred to as contaminants of concern (COCs).
2. The water and soil concentrations shall remain at or below the cleanup goals listed Table 1 for a minimum of 24 weeks after the completion of remediation. The completion of remediation is when active heating operations are stopped or the cleanup goals, as described in the first bullet of this section, are met, whichever is later. If concentrations exceed the cleanup goals within the 24-week period, the subcontractor (WRS) shall continue or resume remediation, at their own expense, to reduce water or soil concentrations to below the cleanup goals in Table 1.
3. Confirmatory soil and ground water samples will be taken to determine when the cleanup goals listed in goals have been met. The criteria for the samples are that there must be a 90 percent certainty that 90 percent of the site is at or below the cleanup goals. In addition, no soil sample may have a concentration that exceeds a cleanup goal by more than 100 percent and no ground water sample may have a concentration that exceeds a cleanup goal by more than 50 percent. In addition, for soil samples taken in the Hawthorn, a third criterion must be met. No more than 50 percent of the soil samples from the Hawthorn can exceed the soil cleanup criteria. Table A.10 from *Methods for Evaluating the Attainment of Cleanup Standards, Volume 1: Soils and Solid Media* (EPA 1989) will be used to determine the number of samples that can exceed the cleanup goals based on the number of samples taken. Sample locations will be determined randomly based on a minimum grid size of approximately 20 ft by 20 ft.
4. Confirmatory ground water samples will be collected three times after completion of remediation: once at approximately 6 weeks after active heating is completed or when all parts of the remediation area are less than 100 °C, once at approximately 12 weeks after

completion, and once at 24 weeks after completion. Confirmatory soil samples will be collected once after remediation. Each round of confirmatory ground water samples must meet the statistical criteria for cleanup. If the statistical criteria are not met by the confirmatory soil data or each round of confirmatory ground water data, the subcontractor shall immediately resume remediation.

5. The subcontractor shall conduct the remediation in a manner that maintains hydraulic control of the ground water in the remediation area, that follows the subcontractor's operational plan, and that ensures the ground water and soil cleanup goals listed in Table 1 are not exceeded outside the remediation areas. If remediation activities cause concentrations to exceed the cleanup goals listed in Table 1 in areas outside the remediation areas, the subcontractor shall expand the remediation system to remediate the affected areas so as to reduce the concentrations to the levels listed in Table 1, at no additional cost to Stoller. In addition, the subcontractor shall prevent mobilization of NAPLs to areas of the Hawthorn deeper than they already exist. If contamination is spread downward, the subcontractor shall remove contamination from those affected areas at no additional cost to Stoller.

6. The subcontractor shall ensure that all components of the remediation system, and discharges from those components, are in compliance with applicable regulatory requirements at all times during remediation. Fines assessed by a regulatory agency to Stoller or DOE for activities performed by the subcontractor that are not in compliance with requirements shall be paid by the subcontractor.

7. The subcontractor shall maintain a minimum operating temperature of 85 ºC (Celsius) at all times after this temperature is initially reached. The minimum operating temperature shall be maintained over the entire remediation area and from 10 ft into the Hawthorn to within 5 ft of land surface. Temperatures from land surface to 5 ft below the surface shall be maintained so as to prevent a condensation front from occurring in this area. After the minimum temperature has been reached, if the subsurface cools to less than 85 °C during downtime that is the subcontractor's fault, the subcontractor shall extend the heating duration. The duration of the heating extension shall be equal to the amount of time the temperature is less than 85 °C.

8. The subcontractor shall limit subsurface temperatures to a maximum of 40 °C at the outer edge of a defined zone under and adjacent to Building 1400 and to a maximum of 30 °C at the building's floor. The zone where temperature increases are to be controlled extends from under Building 1400 to 6 ft north of the building and from the surface to 6 ft below the surface (or under the building). Also, the subcontractor shall ensure that no subsurface vapors resulting from remediation activities enter Building 1400.

1.3 Site Information

1.3.1 Geology and Hydrogeology

The geology at the Northeast Site is comprised of three distinct stratigraphic units. These units, in descending order are: 1) undifferentiated surficial deposits, 2) the Hawthorn, and 3) the Tampa Limestone. Only the surficial deposits and the Hawthorn are relevant to NAPL remedial activities at the Northeast Site.

The surficial deposits have been characterized as composed of well-sorted to fine-grained silica sands with variable amounts of silt and clay. The thickness of the surficial deposits ranges from 26 to 34 ft. Generally, fine silty sand extends from ground surface to a depth of 5 to 10 ft bgs. Underlying the uppermost sand unit is fine sand containing variable amounts of shell. The fine silty sands and very fine, very silty sands are more laterally extensive than this shelly sand. Also significant is the presence of a thin, dense layer of silty sand in the middle portion of the surficial deposits in the northern portion of the site. The base of the surficial deposits is comprised of fine sand with shell and gravel and varies in the amount of clay content and thickness. This fine sand/shell/gravelly/clay layer consists of green phosphatic silty to sandy clay of various consistency and hardness and is typically less than 1 ft thick. This unit has been interpreted as the contact between the surficial deposits and the Hawthorn.

The Hawthorn is approximately 70 ft in thickness. The top of the Hawthorn consists of silty clay with variable amounts of limestone and phosphate gravel. A weathered limestone and clay were present at the contact between the overlying surficial deposits and the underlying Hawthorn. This layer is less than 3 ft thick and is laterally discontinuous. Silty, sandy, phosphatic clay of variable thickness underlies the silty clay and limestone. Below this unit, dry clay with up to 50 percent carbonate inclusions and fissile layers is present. This unit is approximately 10 ft in thickness and ranges in depth from 38 to 48 ft bgs. Observation of soil cores has indicated that desiccation cracks may be present in the upper 5 ft of the Hawthorn at a few locations. These cracks may have acted as preferential pathways for the vertical movement of NAPLs at the site.

Three ground water units have been identified at the site. These hydrogeologic units in descending order are:

1. The upper surficial sand unit (the surficial aquifer)
2. An intermediate clay confining unit (the undifferentiated portion of the Hawthorn)
3. A lower limestone unit (the Upper Floridan aquifer).

The depth to the top of the surficial aquifer ranges from 1 ft bgs during periods of heavy precipitation to approximately 6 ft bgs during extended dry periods. The overall saturated thickness of the surficial aquifer ranges from 28 to 33 ft depending on recharge conditions. The average hydraulic conductivity for the surficial aquifer is 1 foot per day (ft/day) for the very silty to clayey sands. The hydraulic conductivity of sands with lower silt content has been estimated at up to 15 ft/day. This variation in hydraulic conductivity is attributed to the lithologic heterogeneity that exists within the surficial aquifer. The vertical hydraulic conductivity of the surficial aquifer was estimated at 10 to 100 times less than the horizontal conductivity, ranging from 0.003 ft/day to 0.3 ft/day. Ground water flow within the surficial aquifer is generally to the east. The Hawthorn acts as a lower confining unit for the surficial aquifer. The reported vertical hydraulic conductivity of this unit ranges from 0.001 ft/day to 0.02 ft/day.

1.3.2 Nature and Extent of Contamination

Based on analytical results of samples collected from the site prior to thermal remediation, the primary light NAPL (LNAPL) compound was toluene. The primary dense NAPL (DNAPL) compounds were TCE, cDCE and methylene chloride. Heavy petroleum hydrocarbons were also present within the treatment area. These compounds were present due to their use during plant operations and subsequent disposal at the Northeast Site.

The distribution of the NAPLs within the subsurface was dependent on the type of NAPLs present. The majority of NAPL mass was located at the bottom of the surficial aquifer. NAPLs detected at shallower locations within the surficial aquifer contained the compounds toluene and TCE, while NAPLs at deeper intervals contained more TCE. NAPLs present in the upper part of the surficial aquifer existed in individual layers, while the NAPLs at deeper intervals appeared to be more continuous both vertically and horizontally. This indicated the presence of a more uniform or competent confining unit at depth (the Hawthorn). Another trend identified in the NAPLs distribution was for the NAPLs to be present just above the contact between different lithologies. This was an indication of the presence of lithologic heterogeneities within the surficial aquifer.

The areal extent of NAPLs within Area B was 36,000 ft^2. The area targeted for remediation extended to a depth of 40 ft, so the volume of Area B was approximately 54,000 yd^3.

1.4 Roles and Responsibilities

WRS was subcontracted to Stoller for the Area B remedial action. WRS teamed with subcontractors Mc^2 and PPM. Mc^2 was responsible for the overall technical approach, providing the ET-DSP™ equipment, temperature and pressure monitoring, and web-site management. PPM provided the engineering and construction of the treatment system, well field pumps, and collection piping as well as operation and maintenance of the extraction and treatment system. The responsibilities, authorities, and actions of the participants in the project were described in the NAPL Management Plan (DOE 2006).

All parties of the WRS team attended project meetings throughout the design, construction, operation, demobilization, and final reporting phases of work. During the operations phase an Operations Oversight Team, consisting of the WRS team members along with Stoller personnel was established. The Operations Oversight Team held weekly conference calls to review progress, interpret data and monitoring, and make joint operational decisions before proceeding to the next stage of operations.

1.5 Health and Safety

The Area B project effectively operated 900 calendar days since contract award in February 2004 without a lost time injury. Health and safety plans were developed for the construction, operations, and demobilization phases of the remediation project. Incorporated into these documents were requirements from the *Health and Safety Plan for the Young-Rainey STAR Center Environmental Restoration Program* (DOE 2001). The project was executed over 3 years (2004−2006) during which weather was the major cause of work stoppages. Most notably, three hurricanes impacted the Pinellas County region during September and October 2004. A stringent lightning monitoring program was developed by WRS and Stoller. Implementation of this program prompted work stoppages during the construction and operations phases. Other factors encountered during the project included heavy equipment operation, truck-trailer deliveries, critical lifts of operating equipment, high temperatures and humidity, high voltage electrical lines, high temperature steam lines, extraction of high temperature vapor and liquid streams, and highly contaminated soil vapor and ground water media.

A dedicated Health and Safety Officer was present at least 40-hours per week throughout the construction and operation phases. Prior to each definable work phase (i.e., construction, operations, demobilization), Stoller and WRS team personnel would participate in a review of the Health and Safety Plan. During these reviews, participants reviewed and discussed the upcoming work activities and how safe work practices were to be conducted. Personnel were required to acknowledge through signature that they had read and reviewed the safety plans. In addition, worker certifications were collected prior to allowing the participants site access. Safety briefings were held on a daily basis, usually in the mornings, by the Health and Safety Officer. These meetings discussed pertinent safety topics or a review of potential hazard conditions for the current day's work. For any hazards not specifically addressed in the plans, a Job Safety Analysis was executed.

1.6 Quality Assurance

Quality control (QC) plans were developed for the construction, operations, and demobilization phases of the remediation project. These plans described the policies and practices for a planned and disciplined approach to achieve the standards for quality, safety, and reliability of products and services supplied relative to the contract requirements. Through a defined system, personnel, materials, and services are continually inspected for compliance with the specifications and regulatory requirements. Once a deficiency is identified, the QC Plan identifies clearly defined actions to remedy the problem.

These plans provided controls over the activities of employees and lower-tiered subcontractors, each of whom had specific responsibilities for meeting the required quality objectives. The plans consisted of guidelines that collectively provided for: affecting quality under suitably controlled conditions; the use and maintenance of appropriate equipment; the implementation of environmental and special process controls; the conduct of inspections and tests; and the training and qualifications of personnel who perform activities that affect quality.

The final project resulted in achievement of the soil and ground water cleanup goals, compliance with environmental standards and regulations, and zero lost time injuries.

1.7 Project Cost

The total project cost for scope executed by the WRS team was $8,092,953. The approximate dollar breakdown by project phase is provided in Table 2.

1.8 Project Documents

The documents prepared by the WRS team for this contract are listed below.

WRS Infrastructure & Environment, Inc. *Conceptual Remediation Plan, ET-DSP™/Steam Thermal Remediation of Young-Rainey STAR Center,* April 2004.

WRS Infrastructure & Environment, Inc. *Environmental Compliance/Waste Management Plan*, May 2004.

WRS Infrastructure & Environment, Inc. *Stormwater Pollution Prevention Plan,* June 2004.

WRS Infrastructure & Environment, Inc. *Health and Safety Plan for Construction Phase*, June 2004.

WRS Infrastructure & Environment, Inc. *Quality Control Plan*, June 2004.

WRS Infrastructure & Environment, Inc. *Quality Control Plan - Operations Phase*, August 2005.

WRS Infrastructure & Environment, Inc. *Health and Safety Plan for Operations and Maintenance Phase*, August 2005.

WRS Infrastructure & Environment, Inc. *Operations and Monitoring Plan for the Treatment System*, August 2005.

WRS Infrastructure & Environment, Inc. *Health and Safety Plan for Demobilization Phase*, November 2006.

WRS Infrastructure & Environment, Inc. *Quality Control Plan - Demobilization Phase*, November 2006.

1.9 Permitting

Several permits were required to conduct the remediation at NAPL Area B, as described in the following sections.

1.9.1 Air Emissions Permit

The Northeast Site NAPL Area B remediation activity required a Synthetic non-Title V Construction Air Emissions Permit to control two point source emissions from the ground water treatment facility. Prior to continuously operating the treatment system, the construction permit was formally converted to an operating permit. The permit and modifications were subject to public comment and approved by the Florida Department of Environmental Protection (FDEP) pursuant to Chapter 403 of the Florida Statutes and Florida Administrative Code (F.A.C.) Chapters 62-204 through 62-297 and 62-4. The air emissions permit was required because Area B had the potential to emit a large amount of organic contaminants (the estimated mass of subsurface contamination was 15,000 pounds [lbs]). The new permit temporarily suspended the former permit that was put in place to treat dissolved phase organics, and addressed the construction and operation of a new air emissions system, required for the treatment of liquid and vapor phase contaminants at NAPL Area B. The permit also contained descriptions of all exempted units currently operating at the site.

1.9.2 Storm Water Discharge Permit

The subcontractor was required to maintain an FDEP Generic Permit for Storm Water Discharge from Large and Small Construction Activities. This permit required the subcontractor to implement appropriate pollution prevention techniques to minimize erosion and sedimentation and properly manage storm water runoff from the asphalt cap. The Northeast Site was considered

Phase I small construction because the size of land disturbance for Area B construction activities was between 1 and 5 acres. Also, the storm water was discharged to the East Pond, which is considered a surface water of the State. The permit was issued under the provisions of Section 403.0885, Florida Statutes, and Rule 2-621.300(4), F.A.C. pursuant to the FDEP's federally approved National Pollutant Discharge Elimination System storm water regulatory program. Federal storm water discharges associated with small construction activity, as defined at 40 CFR 122.26(b)(15) is regulated pursuant to Section 402(p)(2) of the Clean Water Act.

1.9.3 Industrial Wastewater Discharge Permit

The Pinellas County Utilities Industrial Wastewater Discharge Permit for the STAR Center allows the permittee to discharge wastewater into the Pinellas County wastewater system. The permit establishes maximum constituent concentrations for discharges into the sewer system, and lists the constituents that are sampled and reported on a regular basis. DOE submitted monthly effluent reports to the STAR Center for inclusion in their monthly reports to the Pinellas County Utilities. DOE has an agreement with the STAR Center ensuring that wastewater produced by DOE activities will not exceed the permit limits when it is combined with the wastewater produced by the STAR Center. WRS was required to sample their wastewater stream to ensure that permit limits were not exceeded.

1.9.4 Well Construction/Abandonment Permits

The subcontractor was required to obtain well construction and abandonment permits. *Rules of Southwest Florida Water Management District*, Chapter 40D–3, "Regulation of Wells," requires permits for the construction and/or abandonment of wells. Wells requiring permits include test holes, monitoring wells, and water wells. Any well with an inside diameter of 2 inches or greater must have a well construction permit prior to construction. These permits are issued to licensed drillers who are registered with the Southwest Florida Water Management District and are authorized by the landowner to conduct well development activities. All well abandonments require a minimum 24-hour notice to the Southwest Florida Water Management District prior to abandonment.

2.0 Remediation Approach

2.1 Technology Description

The remediation approach for Area B involved using ET-DSP™ technology in combination with in situ-generated steam as the mechanism for heating the subsurface. ET-DSP™ was the only heating technology used to heat under Building 1400. ET-DSP™ technology provided electrical resistive heating, convective heat transfer, conductive heating, and in situ steam generation through water injection at the electrodes. The approach was based upon the success and "lessons learned" from Area A, the NAPL remediation previously completed at another area at the Northeast Site. The approach also considered the lessons learned from several other steam and ET-DSP™ projects.

The results from a numerical simulation of the remediation approach using site-specific and laboratory-measured data were the basis for the ET-DSP™ design and other remediation components. The numerical simulation is provided in Appendix F, "Numerical Simulation Report." The simulation also was used to determine the time needed to achieve the 85 °C temperature requirement and operational parameters required for the system to achieve the remediation goals.

Extraction of the ground water and subsurface vapors was accomplished with dual-phase extraction wells. Extracted vapor and ground water were transmitted to the treatment system through separate lines. A high vacuum pump located in the above ground treatment area was used to create the vacuum for the vapor extraction. Ground water within the remediation area was extracted using pneumatic-powered pumps. Extraction of ground water was used to remove contamination and to maintain hydraulic control. Another component of the remediation was the asphalt vapor cap that was placed over the entire remediation area. A unique aspect of the vapor cap was use of a vertical skirt around the perimeter to increase vapor recovery from inside the remediation area and to maximize thermal efficiency by blocking ambient temperature soil vapor from outside the treatment area.

The heating approach was designed to heat the upper 10 ft of the Hawthorn; maintain a temperature of at least 85 ºC throughout the volume; create sufficient steam for thorough dynamic stripping; and extract enough liquids and vapors to maintain hydraulic and pneumatic control during contaminant recovery without removing excessive energy from the subsurface. Conservation of energy while extracting vapor and liquids has the greatest impact on the efficiency and economics of the process.

The design of the remediation system used as much available information as possible plus results from earlier resistivity work and full-scale numerical analysis to determine the following:

- Operating strategy for the effective deployment of in situ steam flow and economic use of electrical and steam energy.
- Well-field design (relative placement of electrodes, extraction wells, and steam spears).
- Energy types and quantities for sizing the power delivery system (PDS), steam generator, hot water heater, extraction equipment, and treatment facilities.

- Extraction scenarios, quantities, and contingency plans.
- Types and quantity of waste streams.

The design had several features that are protected in the patents for ET-DSP™ and remediation using steam, of which Mc^2 is a license holder from the University of California Berkeley. Description of the patents and their role in the remediation were provided in the Conceptual Remediation Plan (WRS 2004a). The Conceptual Remediation Plan also described the design and construction of the dual-phase high vacuum and treatment systems, a vapor cap that incorporates a skirt around the perimeter to increase vapor recovery, minimize heat loss, and optimize the well-field geometry.

2.2 Remediation Approach

This section presents the technical approach taken to heat the subsurface and remove the NAPLs. A summary of the project information and components used for the remediation are shown in Table 3.

Central to the thermal remediation plan were the combination electrode/steam wells, or injectors. Eighty-six of these injector wells were placed throughout the treatment area on 23.5 ft centers. Inside each of these injectors were two ET-DSP™ combination electrodes, each electrode was 10 ft long, with every third electrode completed with a shallow steam spear (i.e., 29 of the 86 injector wells). The electrodes within the injector wells were staggered to provide complete and uniform heating from surface to 10 ft into the Hawthorn.

Figure 3 illustrates how steam is formed and contaminants are extracted using ET-DSP™ and in situ steam generation. There are nine fundamental elements of the ET-DSP™ approach that are explained in further detail below.

As shown in Figure 3, the design provided for vertically staggered and stacked electrodes, which are positioned to achieve complete vertical and lateral development of the steam system.

Element 1: The entire treatment area was covered with a vapor cap that has a 5-ft impermeable "skirt" around the perimeter. This skirt was critical for minimizing heat loss and promoting effective and maximum vapor recovery. The skirt facilitated a greater degree of vacuum to be applied during pressure cycling events, resulting in a more rapid removal of the chemicals from the vapor phase. The vertical barrier also reduced the migration of cool vapor into the heated volume during extraction, enhancing thermal efficiency.

Element 2: The electrodes were stacked in two layers and vertically staggered relative to the optimum electrical phasing. This allowed for electrical current to be directed between the electrodes and through the vertical extent of the contaminated soil. The benefits of this approach are a uniform temperature distribution throughout the entire vertical profile of the soil; the ability to create preferential flow paths for steam; and reducing the number of boreholes required for installation. Stacking electrodes in a single borehole is an ET-DSP™ patent.

A principal element covered by the ET-DSP™ patent is the ability to inject water into the electrodes to create steam for the Dynamic Stripping Process and to mitigate the dipole effect caused by overheating of the ends of the electrodes. To heat the injected water to 85 °C and

facilitate in situ steam generation, heat exchangers and an industrial water heater were used. The heat exchangers were used to capture energy from extracted vapors and ground water. In addition, a redesign of the electrodes increased the amount of ET-DSP™ steam generation by 50 percent over previous designs of the electrodes. By using heated water for injection, less electrical energy would be needed for heating and steam would be more rapidly formed in the ground. This modification, combined with the increase in the electrode water temperature, was designed to create the effect of over 170 down-hole steam generators, each one capable of producing 60,000 BTU/hr of steam.

Element 3: The extraction wells were screened from 3 ft below the vapor cap to the top of the Hawthorn. Having the entire well open to flow allowed extraction when the entire area was at steam temperatures, and it was more efficient during pressure cycling. In combination with the vapor cap design, the extraction approach optimized rapid removal of chemicals from the soil and eliminated the potential for upward migration of buoyant chemicals into the vadose zone that may otherwise not be captured.

Element 4: Steam spears (approximately 7 ft long) were installed above all of the deep electrode wells (as indicated previously, at every third of the 86 injector wells or 29 locations). Although the model showed the entire zone would reach temperatures of at least 85 °C, the spears proved to be useful for Area A, and were therefore included in Area B as a strategic contingency.

Element 5: High permeability well construction was used to facilitate the heating between the stacked electrodes, and allowed for steam near the well bore to permeate uniformly into the soil over the entire length of the well bore. Steam injection wells were often limited in length in order to achieve injection of steam at high velocity into the soil. With the introduction of electro-thermal energy in the well bore, the requirement for maintaining high steam velocities is relaxed. Consequently, steam can be forced into a larger volume of soil in a horizontal direction. It was important to design the steam injection well bore with good vertical sweep because the vertical growth of the steam zone was not observed in Area A.

Element 6: The current path between electrodes can be varied using Inter-Phase Synchronization (IPS). These current paths were dynamically controlled during heating operations to ensure that any cold spots, which may result from varying electrical and lithological properties of the soil, were eliminated. The benefits of this patent-protected approach, which was demonstrated during the remediation of Area A, were a more uniform temperature distribution and development of thermal pathways for steam flow into otherwise poorly heated volumes of soil.

Element 7: The steam zone was created in the soil by injection of high temperature water and in situ electro-thermal energy. This approach eliminates the costs of surface steam injection equipment and water softening facilities, and provides better control of steam creation via flow and pressure of water, as well as a simplified well-field infrastructure. In combination with the heating achieved by ET-DSP™ and the vertical extent of the injectivity profile, pressure cycling resulted in a much more uniform development of a steam chamber and subsequent removal of contaminants as they were stripped out of the soil and captured at the extraction wells.

Element 8: The lower electrodes were located to achieve temperatures greater than 85 °C to a depth of 10 ft into the Hawthorn. The properties of the Hawthorn clay are such that electrical current, and therefore electrical heating, occurred there preferentially. Experience dictated that,

when clays are subjected to electrical heating, they have a tendency to micro-fracture, increasing their intrinsic permeability by orders of magnitude. All the electrical heating and extraction well bores were designed to take advantage of the increased permeability to fluid flow. This promoted effective heat transfer in the lateral direction.

Element 9: Buoyancy caused the thermodynamically created contaminant bubbles to rise vertically and escape from the heated volume. The continuous operation of the extraction system was sufficient to overcome the vertical buoyancy and pull the bubbles into the extraction wells. Back-up vapor extraction and treatment equipment was provided in parallel for maintaining operational up time.

2.3 Remediation Approach—Building 1400

The remediation goals for contaminated soil and ground water adjacent to and under Building 1400 were the same as for Area B, and the remediation of this area also used ET-DSP™ heating in combination with multi-phase extraction. The design used "oversized" vapor extraction in order to protect building occupants from potential fugitive emissions. In addition, a vapor-monitoring program was implemented during the remediation to verify there was no exposure to vapor phase contaminants inside the building during remediation.

The vapor flow rate and vapor pressure from under Building 1400 were monitored during the remediation. Vapor monitoring was performed to ensure that the vapor flow rate was high enough to capture the contaminants. Pressure monitoring also was performed to ensure there was negative pressure under the building. Maintaining a negative pressure under the building ensured that vapor flow was away from the building foundation and into the extraction wells. Although not part of this remediation, the ventilation system in the building created a positive pressure inside the building. The positive pressure inside the building with the negative pressure under the building ensured vapor flow was away from the building and not into the building.

Figure 4 shows the layout of extraction wells and electrodes for thermal treatment under Building 1400. Further details regarding Building 1400 are provided in Sheets S-3 and W-4 of Appendix G. The electrodes under the building (red circles inside blue squares) were set in place using slant hole drilling technology. These electrodes were also designed to function as extraction wells, if needed, although they were not used as such during the remediation. The vapor skirt, which prevented migration of vapors from Area B to under Building 1400, was placed between the C-A-B-C and B-C-A row of electrodes. The vapor barrier also helped in creating preferential flow of cooler vapors immediately under the building.

The electrode locations were determined as follows:

1. It was assumed that the contaminants under the building are DNAPLs and the migration path had been along ground water gradients in a generally downward direction. This was verified by the higher level of chemical concentrations in sample data near the top of the Hawthorn.
2. The deeper placement of the electrodes below Building 1400 resulted in heat flow vectors that were directed away from the surface and from beneath shallow depths around Building 1400, and

3. To address concerns about heating up the foundation of the building while maximizing thermal treatment in the area next to Building 1400.

The temperature gradients under Building 1400 that were modeled by the numerical simulation are shown in Figure 5 and Figure 6. Figure 5 shows that the heat flow gradients under Building 1400 at 5 ft below the building would be much less than at the top of the Hawthorn (the temperature gradient is the amount of color change over distance). The calculations demonstrated that an electrode and extraction design could be implemented that would meet the remediation objectives and thermal constraints (i.e., minimum temperature requirements) around Building 1400. Figure 6 shows that the required temperature of 85 ºC could be achieved under the building. The Building 1400 remediation operated at the same time as the Area B remediation.

2.4 Well-Field Layout and Construction

2.4.1 Well-Field Layout

The well field for Area B, as initially constructed, consisted of a network of 86 electrode boreholes (29 of these boreholes included shallow steam spears), 64 temperature monitoring boreholes, 30 pressure monitoring locations, 6 shallow steam spear boreholes, 23 extraction well boreholes, 10 contingency well boreholes, and 6 outside monitoring well pairs at the onset of operations. Additionally, the well-field layout for remediation at Building 1400 was comprised of nine additional electrode boreholes, one pressure and temperature monitoring location, and three horizontal vapor extraction wells.

A well-field layout map for Area B is presented in Figure 7. The Building 1400 well-field layout is presented in Figure 4. Modifications made to the well field during the operations phase are discussed in Section 3.11.

Components of the Area B well-field layout were as follows:

- Eighty-six shallow and eighty-six deep stacked ET-DSP™ electrodes for heating of the surficial aquifer and Hawthorn (E01S through E86S and E01D through E86D, respectively);
- Sixty-four digital temperature sensor locations integrated with the local area network for capturing real-time temperature data. Each temperature string had sixteen individual sensors, which provided over a thousand independent temperature monitoring locations (d01t through d67t). Additionally, digital thermocouples (digiT/Cs™), were installed in each electrode borehole;
- Thirty digital pressure sensors integrated with the local area network for capturing real-time pressure data across the well field;
- Twenty-nine shallow steam spears to heat the upper treatment zone installed in each of the deeper electrode pairs plus six dedicated steam spears;
- Twenty-three multi-phase extraction wells with independent vapor and liquid recovery header systems consisting of submersible pneumatic pumps and high-vacuum vapor extraction to extract water during heat up, to pump water that may not reach boiling

temperatures, and to contain ground water in the treatment area that otherwise may not be accomplished by vapor extraction alone (X01 through X23);

- Ten contingency extraction wells to assist with ground water and vapor recovery activities (C01 through C10); and,
- Twelve existing monitoring wells for sampling of the perimeter outside the treatment area presented in Sheet S-2, Appendix G (M29S, M29D, M30S, M30D, M31S, M31D, 0557, 0579, 0580, 0581, 0582, 0583).

Components of the Building 1400 well-field layout were as follows:

- Eight stacked shallow and deep vertical electrodes (EV01S through EV04S and EV01D through EV04D, respectively);
- Five slanted electrodes extending underneath Building 1400 (ES01 through ES05);
- One horizontal temperature sensor well (dh01);
- One digital pressure sensor well (d02);
- Three horizontal vapor extraction wells (XH01 through XH03); and,
- Shared electrodes and temperature sensors with Area B.

The aforementioned well-field layout was modified in January, February, and March 2006 in an effort to improve heating and extraction operations in a recalcitrant area. Well-field modifications are discussed in more detail in Section 3.9.

- January 18−20, 2006: Three additional digiTAM™ (digital temperature acquisition modules) boreholes were installed for sensor locations d65t, d66t and d67t.
- February 13, 2006: Existing 2-inch monitoring wells d26 and d30 were converted to dual phase extraction wells in Area III.
- February 22−24, 2006: Twelve shallow steam spears NSS01 through NSS012 were installed across the site for additional heating in the shallow treatment zone.
- March 6−9, 2006: Boreholes for two additional multi-phase extraction wells, X24 and X25, were installed in the area near extraction well X15. Six additional vapor extraction wells, VX01 through VX06, were installed across the site. Two additional digiTAM™ boreholes were installed for sensor locations d68t and d69t in this same area. Also, two contingency wells (C04 and C05) were retrofitted with submersible pumps.

2.4.2 Well Construction Details

A total of 172 electrodes were installed in 86 electrode locations in the Area B treatment area (electrode locations E01 through E86 shallow and deep). The Area B electrodes were installed according to the electrode phase (i.e., A, B or C Phase) and stacked in two layers and vertically staggered to the optimum electrical phasing. Each electrode was constructed of 10-ft long, 8-inch diameter metal with slots at the top, middle and bottom to allow for the circulation of heated injection water. Water circulation lines for each of the slots and a power cable extended from each electrode to the land surface. The digiTAM™ temperature monitoring strings were also installed adjacent to the electrodes in each borehole.

Sonic drilling techniques were utilized to install each electrode in a 10-inch diameter borehole, which was drilled to between 37.5 to 42 ft bgs. The annulus around the electrode consisted of approximately 9 ft of granular graphite material. A minimum of 0.5 ft of ASTM-E11 20/30 silica sand was installed above and below each electrode interval. A 1- to 3-ft bentonite seal was also installed in the B and C Phase boreholes above the silica sand layer located above the upper electrode. This was followed by an additional 2- to 5-ft 45/65 fine silica sand seal in the case of the C Phase boreholes. All of the electrode installations were completed with a 2.5- to 5.5-ft Class H oil well high temperature grout seal to land surface. Electrode construction details are shown in the as-built drawings W-1 and W-1a (Appendix G).

2.4.2.1 Slant and Near-Vertical ET-DSP™ Building 1400 Electrodes

Four near-vertical boreholes were constructed and each borehole contained stacked electrodes (EV01 through EV04 shallow and deep). These were installed 5 ft north of Building 1400 and angled 5 degrees downward and inward towards the building. Likewise, five single slanted electrodes (ES01 through ES05) were installed approximately 30 ft bgs at approximately 35 degrees to 37 degrees towards the building. The bottom of each slanted electrode was installed 15 ft in the horizontal direction below the building foundation. Both the near-vertical and slanted electrode boreholes were installed by employing sonic drilling techniques. Building 1400 electrode construction details are presented in as-built drawings W-4 and W-5 (Appendix G).

2.4.2.2 Extraction and Contingency Wells

Twenty-three extraction wells (X01 through X23) and ten contingency wells (C01 through C10) were installed throughout the treatment area with identical construction characteristics. Wells were advanced using sonic drilling techniques to approximately 40 ft bgs in an 8-inch diameter borehole. Each well was constructed with 35 ft of 4-inch diameter continuous wire wrap, 0.010 (10 slot) stainless steel screen threaded to a 4-inch diameter carbon steel tubing riser. The annular space surrounding the well screen was filled with 20/30 silica sand filter pack to 1.0 ft above the screen. The annular space above the filter pack was then filled with a 1.0-ft 45/65 fine sand seal. The remaining annular space was completed to land surface with a Class H oil well cement and 40 percent silica flour mixture. A 4-inch diameter steel bolt flange was welded to the top of each riser for connection to the well head or a blind flange for the extraction and contingency wells, respectively. Extraction and contingency well construction details are shown in as-built drawings W-3 (Appendix G).

2.4.2.3 Shallow Steam Spears

Twenty-nine shallow steam spears were installed at the C Phase electrode locations. Each steam spear was constructed of 5-ft of 1-inch diameter slotted steel screen threaded to a 2-ft steel riser. The annulus surrounding the steam spear screen was filled with a 45/65 fine silica sand filter pack. The remaining annular space above the fine sand pack was then filled with a high temperature grout to land surface. The six dedicated steam spears also were installed. These steam spears were constructed the same as the steam spears located in electrode borings.

2.4.2.4 Digital Temperature Sensor and Combined Digital Temperature/Pressure Wells

A total of 33 dedicated temperature-monitoring locations were installed across the site. A direct push technology (DPT) drill rig was utilized to advance each well in a 3.25-inch diameter borehole. Each dedicated digital temperature sensor location was constructed with 40 ft of 1-inch diameter Schedule 80 Chlorinated Polyvinyl Chloride (CPVC) casing with a 1 ft stub-up above land surface. The annular space surrounding the well casing was filled with high temperature grout. Additionally, digiT/Cs™ were installed in each electrode borehole.

Seventeen sensor locations were combined digital temperature and pressure sensor wells installed via DPT technology in 3.25-inch diameter boreholes to approximately 40 ft bgs. Each combined sensor location was constructed with 20 ft of 2-inch diameter Schedule 80 CPVC well screen and 20 ft of Schedule 80 CPVC riser with a 1 ft stub-up above land surface. The annular space around the well screen was filled with a 20/30 silica sand filter pack to 5 ft bgs and completed to land surface with high-temperature grout.

The remaining temperature and pressure monitoring locations consisted of existing monitoring-, extraction-, and contingency-well locations, which had been retrofitted to accommodate the digital temperature and/or pressure string.

2.4.3 Vapor Cap Construction

A plan layout of the vapor cap and skirt boundary is shown on as-built drawing VC-2. A detailed cross section of the vapor cap and vapor skirt is shown on as-built drawing VC-3.

The vapor cap was constructed to act as a barrier for subsurface vapors and to also limit the cooling effect of rainwater on the treatment volume. The total area of the cap was 38,144 ft^2. In addition, an 5-ft impermeable vertical barrier or 'skirt' was placed around the perimeter of the treatment area. The skirt limited the cooling effect of perimeter air flow into the treatment volume. Also, it would allow for a greater vacuum to be applied to the vadose zone and would further mitigate the possibility of vapor accumulation and condensation beneath the vapor cap.

Prior to construction, the limits of Area B, as well as a drainage swale, were delineated from surveyed coordinates. The original ground was stripped of any remaining vegetation and topsoil and a low spot was filled and compacted with imported fill. A trench was excavated approximately 2 ft outboard of the perimeter and to a depth of 5 ft below original grade. The skirt, consisting of 5 ft of 20-mil high-density polyethylene (HDPE) liner, was placed vertically into the trench and backfilled. An initial sub-base course of fill was placed on average in a 6-inch loose lift and compacted to 4 inches over the Area B footprint. A second lift of crushed concrete and limestone was also placed in a 6-inch loose lift and compacted to 4 inches. More sub-base material was required at the northern half of the footprint so as to create a slope for stormwater run-off. In general, the slope of the asphalt cap was at a one percent grade to the drainage swale that was constructed adjacent to the south perimeter of the footprint. The drainage swale itself was built from original grade with the sub-base material and sloped from the west to the east terminating with a rip-rap apron at the East Pond. Asphalt was then placed in two 2-inch lifts for a total cap thickness on average of 12 inches.

The vapor skirt was then extended around the Area B perimeter along the north side of the asphalt cap. The skirt extension occurred at areas where the asphalt sub-base layer exceeded

6 inches in depth. This location corresponded to the beginning of the west side of Building 1400 and proceeds along the Area B north perimeter for approximately 600 lineal feet. At certain locations, it was necessary to extend the skirt up to 2.5 ft below top of asphalt grade. This depth varies as the grade of the asphalt varies. The HDPE liner was extended approximately 6 inches above the asphalt grade. The trench was then backfilled with the excavated spoils. In order to seal the "gap" between the edge of asphalt and top of the geomembrane, a 1-inch thick cement-slurry "plug" was placed on top of the membrane.

2.4.4 Abandonment

After remediation activities, all newly constructed wells and existing wells that were retrofitted for monitoring were abandoned using a tremie method with a Portland cement grout. A total of 41 extraction/contingency wells (4-inch diameter), 63 digital sensor wells (1−6-inch diameter), and 4 horizontal wells were abandoned in place. All abandonments were completed in accordance with the requirements of the Southwest Florida Water Management District.

2.5 ET-DSP™ System and Thermal Components

This section describes the ET-DSP™ equipment along with the other thermal equipment that was used to heat the subsurface. The equipment is listed in Table 4 and described in the following sections. The 3.3 million BTU/hr diesel-powered steam generator was brought on site in the later stages of the operations phase to provide additional steam injection capability (i.e., in addition to what the ~1 million BTU/hr electrical steam generator could provide).

There are three main equipment components required for ET-DSP™ thermal remediation: PDS, water circulation system, and electrodes.

2.5.1 ET-DSP™ Electrodes

***Electrodes*:** The ET-DSP™ electrodes for Area B (Figure 8) were all 10 ft in length with an outside diameter of 8 inches and an approximate weight of 125 lbs. The ends were electrically isolated to ensure lateral current distribution (patented) and were designed with a revised internal chamber to accommodate maximum steam injection rates into the subsurface via slots in the side of the electrode.

2.5.2 Power Delivery Systems

The ET-DSP™ PDSs (Figure 9) consisted of a paralleled pair of transformers with a combined rating of 400 kilovolt amperes (kVA). The PDS units were all completed with time-distributed control modules, multiple tap settings to handle a range of soil resistivities, and were accessible over the internet for individual electrode control.

2.5.3 Water Circulation System

The ET-DSP™ water circulation system (Figure 10) was integrated with the hot water feed system. Each electrode/steam injector had an independent water feed system with complete internet control with manual override for local operator control. Each electrode/steam injector had a total capacity of more than 5 gallons per minute (gpm) cold water equivalent.

2.5.4 Industrial Water Heater

An industrial water heater (Figure 11) was used to preheat water injected at the electrodes. It was rated at 6 million BTU/hr and was capable of delivering >100 gpm at 80 °C with an overall efficiency rating of 99 percent. The water intake consisted of a standard potable water line and required no softening or chemical alteration.

2.5.5 Steam Generators

The electric steam generator, shown in Figure 12, was a dual-purpose steam generator that was used to regenerate carbon and to generate steam for the 29 shallow steam spears. The unit had a rating of 0.8 to 1.4 million BTU/hr. This unit proved to be too small to provide the steam injection needed for the operations and, therefore, another diesel-fired steam generator was used for the last 2 months of operations. This steam generator had a capacity of 3 million BTU/hr.

2.6 Extraction and Treatment System

2.6.1 Vapor Extraction from Wells

The typical vapor extraction wellhead configuration consisted of a 4-inch diameter, custom-fabricated, steel wellhead fitted with the following:

- A 2-inch tee through which vapors were extracted. A 2-inch ID schedule 80 CPVC pipe was connected to the tee to provide electrical isolation from the steel conveyance piping. The CPVC pipe was connected between the wellhead to the conveyance piping with 2-inch diameter, steel-reinforced, temperature and chemical resistant hose fitted with camlocks. The hose attached to a straight run of 2-inch diameter steel piping welded to the header. A pitot tube was installed in the top of the 2-inch steel vapor line for vapor flow measurement.
- A brass tee attached to the wellhead casing fitted with a vacuum gauge to measure the applied vacuum and a sample port to collect vapor samples for screening organic vapors with a flame ionization detector (FID) or photo ionization detector.
- A temperature gauge attached to the wellhead casing to measure the vapor temperature.
- A custom-fabricated well seal/cap through which air and water lines passed for the submersible pumps.

Each wellhead was bolted to the well with a steel flange on the bottom and a CPVC flange on the top to provide additional electrical isolation. A grounding cable was attached to the bottom of the wellhead at one of the bolts. A wellhead detail is provided on sheet M-11 of the as-built drawings in Appendix G. A photograph of a typical extraction wellhead is provided in Figure 13.

Throughout the period of system operation, all 10 contingency extraction wells, selected steam spears, six 2-inch vacuum extraction wells installed during operations, and two monitoring wells were fitted with similar wellheads and connected to the remediation system piping to provide additional vapor extraction. The wellheads for the various configurations were generally equipped as described above.

Periodically during operations, a drop tube configuration was used at several wells to provide air lift for ground water extraction through the vapor extraction system while pump repairs were being performed. The 1-inch schedule 80 CPVC drop tube was inserted through the hole in the well seal/cap where the ground water extraction line was normally located. The drop tube was outfitted with a 1-inch ball valve for manual control of ground water extraction rates through the vapor line by varying the introduction of ambient air into the well at the water table interface.

2.6.2 Liquid Extraction from Wells

In most cases, liquid was extracted from the extraction wells using 3.5-inch diameter, stainless steel, pneumatically driven submersible pumps. The 56-inch long pumps were installed 1 to 2 ft above the bottom of the well and the intake was located on the bottom of each pump. Extracted ground water was pumped through 5/8 inch nylon tubing, routed through the wellhead cap/seal and connected to the steel conveyance piping. Compressed air was supplied to the pump through ¼ inch nylon tubing from the steel conveyance piping, through the wellhead cap/seal. Exhaust air from the pump was routed through ½ inch nylon tubing and discharged in the headspace of the well, between the water table and the wellhead.

At varying times during operations, the submersible pumps in extraction wells X02 and X19 and contingency well C04 were replaced with above-ground, pneumatically driven, double diaphragm pumps. The double diaphragm pumps utilized the same extraction and air supply tubing.

2.6.3 Extracted Fluids Conveyance

The extracted vapor was transported through a 2-inch hose and associated 2-inch piping at each well to the 6-inch diameter steel vapor extraction-piping header. This header teed into a main 8-inch steel pipe to the treatment system.

The liquids from the submersible pumps were conveyed to the liquid treatment system through the 5/8-inch tubing and associated 2-inch piping at each well to the 4-inch ground water extraction-piping header. This header teed into a main 6-inch steel pipe to the treatment system.

2.6.4 Effluent Cooling and Treatment System

The effluent streams that were treated were: (1) all vapors and entrained liquids extracted from the subsurface by the vacuum extraction system, (2) liquids (NAPL and water) extracted from the subsurface by the dedicated liquid pumps, and (3) solids mobilized and extracted with the ground water. Sheets M-1, M-2, and M-3 of the as-built drawings (Appendix G) show the process flow for each stream. Sheets M-4 through M-9 of the as-built drawings show the more detailed process and flow diagrams. Sheet M-10 shows the physical layout of the equipment, along with some of the piping. Sheets M-14 and M-15 illustrate equipment details, fluid design parameters at various points along the system, and control logic. Descriptions of the flow process for each stream are presented in the following sections.

2.6.4.1 Vapor Stream Flow Process

The extracted vapors and entrained liquids were carried to the treatment system through surface piping. The vapors first entered a liquid-vapor separator (KO-1A/B), in which NAPL, water, and

solid fines carried with the vapors were removed from the vapor stream. Next, the vapors passed through a series of heat exchangers (HE-1A/B, HE-2A/C, and HE-2B/D), in which the temperature was reduced to below 43 °C (110 °F). HE-1A/B was liquid-cooled heat exchangers where the exchange fluid was the treated ground water to be recycled to the well field as injection water at the electrodes. HE-2A/C and HE-2B/D were air-cooled heat exchangers with large fans. Cooling led to condensation of water vapors and contaminants (the condensable gases). The condensate was removed from the vapor stream in a second liquid-vapor separator (KO-2A/B), and the non-condensable gases continued to the vacuum pump (S-1A/B).

After the vapors were reheated by friction in the vacuum pumps, the vapor stream flowed through a large muffler, then was cooled through another series of liquid-cooled heat exchangers (HE-3A and HE-3B) to 60 degrees Fahrenheit (°F). The exchange fluid in HE-3A was cooled by water processed through a cooling tower to 82 °F. The exchange fluid in HE-3B was municipal water processed through a chiller to 50 °F. The excess liquid was removed in a third liquid-vapor separator vessel (KO-3). The vapor stream was then re-heated to 82 °F in a heat exchanger (HE-4) using hot water as the exchange fluid to reduce the relative humidity in the vapor stream to 50 percent

The vapor stream was then treated through two sets of carbon canisters in series for treatment (VGAC-1A/B and VGAC-2A/B). The primary set of carbon canisters (VGAC-1A/B) contained 1,500 lbs of carbon each, which was regenerated on-site using steam from a steam generator (B-2) that also produced steam for injection. The secondary carbon canisters (VGAC-2A/B) each contained 3,000 lbs of carbon and were used to remove any contaminants that remained in the vapor stream. After passing through both primary and secondary vapor phase carbon vessels, air was emitted to the atmosphere through a 30-ft discharge stack constructed of 8-inch PVC pipe.

During steam regeneration of the carbon in the primary vessels, the condensate was cooled in a series of liquid-cooled heat exchangers (HE-6 and HE-7). HE-6 exchange fluid was municipal water and HE-7 exchange fluid was municipal water chilled to 50 °F. The condensate flowed to two holding tanks (T-7A and T-7B) where NAPL was gravity separated. Water from T-7A/B was vacuumed back into the system, into KO-1A/B, and NAPL was pumped from T-7A/B into storage tanks (T-2 and T-3) or directly to 55-gallon drums for disposal.

2.6.4.2 Liquid Stream Flow Process

The liquids extracted from the recovery wells were combined with the liquids separated from the vapor stream in the liquid-vapor separators (KO-1A/B, KO-2A/B, and KO-3), and pumped into phase separators (T-1A/B), in which both LNAPL and DNAPL were removed if present. DNAPL and coarser solids were removed from the bottom of the tank, and LNAPL was removed from the top of the tank as a floating layer. All LNAPL and DNAPL that was removed from the oil-water separator were transferred via steel 5-gallon buckets to T-2 or T-3.

The water was then pumped through air-cooled heat exchangers (HE-5A/B), treated in 5-tray air strippers (AS-1A/B), and discharged into an equalization tank (T-4). The liquid was then pumped through bag filters (BF-1A/B) to remove solids that didn't settle in T-4, then through one of two 3,000-pound carbon vessels (LGAC-1A/B) for secondary treatment, and finally to a holding tank (T-5). The flow of water pumped from T-5 was split between the STAR Center industrial wastewater system and to on-site water heater (B-1) for injection at the electrodes. An

additional liquid-phase carbon unit (LGAC-2) was staged on site for tertiary treatment, but was never needed.

2.6.4.3 Solids

Solids were removed from the phase separators and holding tanks at the end of the project and drummed for disposal.

2.7 Monitoring and Sampling

2.7.1 Subsurface Temperature Monitoring

Digital temperature sensors called digiTAMs™, designed to withstand temperatures up to 257 °F (125 °C), were used to monitor subsurface temperatures, Figure 14.

The digital temperature sensors used for the Area B project were significantly more accurate and reliable than analog thermocouples. The digital temperature sensors developed by Mc^2 have been termed digiTAMs™ and these were integrated with Mc^2's local area network and overall data acquisition strategy for the project.

Over 2,000 temperature monitoring points were used in 150 locations. The digiTAMs™ were used in dedicated temperature monitoring locations and temperature and pressure monitoring locations. digiT/Cs™ were used in electrode locations.

2.7.2 Subsurface Pressure Monitoring

The remediation at Area B also used 30 digital pressure sensors, called digiPAMs™ (digital pressure acquisition module). The digital pressure sensors used were designed to withstand temperatures up to 135 ºC and harsh chemical environments. As with the digiTAMs™, the digiPAMs™ were integrated with Mc^2's local area network and overall data acquisition strategy for the project. The pressure readings were converted directly to digital signals to limit the effects of high electromagnetic interference from the thermal remediation. Digital sensor locations and type are identified in Sheets S-2 and W-3, Appendix G.

2.7.3 Well Head Measurements

2.7.3.1 Extraction Rates, Pressure, and Temperature

Vapor extraction rates were measured at each 2-inch vapor extraction line using Dwyer DS-300 pitot tubes inserted into the metal piping. The differential pressure across the pitot tube was measured using a digital manometer. The flow rate was calculated from the measured differential pressure using a standard formula supplied by the manufacturer.

Beginning in March 2006, differential pressures were measured across a venturi and a specially fabricated orifice plate. Vapor extraction rates were calculated based on these two measurements to provide additional flow information to compare to the measurements taken from the pitot tubes. This was done because of suspicion that water droplets in the vapor stream impacting on the pitot tubes may have created errors in the readings.

Extracted vapor temperatures and pressures (vacuum) were read directly from permanently mounted gauges at each extraction wellhead.

2.7.3.2 Steam Pressure and Temperature

Steam injection temperatures and pressures were read directly from permanently mounted gauges at each of the steam spears.

2.7.4 ET-DSP™ Rate Controls

During the heating phase, control of power to the electrodes utilized a system of Time-Distributed Control and Inter-Phase Synchronization (TDC/IPS). This process controlled the amount and timing of power sent to individual electrodes. For example, when it became apparent that certain electrodes were located in electrically resistive zones that resulted in cold spots, the power to the electrodes in these areas was increased.

TDC/IPS provided uniform heating to the targeted soil areas by controlling the electrical sine wave of three-phase power down to the millisecond so that each phase was individually manipulated. Additionally, the PDS had an assortment of voltage tap settings to further control the heating process. This system was fully programmable and was accessed over the Internet for remote monitoring and control.

The TDC/IPS method of controlling current was based on the following four principles:

1. Controlling the voltage and phase between electrodes to force electrical current to flow into soil with varying electrical properties using IPS;
2. Controlling power to each electrode so that maximum power can be delivered to the soil during heating operations. This is called TDC;
3. Deliberate cooling at the ends of the electrodes by circulating water so that the current can flow more uniformly from the electrode into the soil. This also prevents boiling off of the water phase necessary for maintaining current flow in the soil and making it possible for more power to be input to the electrode; and
4. The pattern of electrodes, which allows for more even distribution of power.

Although all of the above are critical for reaching and maintaining temperature, the most important aspect of heating the subsurface was the ability to control power to each electrode. This allowed the system to operate at maximum capacity despite the heterogeneity of the geology and the resulting variability in the power density associated with each electrode.

2.7.5 Treatment System Monitoring

2.7.5.1 Water Sampling

Water samples were collected from the treatment system ground water influent and effluent streams daily for the first week of operations and on a weekly basis thereafter. The influent sample was collected from the influent pipe containing the combined ground water influent from the submersible pumps in the extraction wells. The effluent sample was collected from the

discharge line after the treated water holding tank (T-5), which contained the water that had been treated through the air strippers and the carbon units. Sample locations are shown in Figure 15.

The influent and effluent samples were submitted to Severn Trent Laboratories of Tampa, Florida. Influent samples were analyzed for the following:

- Volatile organic compounds (VOCs) by U.S. Environmental Protection Agency (EPA) Method 624, and
- TPHs by the Florida Petroleum Range Organics (FL-PRO) Method.

Effluent samples were analyzed for the following:

- BTEX (benzene, toluene, ethylbenzene, and total xylenes) by EPA Method 624,
- VOCs by EPA Method 624,
- Phenol and bis (2-ethylhexyl) phthalate by EPA Method 625,
- Arsenic by EPA Method 200.7,
- Total Suspended Solids (TSS) by EPA Method 160.2, and
- pH by EPA Method 150.1.

VOC analyses of the influent and effluent were used to determine mass removal in the liquid phase and to determine water treatment system efficiency. TPH analyses of the influent were used to determine petroleum hydrocarbon removal from the subsurface. BTEX, arsenic, TSS, and pH were collected in order to comply with STAR Center Industrial Wastewater Discharge Permit requirements.

2.7.5.2 Vapor Sampling

Vapor samples for laboratory analyses were collected weekly from the influent and effluent streams of the vapor treatment system. The vapor influent sample was collected from the second knock-out tank (KO-2A/B), which consisted of a mixture of vapors from all of the extraction wells before treatment. The vapor effluent sample was collected from the discharge piping after the second stage of vapor phase carbon (VGAC-2A/B). Sample locations are shown in Figure 16.

The vapor influent and effluent samples were collected in 1-liter Tedlar bags and shipped to Gulf Coast Analytical Laboratories of Baton Rouge, Louisiana. The samples were analyzed for VOCs using modified EPA Method 18. These analyses were used to determine mass removal in the vapor phase and to determine vapor treatment system efficiency.

At least once a day, vapor samples were also collected from the same locations and an intermediate location (Figure 16) between the first stage and second stage vapor phase carbon using 1-liter Tedlar bags. These samples were analyzed on site using a MicroFID organic vapor analyzer (OVA). The purpose of these samples was to provide more frequent monitoring of vapor treatment system efficiency and to determine if steam regeneration cycles for the first stage carbon needed to be adjusted.

2.7.5.3 Process Monitoring

Readings were collected at least once a day from treatment system flow meters, pressure gauges, temperature gauges, differential pressure gauges, pitot tubes, and liquid level gauges. These measurements were used to determine if the system was operating properly and to determine if system adjustments or maintenance were needed. The pressure readings from the pitot tubes were used to calculate flow rates from the vapor treatment system and the vapor discharge from the air strippers. The water and vapor flow rates were also used to make operational decisions. The flow rates and differential pressures collected from the air stripper vapor flow were used for compliance monitoring required by the air permit.

2.8 Pre-Operations Sampling

2.8.1 Pre-Operations Soil Sampling

DOE conducted a soil investigation in 1999 and 2000 to define the limits of the NAPL remediation area, the results of which are provided in the Northeast Site NAPL Characterization Report (DOE 2000a) and its addendum (DOE 2000b). An additional characterization event for NAPL was conducted more recently in August and September 2003 (DOE 2004). This event consisted of collection of soil data to better define the remediation area boundaries and to demonstrate that no soil concentrations above the NAPL remediation cleanup goals existed outside the remediation area.

2.8.2 Pre-Operations Ground Water Sampling

Prior to the start of operations, baseline ground water samples were collected from 35 monitoring locations in July 2005. Twelve of the monitoring points were monitoring wells located outside the treatment area (wells M29S, M29D, M30S, M30D, M31S, M31D, 0557, 0579, 0580, 0581, 0582, and 0583). The remaining 23 sampling locations consisted of extraction wells X01 through X23 located inside the treatment area. Samples were collected at each location for analysis by EPA Method 8260B and FL-PRO. Baseline analytical results are presented in Appendix C, “Baseline and Interim Sampling Results.”

3.0 Results

3.1 Project Timeline

A summary of the project activities, organized by phases, is presented in Table 5. The information in Table 5 supplements and provides additional details for the activities listed in the project schedule in Appendix B.

3.2 Operational Phases

The operational phases are listed below and are discussed in more detail in the following text.

- Hydraulic and pneumatic control—August 16, 2005 to September 1, 2005
- Preheat—September 1, 2005 to September 23, 2005
- Ramp-up—September 23, 2005 to January 15, 2006
- Maintenance—January 15, 2006 to March 31, 2006
- Extended heating—March 31, 2006 to April 28, 2006
- Cool down—April 28, 2006 to June 12, 2006

Throughout the operations phase, the Operations Oversight Team had weekly conference calls to assess progress, discuss whether to move to the next phase, and address problems. Also, during the cool down period, the area around extraction well X15 was heated for an additional week.

3.2.1 Hydraulic and Pneumatic Control

The hydraulic and pneumatic control phase began on August 16, 2005, with extraction of ground water from wells within the remediation area to establish hydraulic control. Hydraulic control was established within 2 days as indicated by water levels within the remediation area that were lower than levels outside the remediation area. Efforts to establish pneumatic control were initiated on August 19, 2005, with the extraction of vapors from the remediation area. Vacuum levels that averaged 10 inches of mercury were established within a day. To ensure adequate hydraulic and pneumatic control, extraction of ground water and vapors continued without heating being initiated until September 1, 2005. During this phase, treatment system start-up and optimization activities were initiated and ongoing.

3.2.2 Preheat Phase

After hydraulic and pneumatic control had been established and confirmed, the preheat phase was initiated. This phase was initiated on September 1, 2005, and continued until September 23, 2005. ET-DSP™ operations began at the perimeter of Area B and in the Hawthorn. By operating ET-DSP™ from outside the remediation area to inside the remediation area, an additional hydraulic barrier was formed through the injection of heated water and formation of steam at the electrodes. Also, a thermal barrier was created at the Hawthorn to capture possible downward migration of DNAPL. Increases in ground water extraction paralleled increases in water injection to the electrodes so that hydraulic and pneumatic control was always maintained.

Operation of ET-DSP™ electrodes in the interior of Area B began contemporaneously with the heating of the perimeter and Hawthorn. Electrodes on the interior of Area A were operated at half power and with no water injection. Heating at half power at the interior wells accelerated the perimeter and Hawthorn heating by minimizing heat losses. This strategy was followed for 3 weeks.

Heating under Building 1400 proceeded in a manner similar to the main remediation area. During this phase, the Hawthorn electrodes (lower electrodes) under Building 1400 were on full power and with water injection while the upper electrodes were operated at 50 percent power.

3.2.3 Ramp-Up Phase

Ramp-up operations began September 23, 2005, immediately after the preheat phase. At this time, full power and heated water injection was supplied to all the electrodes. During ramp-up operations, the increase in subsurface temperature, power to electrodes, energy injected through heated water, and liquid and vapor streams were closely monitored.

Ramp-up operations were planned to continue for 7 to 10 weeks, but approximately 16 weeks, until January 15, 2006, were required for this phase. The ramp-up phase took longer than expected due to problems getting as much energy as expected from the hot water injection and difficulties in transferring heat to an area where vapor and ground water flow were much lower than anticipated (the area near extraction well X15) and in heating the Hawthorn and shallow treatment zone. Ramp-up operations were completed when the 85 °C temperature guideline was achieved throughout the remediation area.

During this phase, heating at full power to the electrodes began under Building 1400. Heating under Building 1400 was always accompanied by vapor extraction from the horizontal wells under the building and temperature monitoring of the levels in the horizontal wells.

The digiTAM™ data were reviewed regularly during this period to determine if any ‘cold’ spots were evident. When cold spots were identified, a determination was made as to how these areas would be addressed. Actions undertaken to increase temperature to areas with low temperatures included the following actions:

- Increasing the phase voltage to nearby electrodes;
- Altering the phase to neighboring electrodes;
- Increasing the TDC value to nearby electrodes;
- Power cycling to all or select areas of the treatment cell; and
- Connecting and injecting steam at a nearby steam spear location.

3.2.4 Maintenance Heating

After the ramp-up phase was completed when target temperature was reached in all areas of the remediation volume, operations focused on maintaining temperature and cycling the power, injection rates, and extraction pressure to maximize contaminant recovery. This phase of the

operations was referred to as the maintenance phase. This same approach was used for operations under Building 1400.

Power cycling was utilized to maximize volatilization of the contaminants. Power cycling caused pressure and temperature cycling in the subsurface and was done by temporarily and significantly increasing the power and water injection rates to the electrodes. This results in flashing of pore water and residual NAPLs, which are then removed by the vapor extraction process. Power cycling continued until it was determined that the remediation goals had been achieved.

3.2.5 Extended Heating

By the end of March 2006, a significant mass of contaminants was still being removed from the subsurface, primarily in the extracted vapor stream. Vapor removal rates greater than 5 pounds per hour (lbs/hr), or 120 lbs per day, were observed during three of the four treatment system vapor sampling events in March 2006. Rather than begin cool down operations, the WRS team was directed by DOE to continue heating on a weekly basis in an effort to maximize mass removed from the subsurface. Approximately 970 lbs of contaminants were removed during the extended heating operations. During the extended heating period, from March 31 to April 28, 2006, the entire Area B remediation volume continued to be heated with ongoing vapor and ground water extraction.

3.2.6 Cool Down

The cool down period began April 28, 2006, and lasted until June 12, 2006. During cool down, thermal heating operations were stopped in all areas except the low permeability area near extraction well X15. This area was at the 85 °C target temperature but less than 100 °C. Therefore, it was decided that while other areas of the site were being cooled to temperatures that were less than 100 °C, thermal heating operations in this area would continue during the cool-down period as long as temperatures remained less than 100 °C.

Ending thermal operations involved the cessation of energy to electrodes and the injection of ambient-temperature (~20 °C) water to the electrodes in areas where the temperature exceeded 100 °C. Ground water and vapor extraction continued during this period to help remove energy from the subsurface, maintain hydraulic and pneumatic control, and extract any remaining contaminants.

3.3 Extraction Rates

3.3.1 Ground Water Extraction

During operations, the rate and volume of ground water extracted and the rate and volume of water injected to the electrodes and injected as steam was continuously monitored. This calculation was tracked as the water balance. Figure 17 shows the cumulative water injected and extracted along with the water balance ratio (i.e., extracted volume divided by the injected volume). Not shown on the figure is the daily ratio of water extracted versus water injected, which was continuously monitored. The injected water included water injected into the electrodes and water injected as steam. The extracted water included ground water pumped from the extraction wells and condensate extracted with the vapor.

Ground water extraction rates ranged from approximately 40 gpm to as high as 80 gpm. Figure 18 shows the range of ground water extraction rates over the duration of the operations phase. To maintain hydraulic control, extraction rates of ground water from inside the remediation area exceeded the injection rate of water to the electrodes by approximately 25 percent. During the later stages of operations, the over-extraction amount was reduced from 25 percent to 10 percent. This was done to reduce the amount of energy removed from the subsurface, and to facilitate heating areas that were reaching the required temperature slower than expected. Even with the lower over-extraction amount, hydraulic control was maintained at all times.

The total amount of water extracted during the remediation was about 18.8 million gallons while the total amount of water injected through the electrodes was about 15.0 million gallons.

3.3.2 Vapor Extraction

Total vapor extraction rates averaged between 1,000 standard cubic feet per minute (scfm) and 1,400 scfm during the project (Figure 18). Vapor flow rates from the individual wells varied dramatically due to the heterogeneous nature of the subsurface. Vapor extraction from some extraction wells was so low it was essentially negligible. In particular, the area near extraction well X15 had almost no vapor extraction. Attempts to improve vapor extraction from the existing wells and installation of new extraction wells in this area produced only minimal increase in vapor flow from this area.

3.4 Energy Balance

An energy balance for the system was maintained based on the enthalpy flux (i.e., energy) into the subsurface and the energy extracted from the subsurface. The energy balance, showing energy injected to the subsurface and energy extracted from the subsurface, is shown on Figure 19. Energy was put into the subsurface through electrical energy to the electrodes and convective energy, shown as “injected” on Figure 19, in the form of hot water injection to the electrodes and injection of ex situ generated steam.

A summary of the energy injected and extracted during the remediation is shown in Table 6. The energy amounts shown in the table are the total amounts for energy input to and extracted from the subsurface during the remediation. This total energy includes the amount used for Area B, Building 1400, and the extended heating operations directed by DOE-LM.

The amount of electrical energy injected to the subsurface was based on the readings from the transformers located at the remediation area. The hot water energy was based on the enthalpy of the water, specific heat capacity of the water, and the rate of water injection. The value of the enthalpy for the water assumed that water was always injected at a temperature of 80 ºC. The enthalpy of the injected steam was based on the amount of steam injected and the quality of the steam. A steam quality of 75 percent was assumed. The extracted energy was the energy in the extracted ground water and subsurface vapors. The treatment system energy usage was estimated to be 16.6 percent of the total electrical energy used.

3.5 Subsurface Temperatures Achieved

During the remediation, the subsurface was heated to over 85 ºC over the entire remediation area. When the remediation started in August 2005, the subsurface was at approximately 22 ºC. During the first 3 months of operations, the average temperature of the subsurface increased steadily at a rate of approximately 16 ºC per month. By the end of November 2005, the average subsurface temperature was approximately 70 ºC. Over the next 4 months, the average subsurface temperature increased to approximately 95 ºC, as shown on Figure 20. Temperatures in the Hawthorn increased more slowly than the temperatures in the alluvium, but by the end of January 2006, average temperatures in the Hawthorn were approximately the same as average temperatures in the alluvium. Temperatures also were monitored in the electrode borings. These locations were generally the hottest points in the subsurface. However, by the end of March 2006, average temperatures in the alluvium, Hawthorn, and at the electrodes were essentially the same.

To monitor the subsurface temperatures during the operational phase, the remediation area was divided into four smaller areas: Area I, Area II, Area III, and Area IV, as presented in Figure 21. Area I was the southern-most area, the area adjacent to Building 1400. Area II was just north of Area I, Area III was north of Area II, and Area IV was the northern-most area. Figure 22 shows the average temperatures in the Hawthorn and alluvium, by area, for the period from February 2006 to June 2006. As noted in Figure 22, temperatures in the alluvium tended to be hotter than in the Hawthorn, temperatures in Area I were the hottest, temperatures in Area IV were the coolest, and all areas achieved temperatures of over 85 ºC.

3.6 Contaminant Removal Rates and Totals

There are several mechanisms by which mass was removed from the subsurface, as described in the following text.

- Vapor phase extraction: Mass removed as vapor in the vacuum stream was quantified by collecting a sample from vapor influent port PIN15-VI (Figure 16), which was located on knock out tank KO-3. Vapor at this point in the process stream had undergone cooling and condensation via heat exchangers and knock out tanks, respectively.
- Dissolved phase extraction: Mass removed in the recovered liquid stream was quantified by collecting a sample from the ground water influent port PIN15-WI (Figure 15). This sample port was located at the inlet to the oil/water separator units.
- Free phase extraction: NAPL could potentially be recovered at several locations in the process stream in addition to recovery in the influent liquid stream. Knock out tanks KO-1A/B, KO-2A/B, and KO-3A/B could all potentially contribute free phase liquid to the process stream, which would be transferred via pneumatic double diaphragm pumps to the oil/water separators. The primary location in the process stream for NAPL recovery was condensate tanks T7-A/B, where the condensate from regeneration of the vapor carbon beds was collected and allowed to settle prior to transfer of the NAPL fraction into 55-gallon drums (or hazardous waste tanks T-2 and T-3) and the remaining water fraction back into the liquid process stream.
- In situ degradation by biological or chemical processes: In situ destruction of site contaminants was not quantified during active remediation, although both mechanisms could potentially contribute to mass reduction.

It is evident from the aforementioned mass recovery descriptions that there are several points in the treatment process train where recovered contaminants can be quantified. However, samples collected from vapor influent port PIN15-VI and ground water influent port PIN15-WI provide representative data of the "processed" vapor and liquid streams. As recovered mass leaves the subsurface, a number of equilibrium processes may occur as the various streams are cooled, condensed, stripped, separated, and transferred in process equipment. For example, mass recovered in the vapor phase may have condensed in the system knock out tanks, which was then transferred to the liquid side of the treatment process train. This mass was accounted for in the ground water influent sample although it was collected initially in the vapor stream. Furthermore, the mass was not accounted for again in the vapor stream because the vapor sample port was located downstream of this location. Likewise, COCs in the extracted liquid stream may be stripped in system piping, removed under vacuum in the knock out tanks, and processed in the vapor treatment equipment. The recovered mass was captured in the vapor influent sample port.

The mass of extracted contaminants was determined based on the mass flow rates and measured concentrations of samples collected at sample ports PIN15-VI and PIN15-WI, which were applied to a simple mass flow balance. Both sample ports are located prior to NAPL collection points (i.e., the oil/water separators and vapor carbon regeneration condensate tanks), therefore, mass recovered as free phase liquid was not added to the total mass estimate for the site. It was assumed that the average liquid extraction rate, as measured at the totalizer after the air stripper, represented the flow leading up to a given sampling event. Technical difficulties with the influent totalizer resulted in erroneous readings and prevented the use of these flow measurements in the calculations. Analytical results for a given sampling event were considered representative of concentrations in the liquid and vapor streams for the period from the previous sampling event to the given event.

3.6.1 Vapor

The flux of contaminant mass in the vapor stream was calculated as follows:

$$Massflux_{vapor}\left(\frac{lbs}{d}\right) = q(scfm) * C\left(\frac{mg}{m^3}\right) * 1{,}440\frac{\min}{d} * \frac{g}{1{,}000mg} * \frac{lb}{453.59g} * \frac{m^3}{35.3ft^3}$$

where:

q = flow rate in scfm as reported in the site Total Fluids Recovery Database (Appendix E)

C = total influent concentration for detected compounds as measured at sample port PIN15-VI, milligrams per cubic meter (mg/m^3) (Appendix E)

ft^3 = cubic feet

g = grams

During operations, there were three periods of increased vapor mass removal (Figure 23). The peak vapor mass removal rate was 5.92 lbs/hr (i.e., 142 lbs per day) on March 7, 2006. This was towards the end of the maintenance heating phase. The first general rise in recovered vapor mass corresponds to activities associated with the preheating phase of operations. The next highest spike in vapor concentrations occurred from late November 2005 to mid-January 2006. Two major system modifications were made at this time to improve delivery and conservation of

energy. The impeller on the Quikwater™ water heater transfer pumps were replaced with high efficiency units to improve heated water injection in the subsurface, and the ratio of extracted to injected water was adjusted from 125 percent to 110 percent to conserve as much energy as possible without compromising the need to maintain hydraulic control in the treatment area.

The final and most significant vapor mass removal event occurred during the months of February and March 2006 during the maintenance heating phase. This period of operations was signified by a series of intense and focused operational strategies aimed at optimizing mass removal and heating of the subsurface while disrupting equilibrium to ensure mass was captured throughout the treatment zone. These strategies and system modifications will be discussed in more detail Section 3.9.

The largest spikes in vapor mass recovery rates appear to be associated with a combination of pulsing (described in Section 4.3) and the addition of extraction wells to the well-field layout. During the period from March 7 to March 27, 2006, when these peaks were observed, a focused pulsing effort occurred in Area IV along with the addition of two extraction wells in Area III and six vapor extraction wells across the site. Additionally, steam spears were also utilized as vapor extraction points in the shallow treatment zone, tap settings were adjusted to maximize power delivery, and "clean" wells, as demonstrated by analytical results, were taken offline to allow for greater recovery capacity at more contaminated areas.

TCE was the primary contaminant recovered in the vapor stream. The peak TCE concentration occurred on March 7, 2006, of 1,240 mg/m^3, Figure 24. This was followed by toluene, which demonstrated a peak concentration of 467 mg/m^3 on March 27, 2006. Recovery of other COCs generally followed the same trends throughout active treatment, as demonstrated in Figure 25. Temporal spacing of contaminant removal did not appear to be dictated by COC boiling point or other physical properties of individual contaminants, as might be expected during thermal remediation. The analytical data suggest that operational changes and strategies have a much greater impact on when contaminants are recovered from the subsurface.

Screening samples were collected at sample port PIN15-VI for FID analysis. However, a convincing correlation could not be developed between FID measurements and vapor analytical results to provide a high level of confidence in development of mass estimates using this instrument. An OVA and lab data correlation is provided in Figure 26.

3.6.2 Water

The flux of contaminant mass in the water stream was estimated as follows:

$$Massflux\ (\frac{lbs}{day}) = q\,(\frac{gallons}{\min}) * C\,(\frac{mg}{L}) * \frac{3.785L}{gallon} * \frac{1{,}440\min}{day} * \frac{g}{1{,}000mg} * \frac{lb}{453.59g}$$

where:

q = average flow rate as reported in the site Total Fluids Recovery Database (Appendix E)

C = total influent concentration for detected compounds as measured at sample port PIN15-WI, milligrams per liter (mg/L) (Appendix E)

Analytical data for COC ground water concentrations are provided in Appendix E. Peak concentrations for all COCs occurred prior to beginning the maintenance phase of operations

during the ramp-up phase. In the case of methylene chloride and cDCE, peak concentrations of 18,300 and 38,700 micrograms per liter (µg/L), respectively, occurred on August 17, 2005, or 1 day after treatment system startup and prior to preheating. Concentrations for toluene and TCE peaked at 8,400 and 33,000 µg/L during the preheating and ramp-up phases, respectively. A final spike in COC ground water concentrations was observed on December 20, 2005. Ground water influent concentrations then continued to show a downward trend during the remainder of the project with no significant spikes occurring thereafter. Spikes in vapor influent concentrations witnessed during maintenance heating did not correlate to a similar increase in influent ground water concentrations. Ground water concentrations into the treatment are shown in Figure 27 and Figure 28.

3.6.3 NAPL Volume

The three primary mechanisms by which NAPL could occur in the treatment system are as follows:

- NAPL extracted from the subsurface as a liquid;
- NAPL formed as a condensate when extracted vapors were cooled; and,
- NAPL generated from the vapor phase GAC unit during regeneration.

NAPL layers were not observed directly in the treatment system samples. However, both LNAPL and DNAPL were collected in the oil/water separators during operation. This was the only location where free phase liquid was observed through the end of 2005. Beginning on January 9, 2006, measurable quantities of DNAPL began to accumulate in process tanks T-7A and T-7B, and this became the primary location for the collection of NAPL for the remaining duration of the project. All NAPL captured in the oil/water separators or condensate tanks was transferred to hazardous waste tanks T-3A and T-3B after being allowed adequate time to settle and separate into the NAPL and water fractions. Any water remaining in the vessels after this settling period was transferred back into the system for further processing. Sudan IV powder was utilized to distinguish between the water and NAPL fractions to ensure that only product was transferred to the hazardous waste tanks for disposal.

Three shipments of NAPL occurred over the course of the project and were as follows:

- January 26, 2006: Six drums of NAPL shipped off site for disposal.
- May 2, 2006: Ten drums of NAPL shipped off site for disposal.
- September 15, 2006: Three drums of NAPL shipped off site for disposal.

A total of 19 drums and 888 gallons of NAPL were shipped off site as hazardous waste for proper disposal. The NAPL consisted of 14.9 gallons of LNAPL collected in the oil/water separators, 18.8 gallons of DNAPL collected in the oil/water separators, and 854.5 gallons of DNAPL collected in condensate tanks T-7A and T-7B. A NAPL transfer and tracking sheet is provided in Appendix D.

3.6.4 Total Mass Estimates

Contaminants were removed from the system at seven locations (i.e., chemical sinks) shown in Figure 29. Each sink is discussed in more detail below. The total mass recovered from the

subsurface, as calculated from laboratory analytical data and treatment system readings, was found to be 17,867 lbs. Approximately 75.3 percent, or 13,446 lbs, of the recovered mass was in the vapor phase (prior to regeneration and condensation) with the remaining mass (4,422 lbs) being recovered in the liquid stream. TPHs were not measured in the vapor stream. However, an additional 547 lbs of recovered TPH contaminant mass was estimated in the ground water phase and was not included in the total mass estimate to allow for a consistent comparison of recovered mass in the vapor and liquid streams. Cumulative mass recovered in the vapor and ground water phases is shown in Figure 30.

Estimates for total COC mass removal from the subsurface assumed the mass was located in one of several chemical mass sinks described in the following section.

3.6.4.1 Vapor-Phase Spent Carbon

The primary regenerated carbon beds and secondary, sacrificial carbon beds both serve as chemical sinks for contaminant mass. Assuming a vapor-phase adsorption capacity of 0.1 lbs/lbs carbon (Kuo 1999), the primary carbon vessels are estimated to have retained approximately 10 percent of their weight in contaminant mass as a "heel." Given 2,500 lbs of GAC between the two vapor regeneration vessels, the total estimated contaminant mass retained on the primary vapor-phase carbon was calculated to be 250 lbs.

On March 3, 2006, approximately 5,000 lbs of spent carbon was shipped offsite after analytical results indicated breakthrough after the sacrificial carbon filters. Once again assuming a vapor-phase adsorption capacity of 0.1 lbs/lbs, the secondary carbon was estimated to have retained a contaminant mass of 500 lbs. An additional 4,000 lbs of spent sacrificial carbon was shipped off site on February 2, 2007. Breakthrough of these carbon filters was not observed during treatment system operation, therefore it was assumed that 50 percent of the vapor-phase adsorption capacity had been reached, or 0.5 lbs/lbs carbon. The resultant retained contaminant mass on this second set of sacrificial vapor-phase carbon filters was estimated at 200 lbs.

The sum of the estimated contaminant mass retained on the spent vapor-phase carbon was 950 lbs.

3.6.4.2 Liquid-Phase Spent Carbon

Approximately 5,000 lbs of spent liquid-phase carbon were shipped off site on February 2, 2007. Breakthrough of the liquid-phase carbon was not observed during treatment system operation. However, it will be assumed that the carbon was nearly spent given the length of system operation. The liquid-phase adsorption capacity was estimated at 0.01 lbs/lbs carbon (Kuo 1999), thus the contaminant mass retained on the spent carbon was estimated to be 50 lbs.

3.6.4.3 Discharged Liquid Stream

Based on analytical results monitored at sample port PIN15-WE, the estimated contaminant mass loss in the discharged liquid stream was 1.05 lbs.

3.6.4.4 Vapor-Phase Air Emissions

Two chemical mass sinks to the atmosphere were identified. The first sink was located along the vapor treatment train on the discharge side of the system. Based on analytical results monitored at sample port PIN15-VE, the estimated contaminant mass loss to the atmosphere at this location was 1,746 lbs.

The second sink to the atmosphere was the air emissions from the air stripper located along the liquid treatment train. Samples were not collected from this location, therefore, the total emissions from this location was estimated by taking the difference between the contaminant mass entering the liquid side of the treatment system, as calculated from analytical data collected from sample port PIN15-WI, and the mass exiting the liquid side of treatment system in the spent liquid-phase carbon and treated liquids, as provided above. The contaminant mass discharged in the air stripper air emissions was estimated at 4,371 lbs.

3.6.4.5 Accumulation in NAPL Tanks

A total of 888 gallons of NAPL were recovered in the NAPL tanks following adequate settling time and removal of the water fraction. Approximately 98 percent of the recovered mass was DNAPL. In order to calculate the mass of contaminants recovered as NAPL, a weighted average of the COC specific gravities was calculated based on the recovered COC mass as determined from analytical results collected at sample port PIN15-VI. The density of the NAPL was estimated to be 11 pounds per gallon (lbs/gal) by this method, which resulted in a recovered NAPL mass of 9,769 lbs.

3.6.4.6 Total Vapor- and Liquid-Phase Mass Removed

The sum of the chemical sinks on the vapor treatment train side of the system was 12,095 lbs, which includes mass recovered as free phase NAPL from regeneration of the vapor-phase carbon. A small fraction of the recovered NAPL (i.e., approximately 4 percent, or 370 lbs) was collected from the oil/water separator and transferred to the hazardous waste tanks. This mass was not included in the total of the vapor-side chemical sinks because it was generated on the liquid side of the treatment system.

This mass estimate was within 10 percent of the vapor influent mass. The discrepancy between the estimated mass recovered from the subsurface and mass captured in the chemical mass sinks could be attributed to the conservative NAPL density utilized in the calculations. Nearly 20 percent of the recovered COC mass in the vapor influent stream was toluene, which is an LNAPL. However, no LNAPL was observed in the condensate tanks during NAPL transfer operations. Consequently, the weighted average utilized to estimate the specific weight of the recovered NAPL most likely underestimates the actual specific gravity. If toluene was removed from the weighted average calculation, the estimated specific weight of the NAPL was approximately 12 lbs/gal, and the resultant change in recovered NAPL mass would be about 820 lbs. This would place the mass balance between the recovered mass and chemical sinks within 4 percent.

Additionally, 13 drums of rinsate and sludges generated from demobilization activities were shipped offsite on November 13, 2006. The mass contained in these waste streams was not

quantified and, therefore, this could account for the discrepancy between the estimated mass recovered from the subsurface and mass captured in the chemical mass sinks.

The mass removal estimates for individual COCs in the vapor and liquid phases are shown in Table 7.

3.7 Vapor and Water Treatment Operations

3.7.1 Vapor Treatment Operations

All non-condensable vapors were treated by two stages of vapor phase carbon. Based on the analytical data from the vapor influent samples collected on a weekly basis over the course of the entire period of system operation, and based on the system vapor flow rate, a total mass of 13,446 lbs of chlorinated solvents and petroleum hydrocarbons were estimated to have been removed from the subsurface by the vapor extraction system. The analytical data from the weekly vapor effluent samples and the effluent flow rates were used to calculate a total mass of 1,746 lbs of contaminants emitted to the atmosphere. The resulting estimated treatment efficiency for the vapor treatment system was 87 percent.

Slightly more than half of the mass emitted to the atmosphere was emitted between December 14, 2005, and January 12, 2006. Ironically, this occurred immediately after the second stage vapor phase carbon had been replaced on December 6 and 7, 2005. However, this does correlate to one of the spikes in influent concentrations and it was during the time frame that there were problems with the electric steam generator used to regenerate the carbon and the associated solenoid valve for the steam generator.

There were several other problems encountered with the first stage (steam regenerated) vapor phase carbon unit during system operations that led to poor efficiencies at times. These include malfunctioning inlet and outlet valves, controls wired incorrectly by the vendor, and a faulty temperature sensor. All of these problems and other smaller problems were resolved during operations, but did contribute to lower efficiencies.

The recovery of NAPL from the vapor phase by recondensing it to liquid was a successful operation. The majority of the 9,769 lbs of NAPL recovered during system operation was from the vapor phase.

3.7.2 Water Treatment and Discharge

Extracted ground water was treated with air stripping and sent through liquid-phase carbon filtration. This level of treatment was required to meet the discharge requirements defined in the Statement of Work (DOE 2003).

Based on analytical data from weekly ground water influent samples and the influent flow rates, the mass of chlorinated solvents and petroleum hydrocarbons removed from the subsurface by ground water extraction was 4,421 lbs. Based on the analytical data from the weekly ground water effluent samples and the effluent flow rates, the total mass of contaminants discharged from the ground water treatment system was 1.05 lbs. The resulting estimated treatment efficiency for the ground water treatment system was 99.98 percent.

With the exception of scaling at the beginning of operations, and periods of frequent bag filter change-outs, the ground water treatment system operated smoothly. The system removed methylene chloride effectively, treating a cumulative influent mass of 444 lbs and only discharging a cumulative effluent mass of 0.43 lbs for a removal efficiency of 99.90 percent.

3.8 Interim Sampling

3.8.1 Interim Ground Water Sampling

The analytical data from ground water samples collected from the extraction wells and the 12 perimeter monitoring wells during interim sampling events are presented in Appendix C. VOC analytical results for perimeter monitoring wells M29D, M29S, 0557, 0579, 0580, 0582, and 0583 remained below detection limits for all interim ground water sampling events. Minor detections below 100 µg/L were encountered at monitoring well locations M31S, M31D, and 0581. COC concentrations at monitoring well M30S peaked on December 1, 2005, and then declined for the remainder of the project. The most significant detections of COCs in perimeter monitoring wells occurred at monitoring well M30D, where an elevated concentration of cDCE at 2,510 µg/L was observed during preheating of the treatment zone perimeter. This concentration continued to decline and was measured at less than 100 µg/L during the final interim sampling event. The elevated cDCE concentrations measured during operations was of no concern because this well had contained elevated concentrations of cDCE prior to remediation.

Each extraction well, with the exception of extraction wells X10 and X24, were sampled at least once during interim sampling activities. The rationale behind selection of extraction well sampling locations was discussed in Section 3.5.5. Exceedances of the numerical goals in Table 1 of at least one COC were observed at extraction wells X02, X05, X07, X08, X11, X15, X16, X23, X25, d26, and d30 during one or more of the interim sampling events. Elevated concentrations of TCE, in some cases greater than 100,000 µg/L, were observed at all of the aforementioned extraction wells. Concentrations of methylene chloride were observed at extraction wells X15 and X16, both in Area III, exceeding 300,000 µg/L.

All extraction well COC concentrations were below the NAPL remediation goals after the last interim sampling event with the exception of Area III extraction wells X25, d26, and d30. All three of these extraction wells were installed during the maintenance heating phase, and, therefore, had a shorter extraction duration than those wells installed prior to commencement of active treatment. Additional efforts in this area of the site are discussed in more detail in Section 3.9.

3.8.2 Interim Soil Sampling

Exceedances of the soil TCE and toluene NAPL remediation goals of 20,400 milligrams per kilogram (mg/kg) and 15,000 mg/kg, respectively, occurred during the first three interim soil sampling events at sampling locations SB-102, SB-111, SB-112, and SB-114, as depicted in Figure 7. The results for individual sample intervals exceeding the NAPL remediation goals are shown below. The interim soil sampling was biased sampling in that samples were taken from

areas that were suspected of having the highest concentrations. The sampling was conducted as a means of determining where additional energy and extraction efforts should be focused.

- SB-102 15-ft sampling interval (1st event): The detected toluene and TCE concentrations were 6.7 and 3.4 times the target concentration, respectively.
- SB-102 32.5-ft sampling interval (1st event): The detected toluene and TCE concentrations were 3.9 and 4.1 times the target concentration, respectively.
- SB-111 15-ft sampling interval (2nd event): The detected toluene and TCE concentrations were 8.4 and 4.9 times the target concentration, respectively.
- SB-111 27-ft sampling interval (2nd event): The detected toluene and TCE concentrations were 27.1 and 20.2 times the target concentration, respectively. The TPH goal of 2,500 mg/kg was also exceeded at a concentration of 3,160 mg/kg.
- SB-111 32-ft sampling interval (2nd event): The detected toluene and TCE concentrations were 29.5 and 17.6 times the target concentration, respectively.
- SB-112 32-ft sampling interval (2nd event): The detected toluene concentration was 1.9 times the target concentration.
- SB-114 5-ft sampling interval (3rd event): The detected toluene and TCE concentrations were 13.9 and 15.1 times the target concentration, respectively.
- SB-114 15-ft sampling interval (3rd event): The detected toluene and TCE concentrations were 2.4 and 2.0 times the target concentration, respectively.

3.9 Adjustments and Modifications

Management of the thermal remediation system required regular data analysis and daily decision-making in the field to optimize operations and contaminant recovery in response to changing conditions. To respond to these changes, several modifications to the system were made during operations and are discussed in this section. The additional features, such as additional wells or steam injection points, are shown on Figure 7.

3.9.1 Well-Field Modifications During Operations

3.9.1.1 Retrofit of Extraction Wells and Pump Repairs/Replacement

A series of manufacturing defects required replacement and/or repair of the submersible pneumatic recovery pumps during treatment. These defects included failure of the stainless steel float welded seams and improper alignment of the valve seat, which was necessary for proper discharge of air to and from the pump.

Several extraction wells were retrofitted with a drop tube to allow for recovery of liquids in the vapor stream where the pneumatic pumps had failed. A section of CPVC was placed through the wellhead with an adjustable valve to allow for regulation of ambient air into the well of less than 8 scfm. This provided an “air lift” so liquids could then be entrained with the recovered vapor stream as the CPVC tube was adjusted such that the opening was just above the water table elevation.

In a couple of instances, a double diaphragm pump was connected to the liquid recovery line of the failed pneumatic pump and placed inline with the liquid recovery stream. The down hole pump served as a foot valve, which allowed for the recovery of liquids at an elevation and under conditions that typically result in an environment where recovery is unachievable with a double diaphragm pump at the land surface. Additional discussion of the submersible pumps and ground water extraction is provided in Section 4.6.

3.9.1.2 Installation of Additional digiTAMs™

Five additional digiTAMs™ were added to the remediation to better monitor areas that needed additional energy. Two digiTAMs™ (d68 and d69) were installed in the middle of the remediation area and three digiTAMs™ (d65 to d67) were installed in the northern portion of the remediation area. The additional sensors provided data that allowed for better system operations to ensure cleanup criteria were met in treatment areas where heating or fluid recovery proved to be more challenging. For example, responses to changes in steam spear or extraction well operation could be observed through temperature data.

3.9.1.3 Versatility in Utilization of Steam Spears

In addition to their use as steam injection wells, the steam spears were also employed as vacuum extraction wells and hot water injection wells to extract recovered vapors and heat the shallow subsurface in this treatment zone.

3.9.1.4 Retrofit of Contingency and Monitor Wells

In areas where the soil characteristics resulted in poor vapor and liquid recovery, nearby contingency wells were brought online and retrofitted with a well head to accommodate submersible pneumatic pumps.

The recalcitrant nature of Area III and the observation of free phase NAPL in monitoring well d30 prompted the need to retrofit this former monitoring well, as well as d26 with 2-inch submersible pneumatic pumps.

3.9.1.5 Additional Well Installation

Poor extraction at existing wells in the area of extraction well X15 and elevated contaminant concentrations in this area was the basis for installation of two additional extraction wells (X24 and X25). Also, six additional vapor extraction wells were installed across the site with four of these pumps in the area near extraction well X15. Several of the highest contaminant removal rates were observed shortly after these system modifications.

3.9.2 Treatment System Modifications during Operations

3.9.2.1 Variable Frequency Drive Blower Adjustments

During operations, vapor extraction from several areas within Area B was cycled on and off to improve mass removal. As a result, the overall air extraction rate was raised and lowered. During times where a lower flow was desired, the variable frequency drive on the vacuum pump and the bleed air valve was adjusted so the system would not shut down due to high amperage on the

vacuum pump. Air flow through the bleed air was measured and subtracted from the total system extraction rates to determine the flow actually coming from the extraction wells.

3.9.2.2 Running First Stage Vapor Separators, Oil-Water Separators, and Air Strippers in Parallel

During operations, ground water extraction rates often increased in the vapor extraction system for various reasons. The typical reasons for this included ground water extraction through the vapor extraction lines when submersible pumps were being repaired, increased hot water injection at the electrodes during pulsing events, and high water table during and following pulsing events where the submersible ground water pumps were cycled off. During these times, both moisture separators (KO-1A and KO-1B) and their associated heat exchangers (HE-1A/B and HE-2A/B/C/D) were operated in parallel.

Also during some of these same events, overall ground water extraction rates would increase. During these times, the liquid phase separators (T-1A and T-1B), and air strippers were operated in parallel to provide adequate phase separation and ground water treatment for the liquid stream.

3.9.2.3 Scale Inhibitor

Scale inhibitor was anticipated in the original design as a contingency if needed. During the first month of operations, the transfer pumps and the air stripper trays were fouled with scale. Consequently, scale inhibitor was purchased in 55-gallon drums and injected at low flow rates with a metering pump into the water treatment stream as it exited the liquid phase separators (T-1A/B). The scale inhibitor contained 10 to 30 percent sodium chloride.

3.9.2.4 Defoamer for Air Strippers

Occasionally during system operations, foam was generated in the air strippers and would be discharged out of the air effluent stack. As a result, spa-grade defoamer was introduced into the air strippers on an as-needed basis to eliminate the foam. The cause of the foam was unknown.

3.9.2.5 QuikWater™

During the first several months of operation, much troubleshooting was performed to determine why the hot water injection rate at the electrodes could not consistently achieve the design flow rate of 66 gpm. Two main problems were discovered. The booster pumps in the water recirculation boxes were not operating properly, and the impellers in the pumps provided with the Quikwater™ were not sufficient to overcome the pressure in the system. In order to overcome this problem, use of the pumps in the recirculation boxes was discontinued, and the impeller was replaced with a high pressure impeller in one of the Quikwater™ pumps. This change allowed injection flow rates as high as 79 gpm to be achieved.

3.9.2.6 Extraction Ratio Adjustments

An initial ratio of ground water extraction to hot water injection of 125 percent was maintained to provide sufficient ground water capture. During the course of operations, it was determined that a lower ratio (110 percent) could be maintained and ground water capture would still be

provided. This was advantageous to remediation because less energy was removed from the subsurface.

3.9.2.7 Vapor Flow Measurements Using Venturi Meter and Orifice Plate

Differential pressures were measured at each vapor extraction well using a Dwyer DS-300 pitot tube in the steel piping between the well and the extraction piping header. The differential pressure across the pitot tube was measured using a digital manometer. The flow rate was calculated from the measured differential pressure using a standard formula supplied by Dwyer.

Beginning in March 2006, differential pressures were measured across a venturi and a specially fabricated orifice plate that were manually inserted in the vapor extraction line between the hose from the extraction well and the steel pipe to the piping header. Vapor extraction rates were calculated based on these two measurements to provide additional flow information to compare to the measurements taken from the pitot tubes. This was done because of suspicion that water droplets in the vapor stream impacting on the pitot tubes may create error in the readings. It was determined that this was a better method; however, water droplets in the vapor flow still created variability in the measurements.

3.9.3 Steam Injection

Twelve additional steam spears were added during the maintenance heating phase of operations. These were added throughout the remediation area where low vapor extraction was noted or where there was difficulty in achieving required temperatures. Most were in the low permeability area near extraction well X15. The new steam spears were numbered NSS01 through NSS012 (Figure 7). To provide additional steam energy for the steam spears, a diesel-fired 3.3 million BTU/hr steam generator with a self-contained 1,000 gallon diesel tank was brought on-site. Steam injection varied in that at times steam was injected into as many as seven injection wells, and at other times it was focused on only a few injection wells.

Steam was also injected into the existing steam spears that were located above the C-phase electrodes. Some of these steam spears were an effective means of injecting steam and others exhibited problems and did not allow steam to be injected. Rehabilitation efforts were undertaken on the poorly functioning steam spears, with mixed results.

3.9.4 Additional DOE Directed Operations

During the last month of baseline heating operations (March 2006), consistently high mass removal rates were experienced, so WRS was directed to extend heating operations an additional 4 weeks to maximize the mass of contaminants removed from the area. The extended heating period employed additional steam injection and electrical energy input into the area around extraction well X15. During this period, it was necessary to maintain the minimum required temperature of 85 °C as well as the vapor and ground water extraction and treatment. Also, the final ground water monitoring event was postponed until after this extended heating period was completed on April 28, 2006.

Following the extended heating phase, cool-down operations began throughout Area B except for the area around X15. An additional 7 days of heating, consisting of steam injection and

electrical heating, occurred in this area while the rest of the treatment area was in cool-down mode.

3.9.5 Additional Operations to Meet Cleanup Goals

After the first confirmatory ground water sampling event, two locations had concentrations of toluene and TCE that were more than 50 percent greater than the remediation goals listed in Table 1. Therefore, additional heating and extraction operations were conducted in the area that exceeded cleanup goals, near confirmatory sample locations CS28 and CS34.

Additional heating operations lasted for approximately 1 month, beginning July 19, 2006. Electrodes in the area of concern, E34, E43, E44, and E52, were energized via PDS units #2 and #7. Monitoring wells CS28 and CS34 were retrofitted for the installation of a compressed air line to each well to assist with air sparging at these locations. Approximately 5−10 cfm was delivered to each location by means of a portable air compressor. Air delivery was manually alternated every 24 hours between monitoring wells CS28 and CS34 through the use of quick-connect fittings in an effort to prevent channeling. The injection of air at these wells served two purposes; the integrity of the CPVC riser was protected from thermal breakdown by pulling heat away from the casing as temperatures increased, and dissolved constituents were volatilized to remove contaminant mass in the vapor stream.

Vapor was extracted from wells C03, C04, X11, X15, SS04, VX03, and VX04 to allow for the removal of volatilized contaminants during air sparging and heating activities. This approach continued until the azeotropic temperature for toluene and water was achieved (i.e., 92 °C). This temperature was then maintained for a period of time followed by initiation of ground water extraction at extraction wells C03, C04, X11, and X15. Contingency well C03 was retrofitted to accommodate liquid extraction via a pneumatic pump. Air sparging at monitoring wells CS28 and CS34 continued throughout this period per the strategy described above. Temperature monitoring was conducted via digiTAMs™ at sensor locations d24 and d29 in the vicinity of the treatment zone. Treatment system readings were collected daily and recorded on the site-specific Operations and Maintenance form.

Treatment system sampling was conducted as necessary to ensure permit and regulatory compliance. Vapor influent and effluent concentrations were monitored with an OVA to demonstrate adequate removal efficiency. Ground water samples were collected on August 8th, 16th, and 23rd from monitoring wells CS28 and CS34 to monitor the progress of the remedial effort and to determine when remedial objectives had been achieved. Ground water samples collected on August 23rd showed that levels of toluene and TCE had been reduced to below required levels and subsequent confirmatory sampling supported this. Operations were stopped at that time.

3.10 Confirmatory Sampling

After operations had been completed, Stoller conducted confirmatory sampling to verify that remediation goals listed in Section 1.2 had been met. During confirmatory sampling activities, 96 ground water samples were collected from the interior of Area B and 36 ground water samples were collected from the 12 exterior wells over the course of three sampling events. A total of 162 soil samples were collected from 34 interior soil borings, and 16 soil samples were

collected from 8 soil borings located outside the perimeter of Area B. Confirmatory Sampling locations are shown on Figure 31. The details of how the confirmatory sample locations were determined are located in the Confirmatory Sampling Plan in Appendix H.

3.10.1 Confirmatory Soil Sampling

Stoller conducted one confirmatory soil-sampling event, approximately 4 weeks after cessation of heating activities. Samples were collected from both the Hawthorn and the surficial soils at 32 randomly determined locations (CS073 to CS104) within the remediation area, 2 locations under Building 1400 (CS071 and CS072), and 8 locations around the perimeter of treatment area (CS105 to CS112). Confirmatory soil sampling analytical results are provided in Appendix A and sampling locations are shown on Figure 31.

A total of 162 interior soil samples were collected using a sonic rig for VOC and TPH analysis as part of the soil confirmatory sampling event. The interior soil samples were collected in the vertical direction at 8-ft intervals from ground surface (i.e., pre-vapor cap ground surface) to a maximum depth of 10 ft into the Hawthorn. The initial sampling depth for each of these locations was randomly chosen to be between 0 ft to 8 ft bgs. Five samples were collected from each location.

A DPT rig was utilized to collect both the perimeter and Building 1400 confirmatory samples. Soil samples were collected from eight locations outside the remediation area to ensure contamination had not spread outside the treatment area and were randomly situated between the perimeter monitoring well pairs. Two soil samples were collected from each boring with the initial depth randomly selected within the top half of the surficial soils and the second sample from 8 ft below the first depth. Two samples were collected from randomly selected angled boring locations under Building 1400 within the 15−30 ft bgs interval.

No exceedances of the sampling target concentrations were observed during the soil confirmatory sampling event. Slight exceedances of the NAPL remediation goals were observed at the following soil boring locations:

- CS076, where a TCE detection of 25,500 µg/kg at the 25-ft interval exceeded the NAPL goal of 20,400 µg/kg,
- CS090, where a toluene detection of 22,000 µg/kg at the 28.7-ft interval exceeded the NAPL goal of 15,000 µg/kg, and
- CS096, where a toluene detection of 17,000 µg/kg at the 32.2-ft interval exceeded the NAPL goal of 15,000 µg/kg.

3.10.2 Confirmatory Ground Water Sampling

Three confirmatory ground water sampling events were conducted by Stoller to verify that cleanup levels had been reached in Area B. The sampling times are listed below.

- June 22 to July 12, 2006: The first ground water sampling event was conducted at 32 sampling locations (i.e., monitoring wells CS17 through CS48) within the treatment area and twelve perimeter monitoring locations.

- August 28 to September 12, 2006: The second ground water sampling event was conducted at 32 interior and 12 perimeter sampling locations.
- September 25 to September 27, 2006: The third ground water sampling event was conducted at 32 interior and 12 perimeter sampling locations.

A total of 132 ground water samples were collected from the interior and perimeter monitoring locations over the course of the three confirmatory ground water sampling events. Sampling locations within the treatment area were selected based on a 35-ft by 35-ft grid that covered the remediation area. The exact horizontal location and vertical depth of each well within a grid was randomly selected. Each monitoring well was installed utilizing a DPT rig to place the middle of a 5-ft screen interval at the chosen depth. Samples were analyzed for VOCs and TPH, consistent with the COCs identified during the baseline characterization work. Confirmatory ground water analytical results are provided in Appendix A, "Confirmatory Sampling Results." Sampling locations are provided in Figure 31.

Prior to treatment system startup, the baseline sampling event results indicated exceedances of the NAPL remediation goals at extraction wells X05, X08, X15 and X16. The concentrations measured at extraction well X16 were the highest observed throughout the remedial effort, whereas concentrations for target compounds rose in the other three extraction wells once heating began. Mobilization of contaminants during active remediation resulted in exceedances of target concentrations at five additional extraction wells (i.e., X02, X07, X11, X12, and X23) during interim sampling where COC concentrations were below the remediation goals during the baseline-sampling event.

Two exceedances of the confirmatory target concentration for toluene of 8,250 µg/L were observed at monitoring wells CS28 and CS34 during the first ground water sampling event at concentrations of 9,600 µg/L and 9,680 µg/L, respectively. A focused remedial effort in this area of the site was conducted shortly thereafter, and no further exceedances of the confirmatory or NAPL remediation goals were observed for the remaining two ground water confirmatory sampling events.

3.11 Contaminant Mass Removed

3.11.1 Original Mass Estimate

An estimate of the mass in the subsurface before remediation is provided in Table 8. This estimate was conducted using laboratory analytical data from approximately 775 soil samples from 96 soil boring locations and Environmental Visualization System software.

3.11.2 Mass Recovered during Operations

The estimates for total mass removed during the remediation of individual COCs are listed below. The estimates are based on laboratory analysis of the vapor and ground water extracted from the remediation area.

- Toluene = 2,947 lbs
- Methylene Chloride = 1,220 lbs
- TCE = 10,691 lbs

- cDCE = 1,896 lbs
- TPH = 547 lbs (ground water only—this analyte was not measured in the vapor treatment system samples)

The estimated total mass of COCs removed was 17,301 lbs. In addition to the COCs, an estimated mass of 1,113 lbs of several other contaminants was removed (Appendix E). The estimated total mass of all contaminants recovered during active remediation was 18,414 lbs.

3.11.3 Post Operations Mass Estimate

The estimate of the mass remaining after the remediation is provided in Table 9. The mass estimate was based on the confirmatory soil samples. Because only one round of soil samples was obtained, the soil concentrations after the additional heating was not known. For purposes of this calculation, the remaining soil sample results were adjusted in the areas that received additional heating based on the reduction in ground water concentrations.

Confirmatory soil sample results from the majority of the remediation area were non-detect or very low concentrations (i.e., less than 1 mg/kg). The majority of the mass remaining after remediation was in the areas that had low vapor and ground water flows, the area in the middle of the remediation area.

4.0 Effectiveness of Remediation Approach

This section presents an assessment of the remediation approach, its effectiveness, lessons learned, and potential improvements. Overall, the remediation approach to removing NAPLs from the subsurface at Area B was effective and successful, as evidenced by all remediation goals specified in the Statement of Work being met, over 18,000 lbs of contaminants removed from the subsurface, and the recovery of 880 gallons of NAPL.

4.1 Cleanup Levels Achieved and Unexpected Conditions

The final cleanup levels achieved met the required cleanup goals in all areas. As previously discussed, confirmatory ground water samples from the 1st sampling event exceeded the required cleanup goals in two sample locations (locations that were especially recalcitrant to vapor and ground water flow) and additional remediation was required in this area.

Confirmatory ground water samples from the 2nd and 3rd events showed all samples had concentrations below the cleanup goals. The average concentration for Round 2 and 3 are presented in Table 10. As can be observed in the table, average concentrations were significantly below the remediation goals.

The extremely low permeability in the area near extraction well X15 was not anticipated at the start of the remediation. Even after the installation of several additional vapor extraction, ground water extraction, and steam injection wells, vapor and ground water flow from this area was minimal. Lithologic logs from borings in this area did not reveal information that would indicate such extremely impervious conditions. There was anecdotal information about past landfill activities that may have leaked substances such as the resin materials found in drums removed from the subsurface that could have significantly reduced permeability. Also, a past large-auger steam stripping remediation may have altered the subsurface in a way that significantly reduced permeability. It was never known why this area was so impervious. However, because the highest concentrations of contaminants were in this area, the additional efforts to remove the contamination were required. The additional remediation efforts were successful at reducing contaminant concentrations to levels below those required but there was still mass remaining in the area. If this same level of remediation effort (i.e., energy input, number of extraction wells, and number of steam injection wells) were applied to a more permeable area, it is likely that the resulting concentration of contaminants would be nondetect.

Only one round of confirmatory soil samples was collected. Soil concentrations in two locations exceeded the remediation goals but did not exceed the level that would have required additional remediation. A statistical analysis of the soil results was not done other than to note that the number of soil samples exceeding allowable levels was less than the allowable number. Again, the highest soil results were observed in the area near extraction well X15 where an additional 6 weeks of remediation were performed after the sampling event.

4.2 Energy Usage

The ET-DSP™ technology provided the needed energy to the subsurface to increase temperatures to the required levels. Energy from ET-DSP™ equipment along with convective energy in the form of hot water injection and ex situ generated steam provided the balance of the

energy input to the subsurface. Figure 32 presents the predicted and actual energy input during the remediation. The predicted energy values shown in Table 11 are the energy values calculated by the numerical simulation for 180 days of operation at Area B only (i.e., not including remediation of Building 1400 and the extended heating directed by LM).

The Area B actual energy of 11,645 kilowatt-Hour (kW-Hr) was comparable to the predicted input energy of 11,558,000 kW-Hr for Area B. In addition, the kilowatt-Hour per cubic yard (kW-Hr/yd^3) were comparable, 214 kW-Hr/yd^3 predicted energy density versus actual energy density of 216 kW-Hr/yd^3. Electrical energy used for the Building 1400 remediation was not metered separately from electrical energy used for Area B, therefore, the Building 1400 energy amounts shown in the table are the amounts predicted by the simulation.

The primary differences between predicted and actual energy input are that more electrical energy was needed, less than predicted hot water energy was inputted, and steam injection supplied almost 10 percent of the actual input energy whereas no ex situ steam injection was assumed for the numerical simulation. Another difference was that the energy was input at a slower than predicted rate. Figure 32 shows the rate of energy input predicted by the numerical simulation and the rate of actual energy input for the Area B portion of the remediation.

For both electrical and convective energy (hot water and ex situ generated steam), the rate of actual energy input was less than the predicted rate of energy input. The simulation predicted that it would take 127 days to input 4,000,000 kW-Hr of electrical energy and it actually took approximately 145 days, 18 days longer than predicted. At 180 days of operation, the simulation predicted that 5,400,000 kW-Hr of electrical energy would have been input. Actual electrical input at 180 days was approximately 5,000,000 kW-hr, 400 kW-Hr less than estimated. For convective energy input, the simulation predicted it would take 120 days to input 4,000,000 kW-Hr and it actually took approximately 180 days, 60 days longer than predicted. Also, the simulation predicted that at 180 days operation, 6,000,000 kW-Hr would have been input via convective energy whereas the actual energy input at 180 days was 4,000,000 kW-Hr, a deficit of 2,000,000 kW-hr.

The slower than predicted rate of energy input meant that it took longer to reach the target temperature. Also, additional convective energy in the form of ex situ generated steam and additional electrical energy were needed to compensate for the slower than predicted rate of hot water energy input. The slow rate of hot water input energy was primarily due to operational problems with the Quikwater™ that resulted in less hot water energy being input during the early stages of the project.

A lesson learned was that the consequences of less than predicted energy input should have been recognized earlier and addressed earlier. For example, if problems with the Quikwater™ could not be fixed, additional convective energy in the form of ex situ generated steam should have been added earlier in the project. Additional steam energy was not added until the end of February 2006. Additional energy earlier in the project likely would have reduced the amount of time needed to reach target temperatures.

4.3 Operational Approach to Heating

The operational phases used for the remediation proved to be effective in heating the subsurface and thus allowing removal of contaminants via vapor and liquid extraction. In summary these phases were:

- Establish hydraulic and pneumatic control
- Preheating phase
- Ramp-up heating phase
- Maintenance heating phase
- Cool down

Pulsing and power cycling operations were conducted during the maintenance heating phase. These operations involved episodic events of maximizing power to the electrodes and varying vapor and liquid extraction rates. These operations were meant to vary the subsurface pressure to maximize the release of contaminants. They also were meant to vary the vapor and liquid flow paths to overcome the established preferential flow paths. These operations were considered effective because they resulted in spikes in the extracted contaminant mass.

A key aspect of the operational approach was maintaining hydraulic and pneumatic control at all times. This was done to prevent contamination from spreading outside the remediation area. The remediation was successful in this aspect as shown by no significant increase in the concentration of contaminants in areas outside the remediation zone. The success at controlling the spread of contamination was largely due to emphasis placed on establishing hydraulic and pneumatic control. This action was the first operational phase, an action that continued throughout all operations, and it was the last operational phase.

4.4 Response to Unexpected Conditions

The areas near extraction well X15 and the northern part of the remediation area both provided unexpected conditions that required operational changes. The area near X15 proved to have much tighter soils than expected and that led to very low ground water and vapor extraction rates. Some of the extraction wells had no vapor extraction. Several methods were used to improve extraction, such as acid flushing and surging. This resulted in only a marginal increase in vapor flow. Therefore, additional vapor and ground water extraction wells were installed in this area. Also, existing contingency wells and monitoring wells were converted to extraction wells, and additional steam injection points were added. These efforts resulted in a small increase in vapor and ground water flow from the area that allowed most of the contamination to be removed. However, this was the area where most of the post-remediation contaminant mass remains.

The northern portion of Area B also provided unexpected challenges. This area proved very difficult to heat to the required temperature. When it was recognized that the area was not heating as quickly as required, several steps were taken to expedite the heating. To maximize power into the subsurface, power to the electrodes was significantly increased, as hot water was injected into the electrodes. To minimize energy removed from the subsurface, the liquid and vapor extraction rates were reduced. As these changes were made, particular attention was paid

to hydraulic control in the area. Also, three additional digiTAMs™ were installed in the northern portion of the remediation area to better monitor the temperature response in an area that was heating slowly. These changes proved to be successful as the required temperatures were achieved and required cleanup levels were reached.

4.5 Building 1400

The challenge of heating under Building 1400 was to get the subsurface hot enough to volatilize the contaminants but keep the area near the building's foundation cool enough so the occupants and building were not affected by the heating. Also, as the volatilized vapors rose, they had to be captured before they could potentially impact building occupants.

The approach to the Building 1400 remediation proved to be effective. Results from the confirmatory soil samples taken from under the building were "nondetect" for all contaminants, temperature levels under the building were achieved, and temperatures near the building were kept below required levels.

The electrodes installed on a slant were able to heat the subsurface in the area under the building to the required temperatures. Also, the horizontal wells installed under the building were effective at removing vapors and excess heat. They also ensured a negative pressure existed at all times under the building so that vapors would not travel from the subsurface up through the building's foundation. There were a few occasions when the allowable temperature in the horizontal wells increased to levels near the maximum allowable temperature (53 ºC at the horizontal well). At these times, cool water was injected into the wells to quickly reduce temperatures. This technique proved to be effective at controlling the temperatures in the wells. Adjusting the vapor flow rates was also a technique used to control temperature in the wells.

4.6 Extraction System

4.6.1 Ground Water Extraction

Ground water extraction was primarily accomplished with pneumatically-driven, stainless steel, submersible pumps. During operations, many of the pumps failed due to several problems. One of the main problems was a manufacturing defect. An insufficient amount of Loctite® thread sealant was applied to the set screws that regulated the amount of air that enters the pump when ejecting the ground water. This led to pump damage such as cracked float rod controllers and bent float rods. The other main problem was pitting of the stainless steel floats, likely due to the presence of chloride ions and the electrical properties of the subsurface during electrical heating. Once the stainless steel floats became pitted, they filled with water, rendering the pump inoperable.

These problems were addressed by removing the pumps, replacing damaged parts, applying sufficient Loctite® to the set screws, replacing the stainless steel floats with epoxy-coated floats, and fitting the pumps with sacrificial anodes. The process of determining the source of the damaged parts took several months and required many man-hours of removing the pumps from the extraction wells, cleaning, troubleshooting, shipping to the manufacturer, and on-site repairs. The process of removing and installing pumps in the extraction wells was further complicated by electrical heating and a hot subsurface. Electrodes surrounding the extraction well had to be shut

off and special precautions taken to protect the workers from exposure to water near steam temperatures.

In most cases, these repairs worked, but for a few extraction wells, the problems persisted. At these wells, pneumatically driven, double-diaphragm pumps were installed next to the extraction well and connected to the ground water extraction tubing. These pumps performed very well. An important advantage of an above ground pump assembly is that pump maintenance and repair is much simpler and safer. The drawback is that the double diaphragm pumps are limited to relatively shallow water table depths; however, the water table depths at Area B were appropriate for these pumps.

4.6.2 Vapor Extraction Flow Rate Measurements

Measurement of vapor flow rates from the extraction wells was difficult because of entrained fluids in the vapor stream. An orifice plate and venturi tube flow measuring devices were tried later in the operations and these seemed to provide a better measurement than the pitot tubes installed in the extraction piping. However, water droplets in the vapor stream still affected the measurements. In addition, both are needed if the flow rate from the well fluctuates between their ranges. The portable orifice plate and venturi were used and these were difficult to maneuver and made flow measurement very time consuming.

The best method of measuring vapor flow rates would be to remove the moisture from the air stream prior to measurement. Then more simple measurement devices such as rotameters, pitot tubes, or anemometers may be used and a more accurate measurement can be obtained. This may be accomplished by installing a small moisture separator at each well and also requires additional piping to remove the liquid from the moisture separator. During operations, a small moisture separator was fabricated and used as a temporary bypass to take flow measurements. This worked well, but was more cumbersome and time-consuming than the orifice plate and venturi; therefore, was discontinued. This method may work better if a bypass configuration was provided at each well and a method of pump-out provided.

4.7 Treatment System

There were operational problems that arose with the steam-regenerated carbon unit. The system worked well at removing contaminants, but there was a learning curve for maintenance staff with getting the equipment to operate at peak performance. Also, the capacity of the steam generator that provides the steam for regeneration must be large enough (i.e., provide enough steam to allow rapid regeneration of the carbon during periods of high contaminant concentrations in the vapor). A suggested improvement to the system would be an in-line organic vapor monitor to control regeneration cycles, which would reduce the level of human monitoring required to perform this function.

4.7.1 Moisture Separator Tank Appurtenances

Float-type level switches should be utilized in the moisture separators to minimize false alarms. Flow through the moisture separators is turbulent and whenever one of the probes touched the side of the steel tank, it caused the level probes to short out and give a high level alarm. Because steel tanks are required due to high vacuum, changing to float switches is recommended.

When ground water extraction rates through the vapor lines were high, the double diaphragm pumps experienced operational problems. As a result, centrifugal pumps are recommended for removal of the water from the moisture separators. In addition, the piping for the pump-out system should be oversized to handle higher flow rates, or a back-up drain line and pump should be installed.

5.0 References

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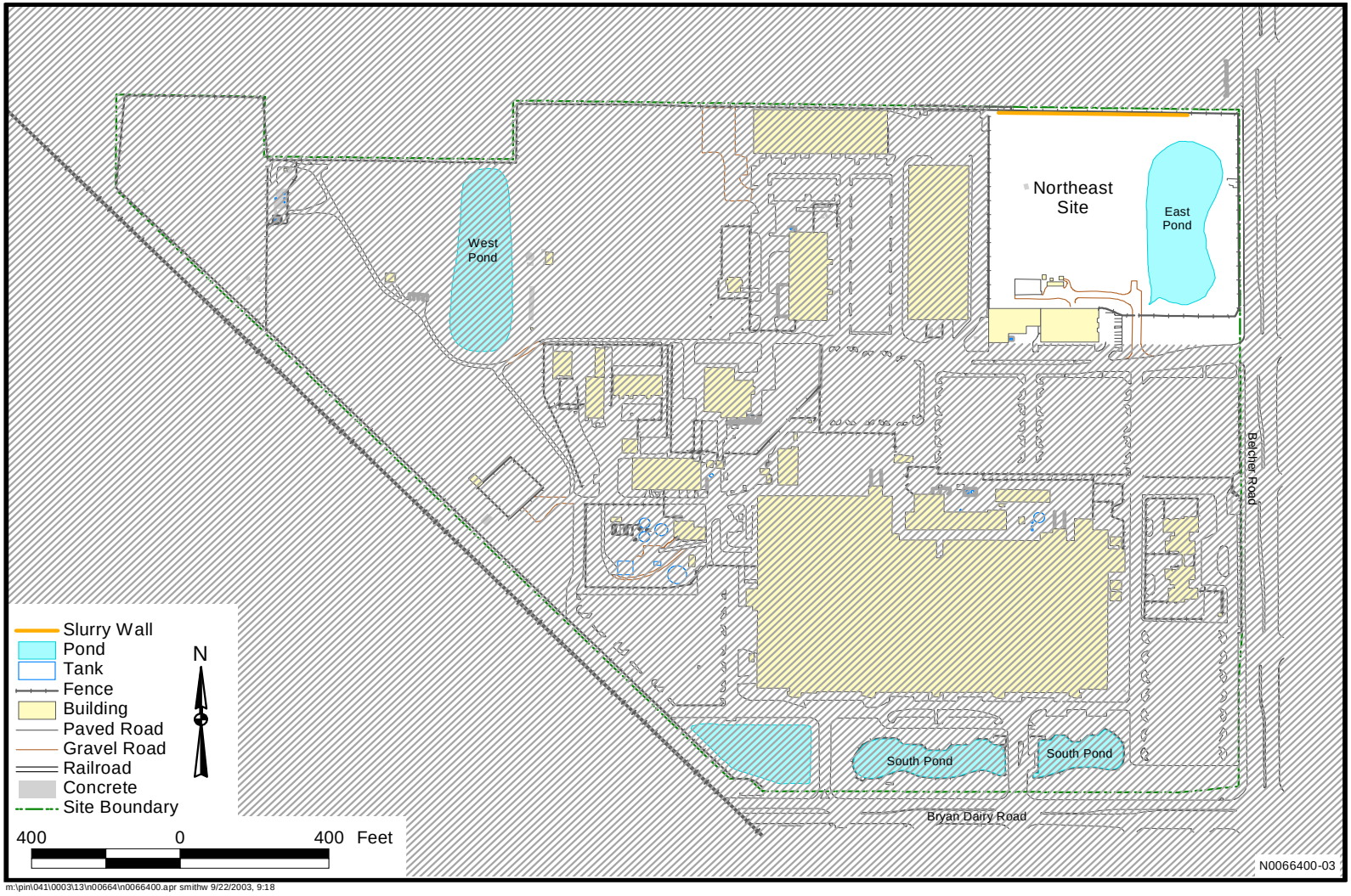

Figure 1. Northeast Site at Young-Rainey STAR Center

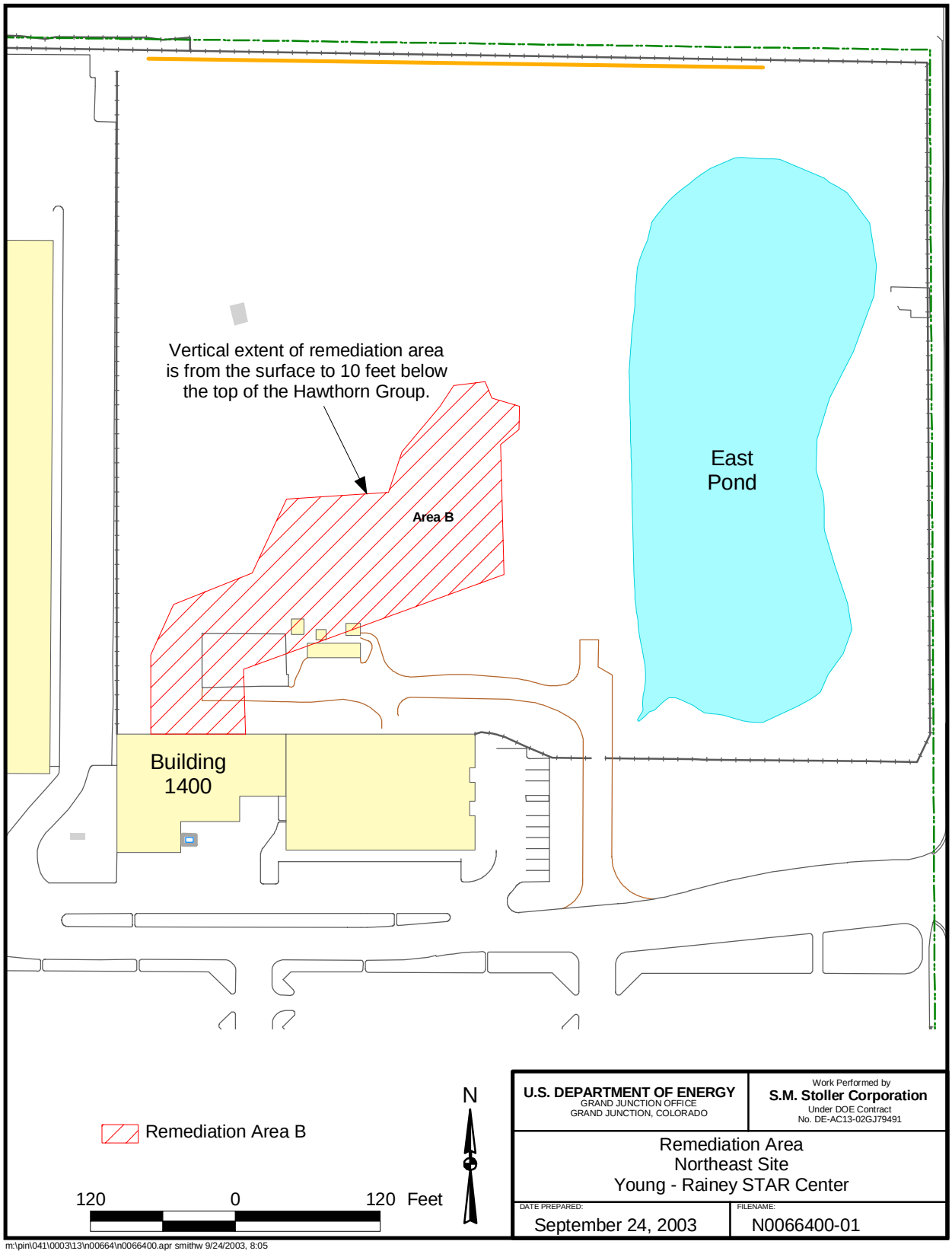

Figure 2. Area B at Northeast Site

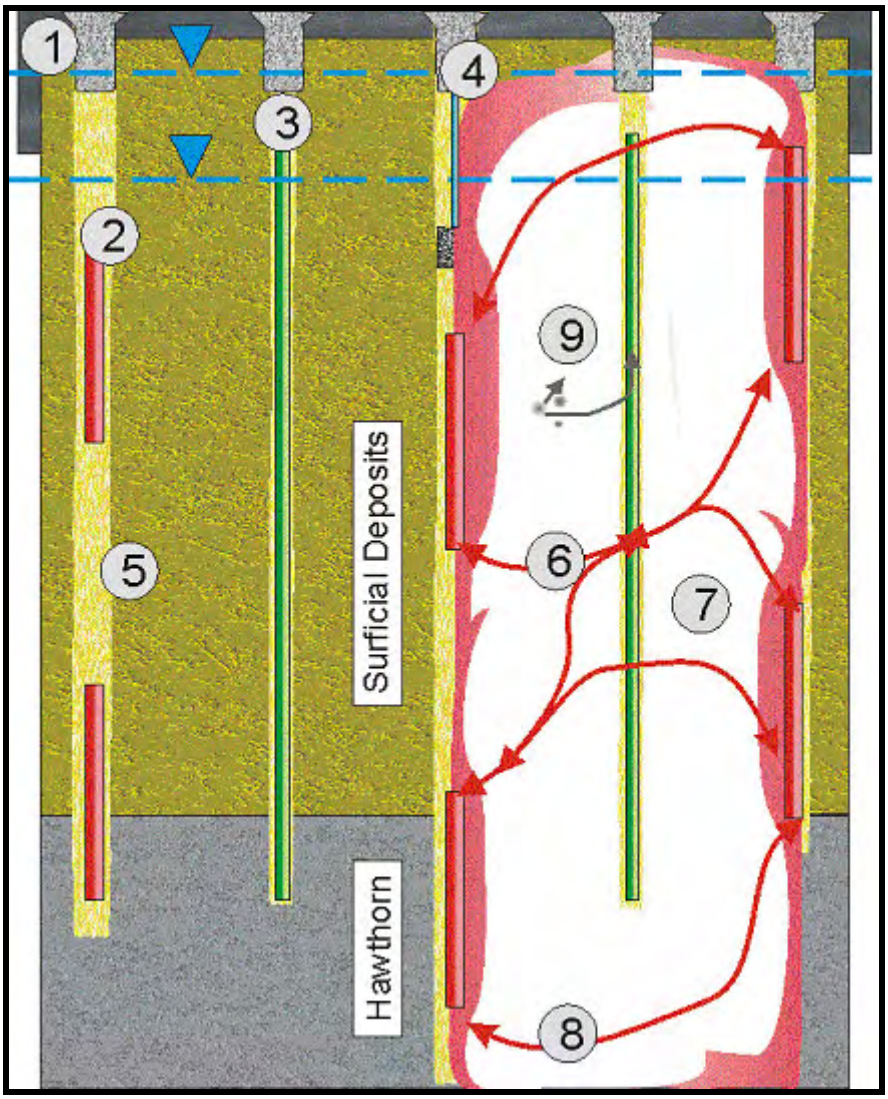

Figure 3. Formation of In Situ Steam and Contaminant Removal

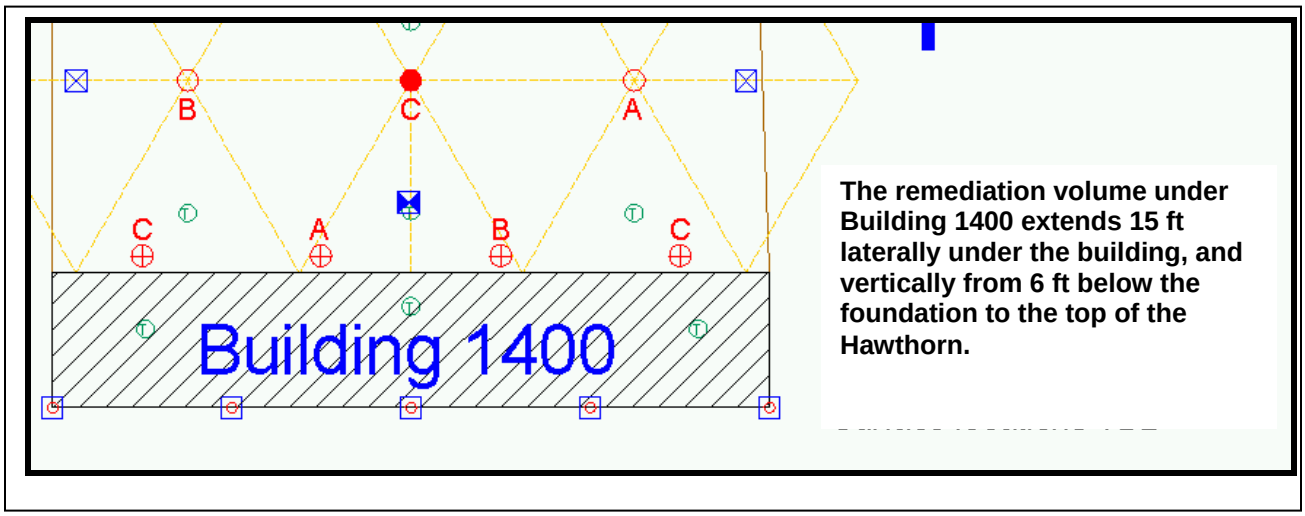

Figure 4. Plan View of Building 1400 Electrode and Extraction Well Layout

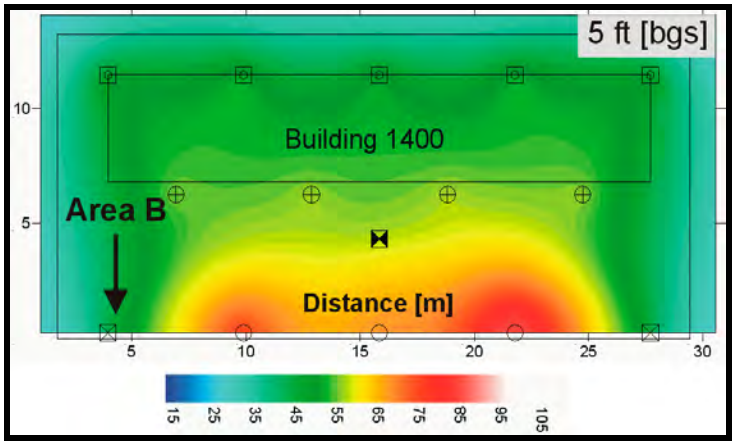

Figure 5. Plan View of Modeled Temperature Distribution 5 ft Below Building 1400

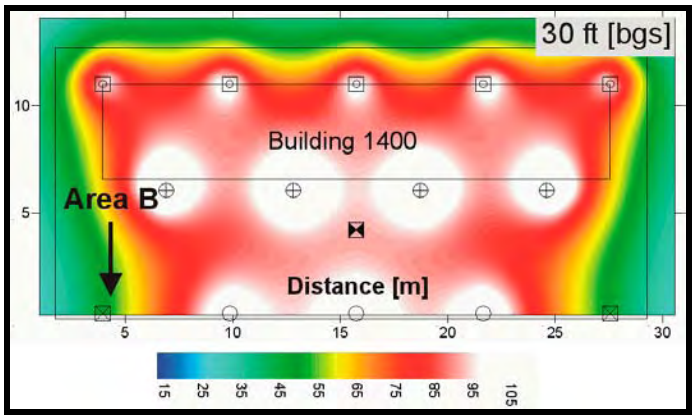

Figure 6. Plan View Modeled Temperature Distribution 30 ft Below Building 1400

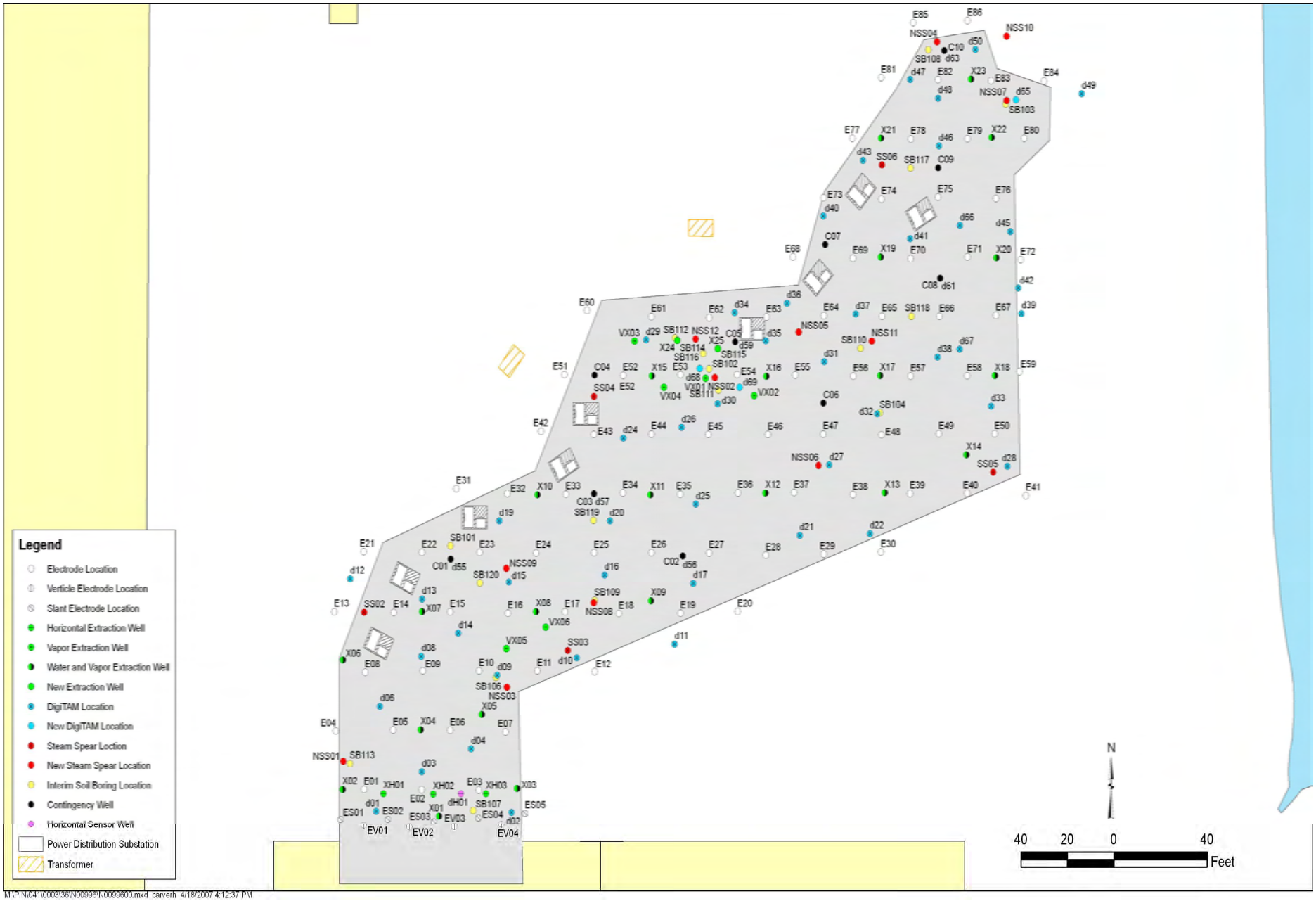

Figure 7. Area B Well Field Layout

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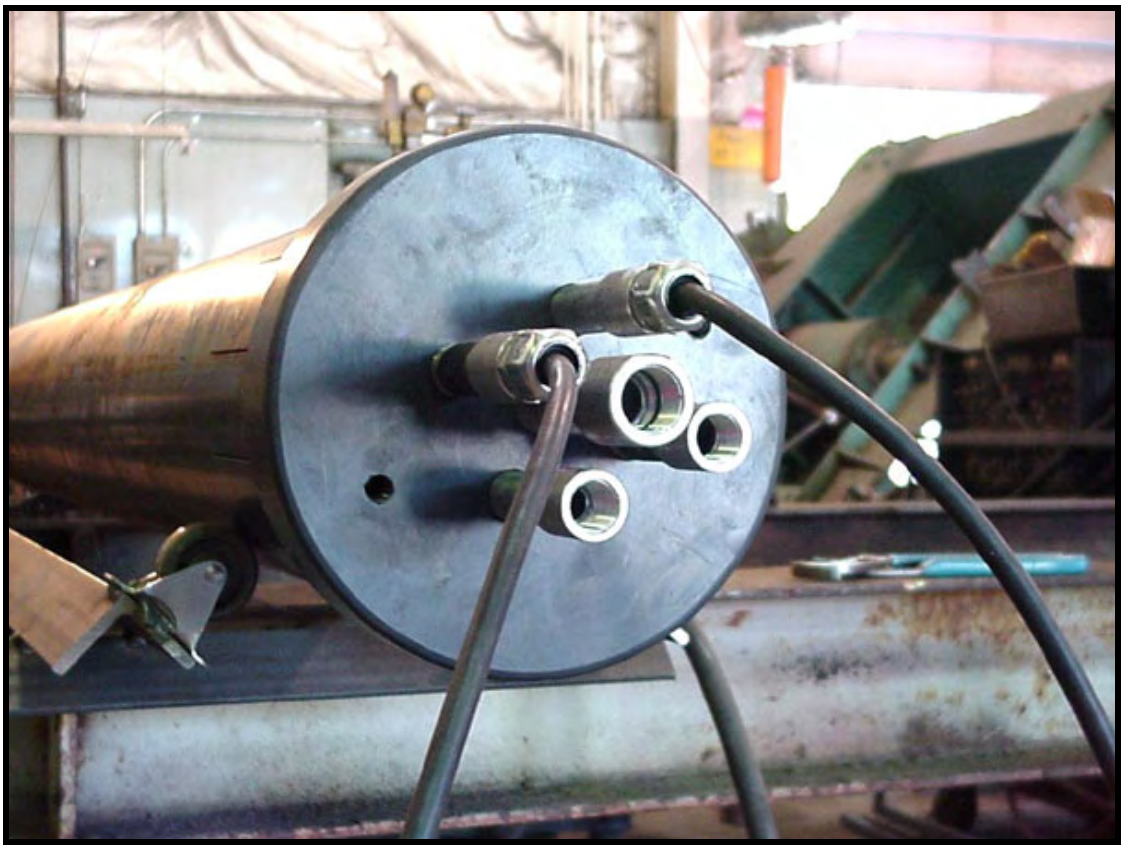

Figure 8. ET-DSP™ Electrode

Figure 9. ET-DSP™ Power Delivery Systems

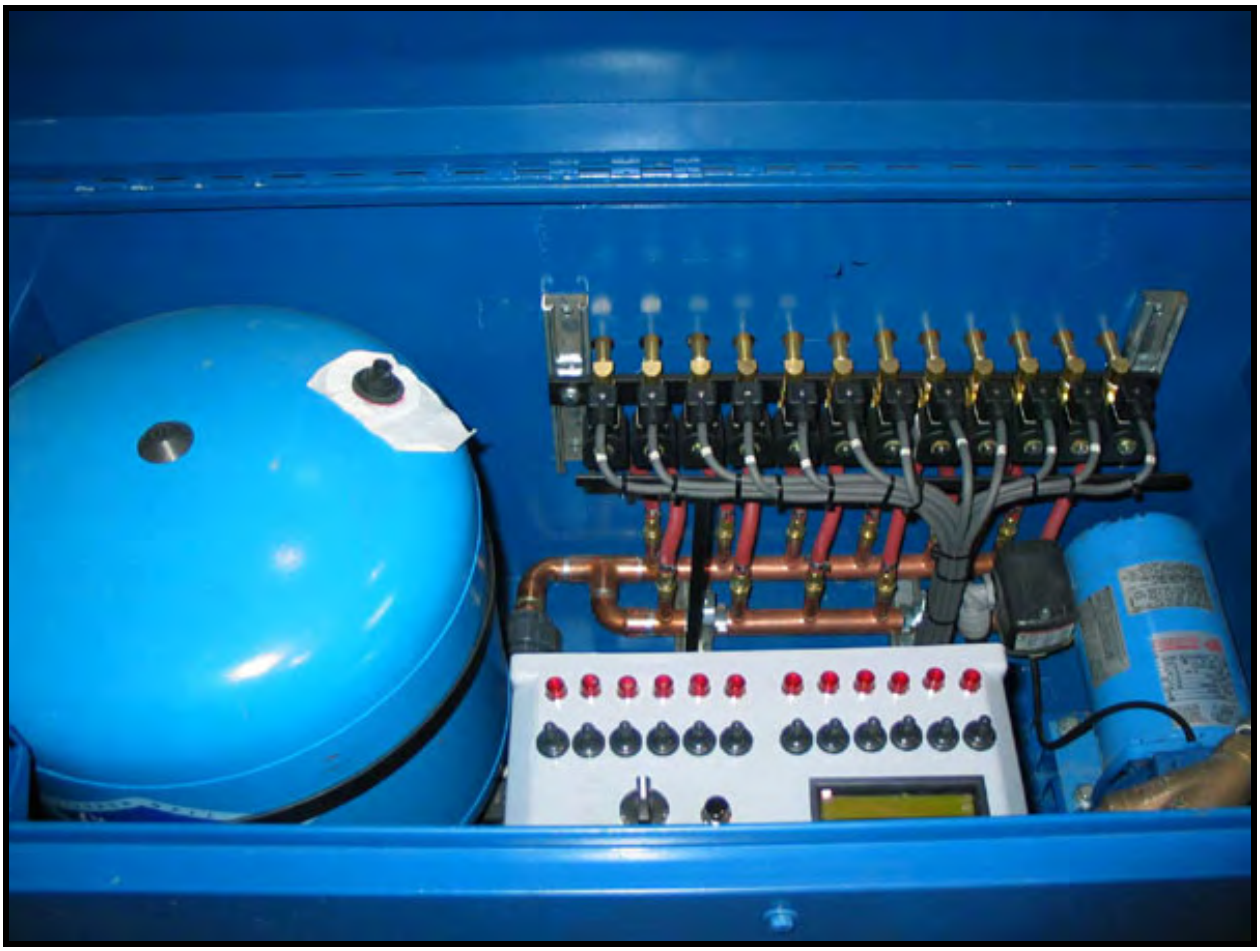

Figure 10. Water Circulation System

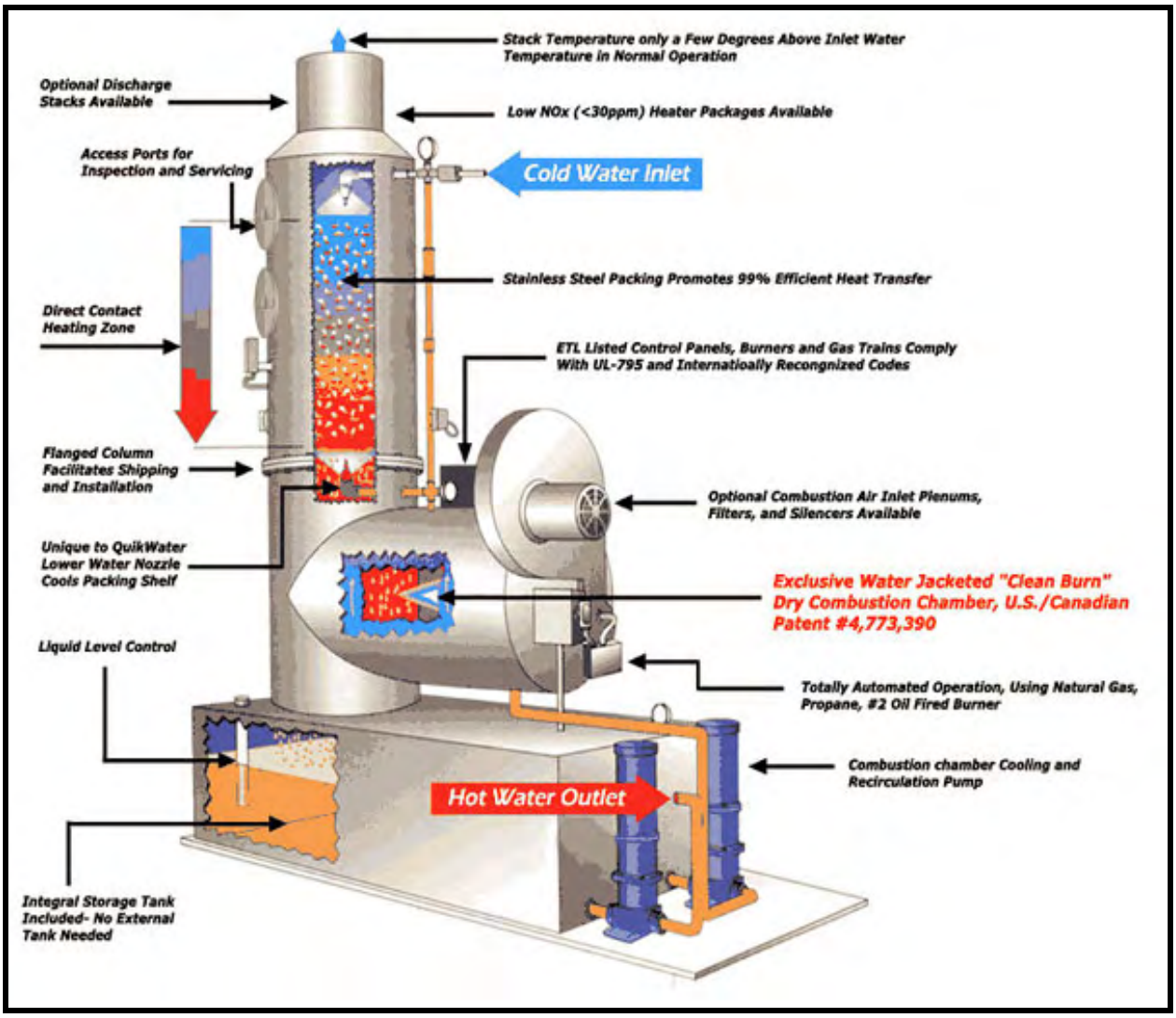

Figure 11. Industrial Water Heater, Quikwater™

Figure 12. Electric Steam Generator

Figure 13. Extraction Well

Figure 14. digiTAM™ Temperature Sensor

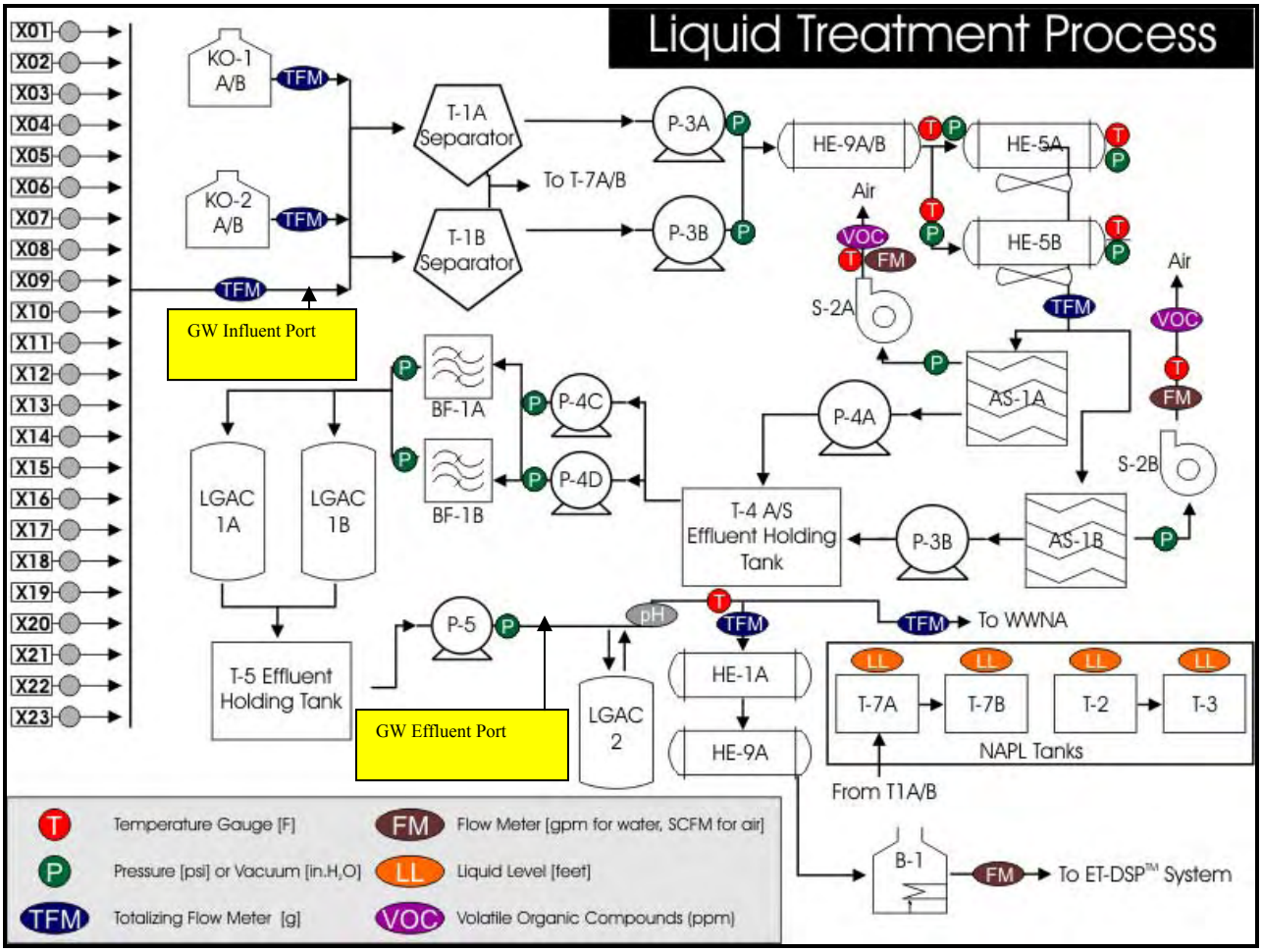

Figure 15. Ground Water Sample Locations

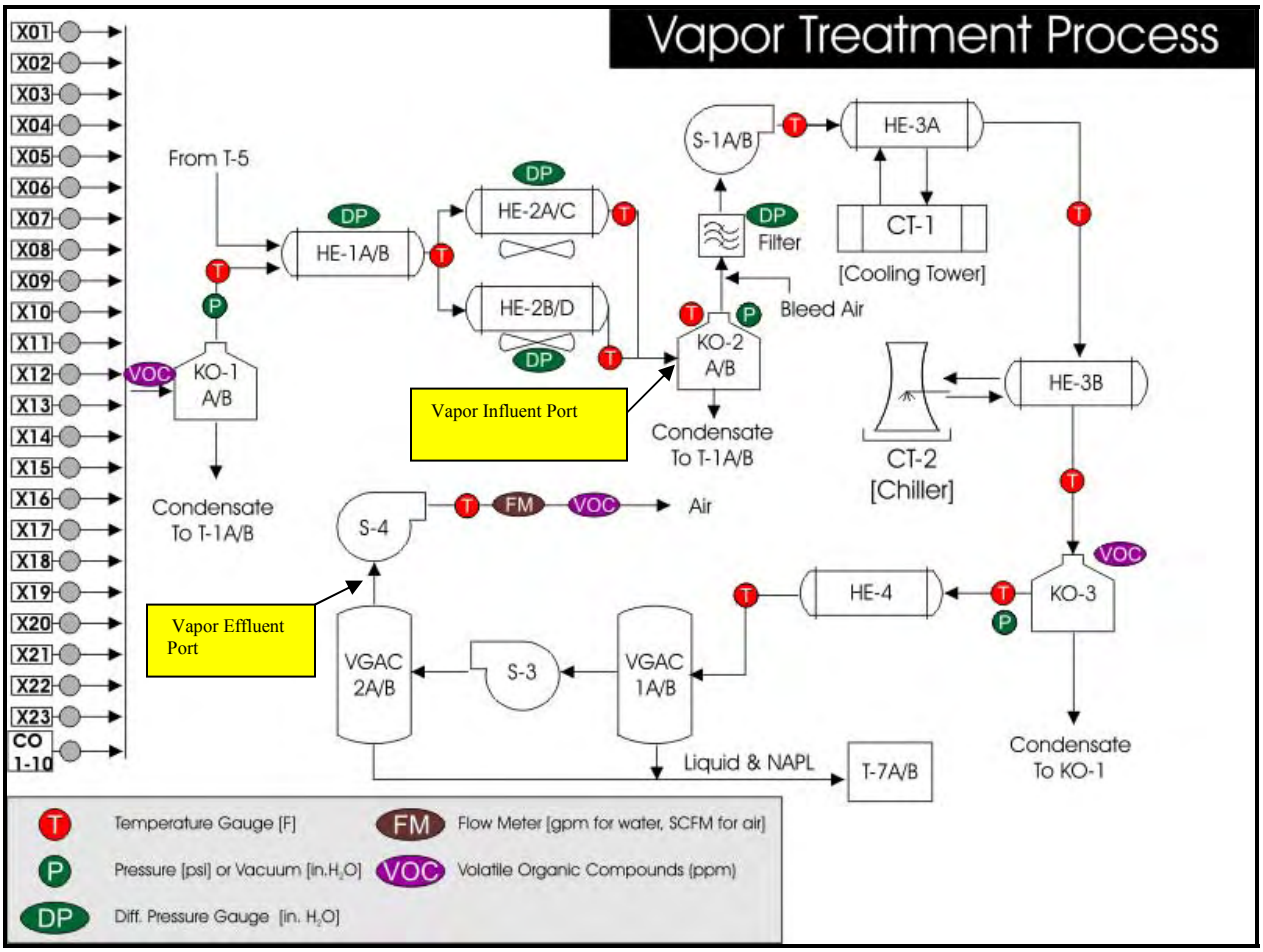

Figure 16. Vapor Sampling Locations

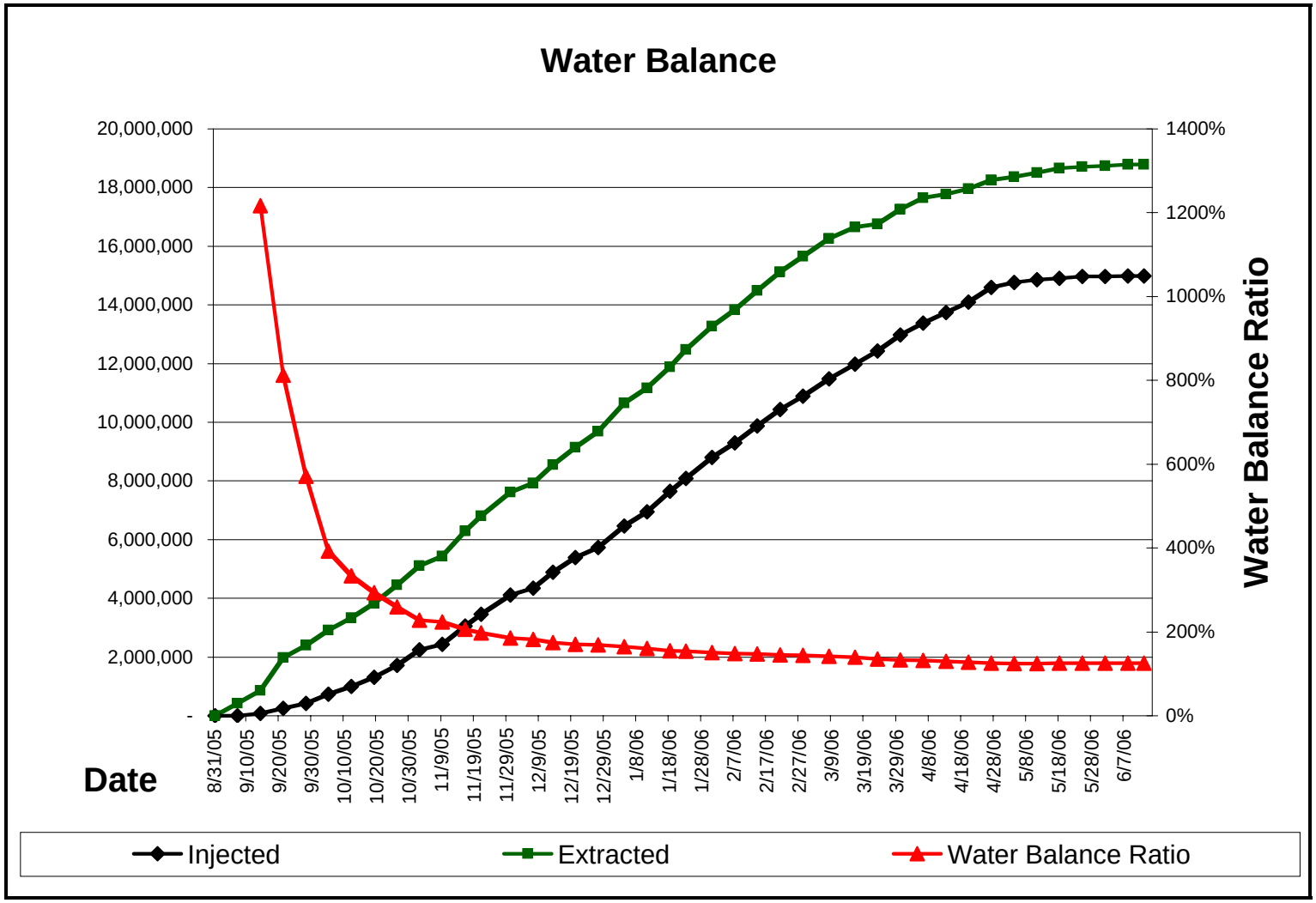

Figure 17. Water Balance

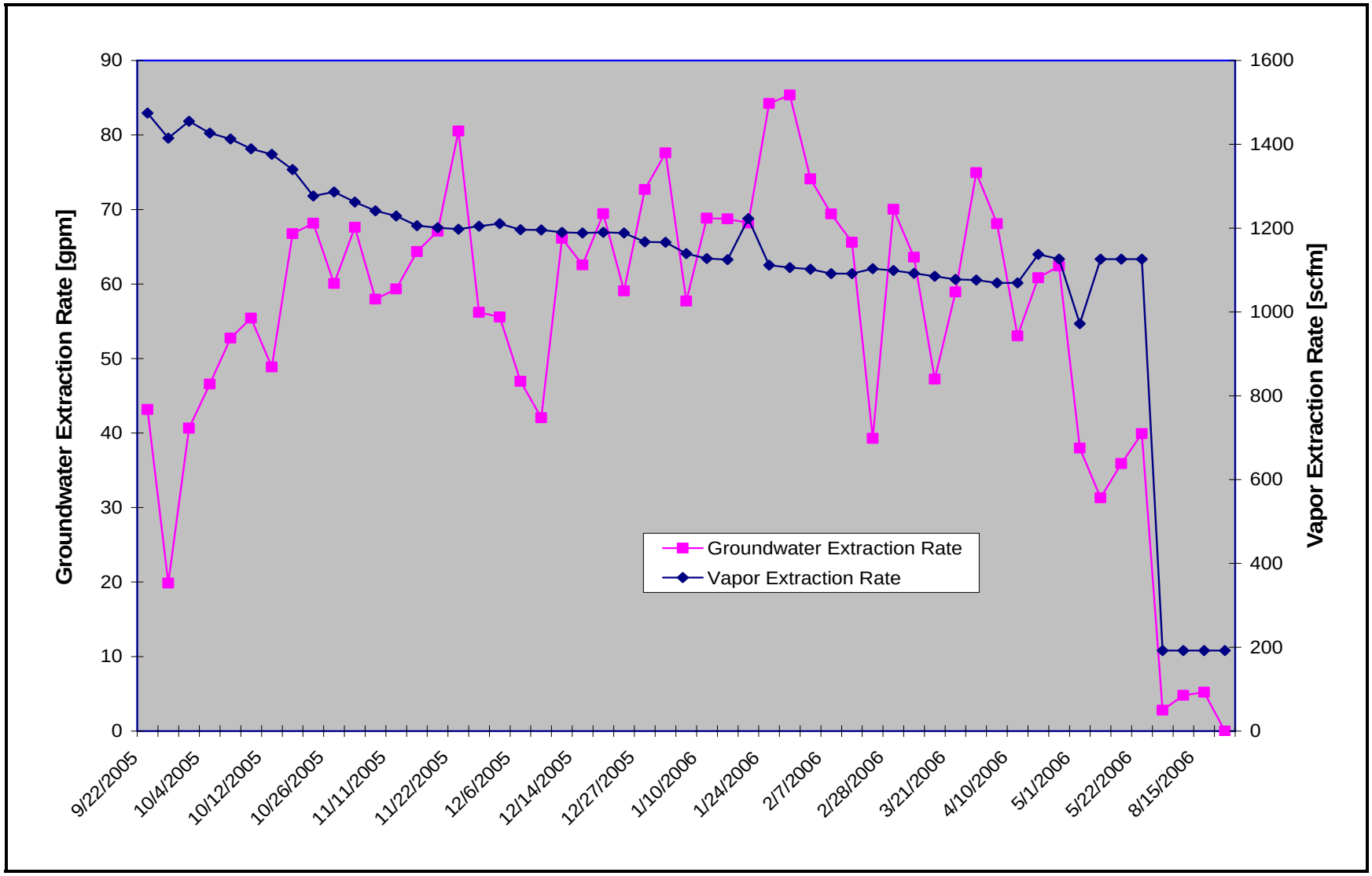

Figure 18. Ground Water and Vapor Extraction Rates

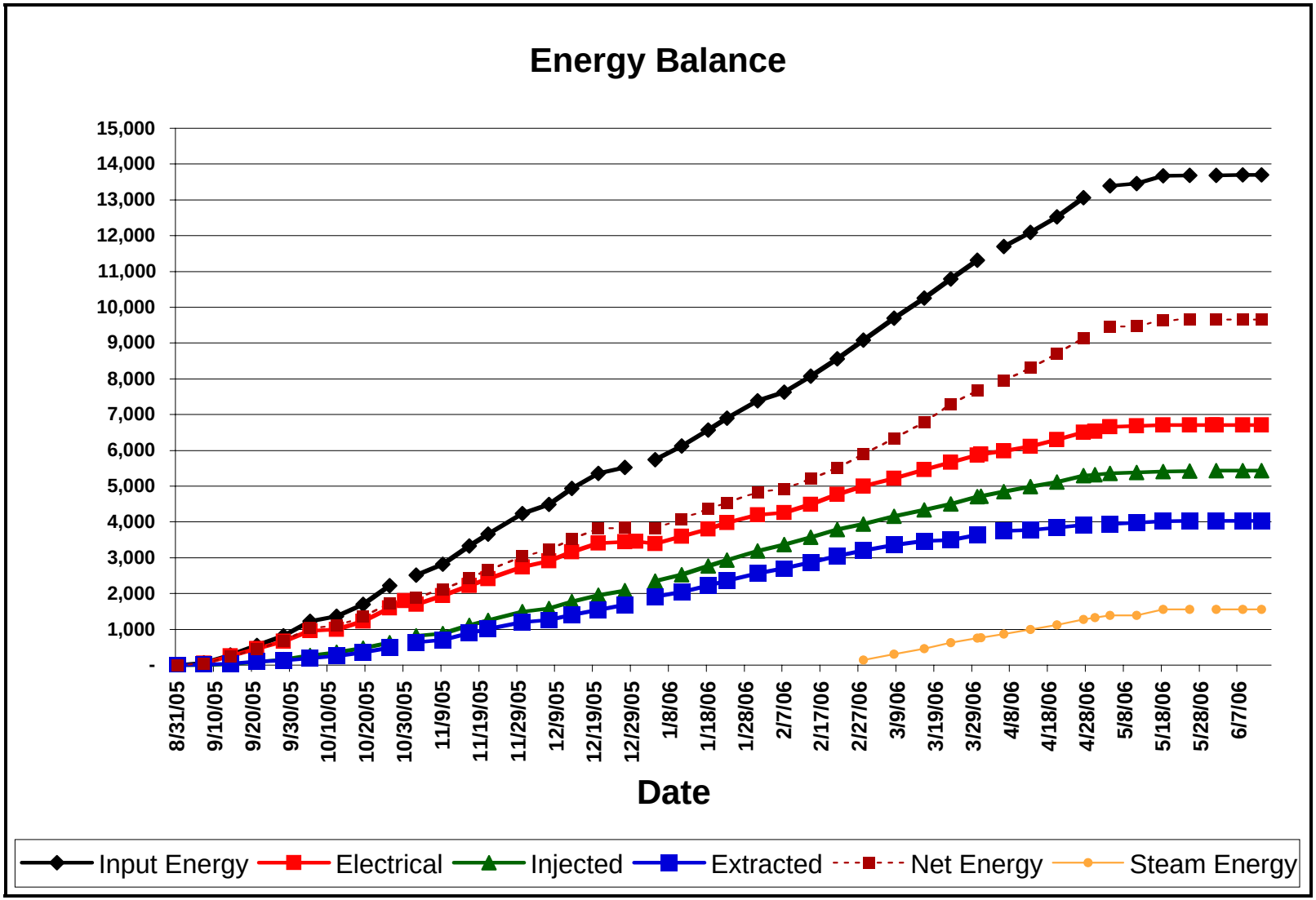

Figure 19. Energy Balance

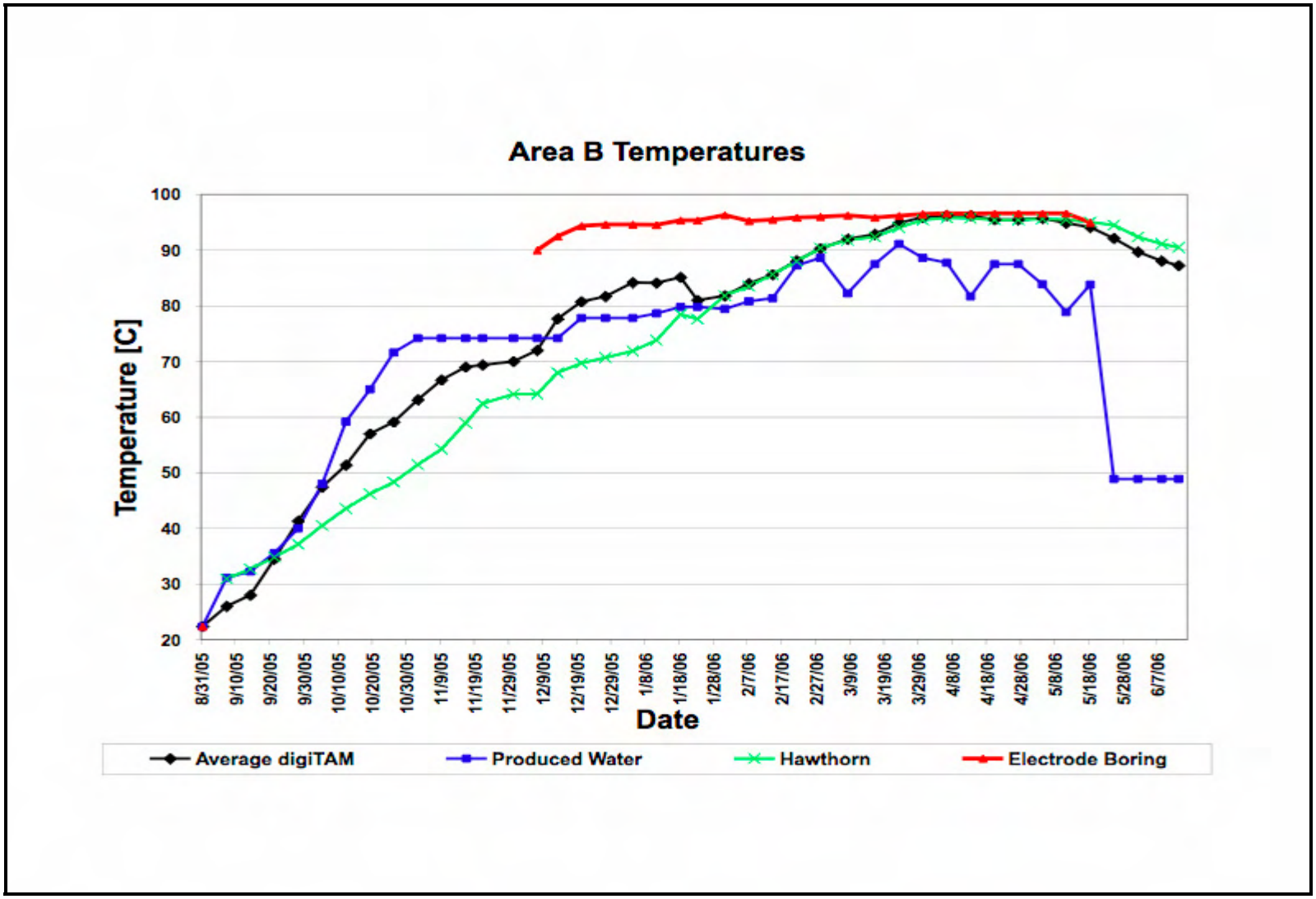

Figure 20. Area B Average Temperatures

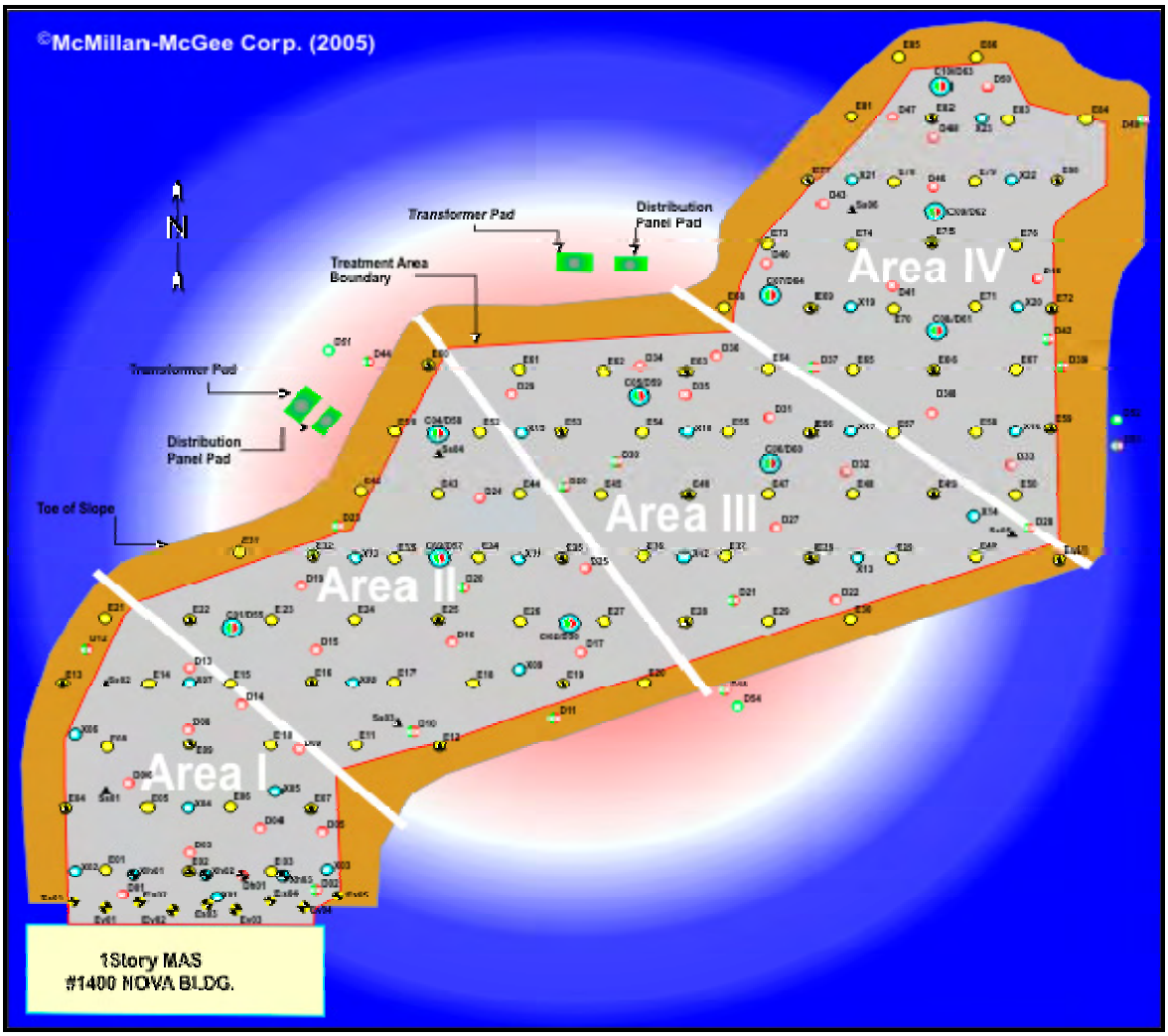

Figure 21. Location of Remediation Areas I through IV

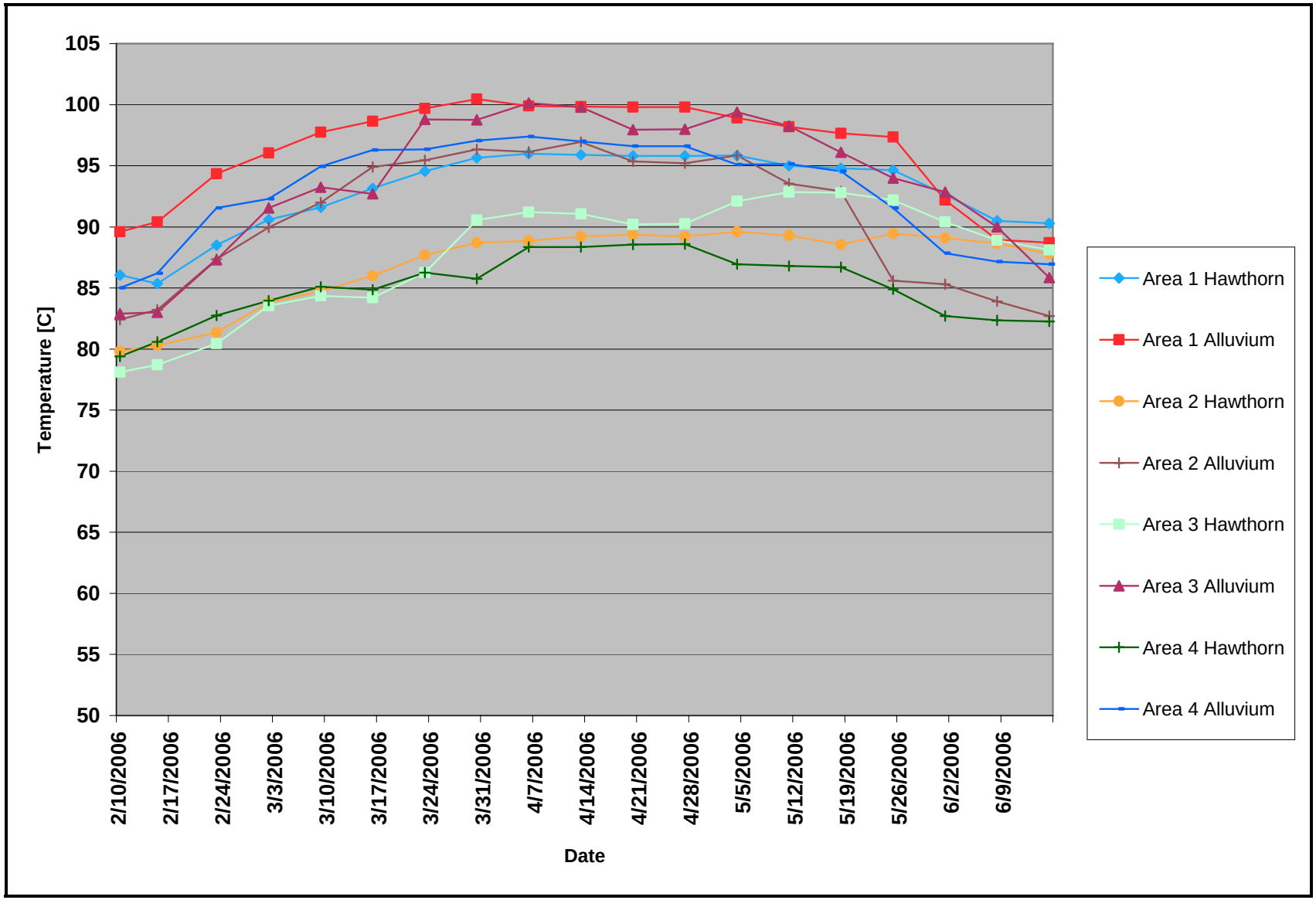

Figure 22. Temperature in Hawthorn and Alluvium, by Area

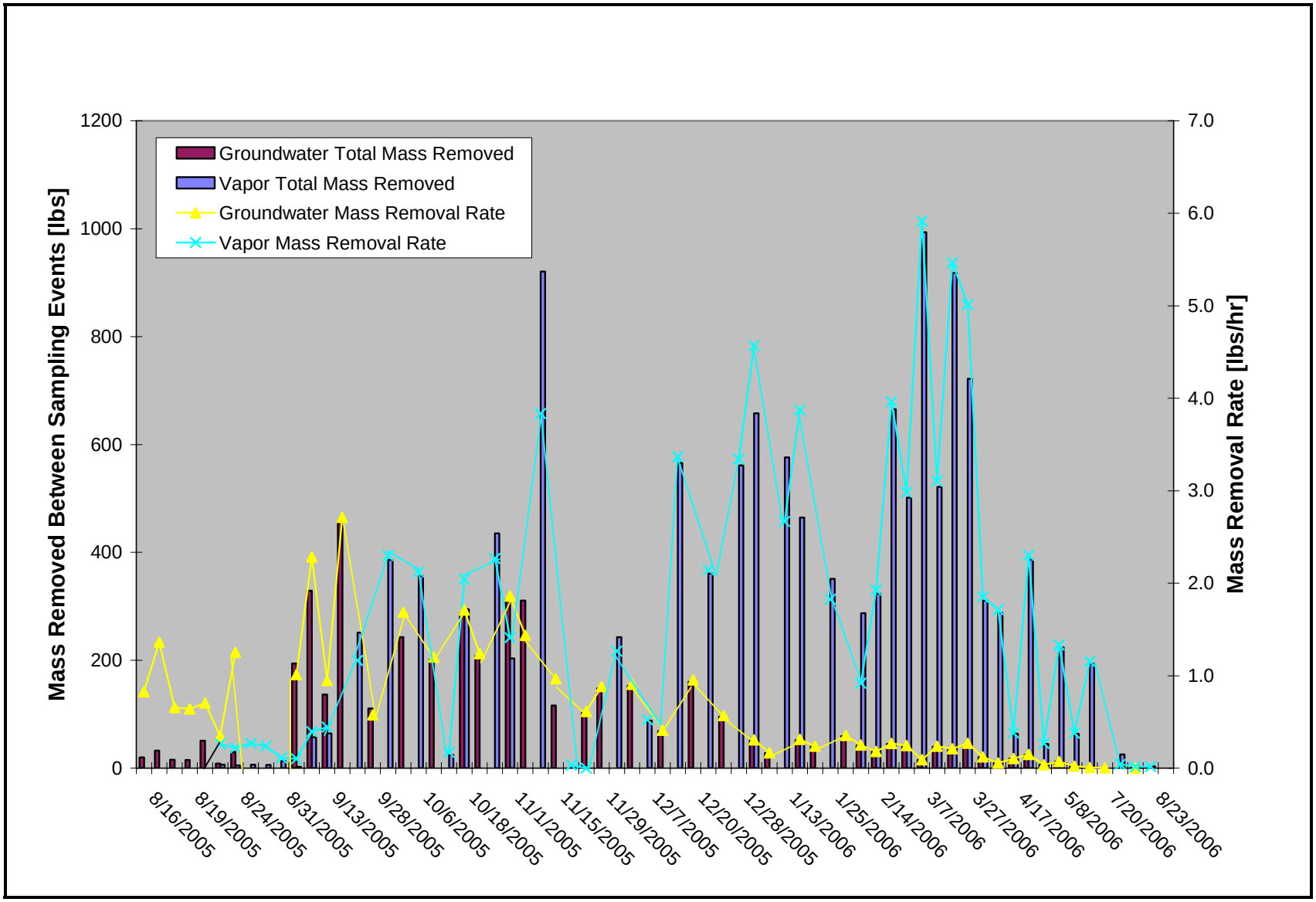

Figure 23. Vapor and Ground Water Mass Removal Rate

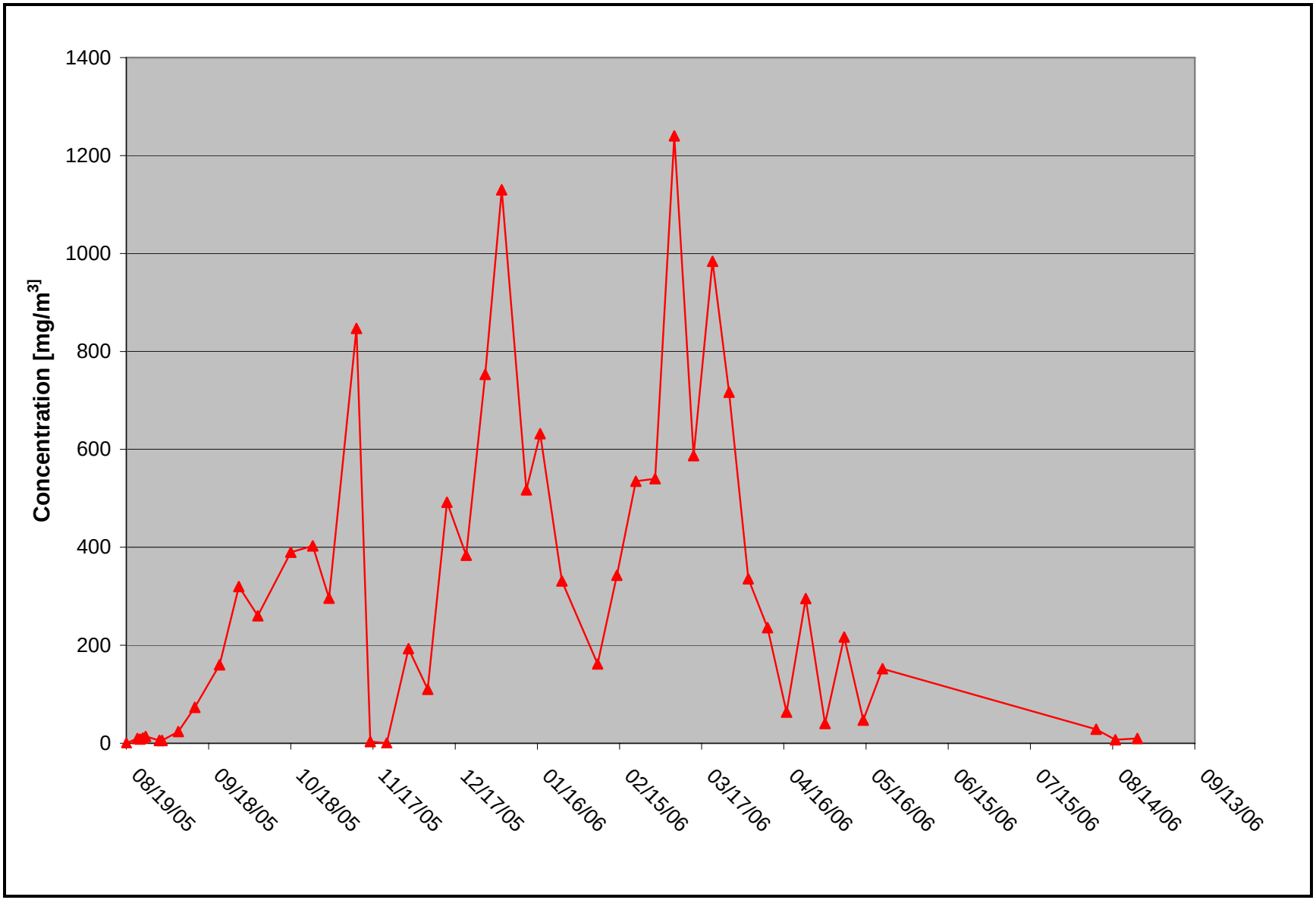

Figure 24. TCE Vapor Influent Concentration

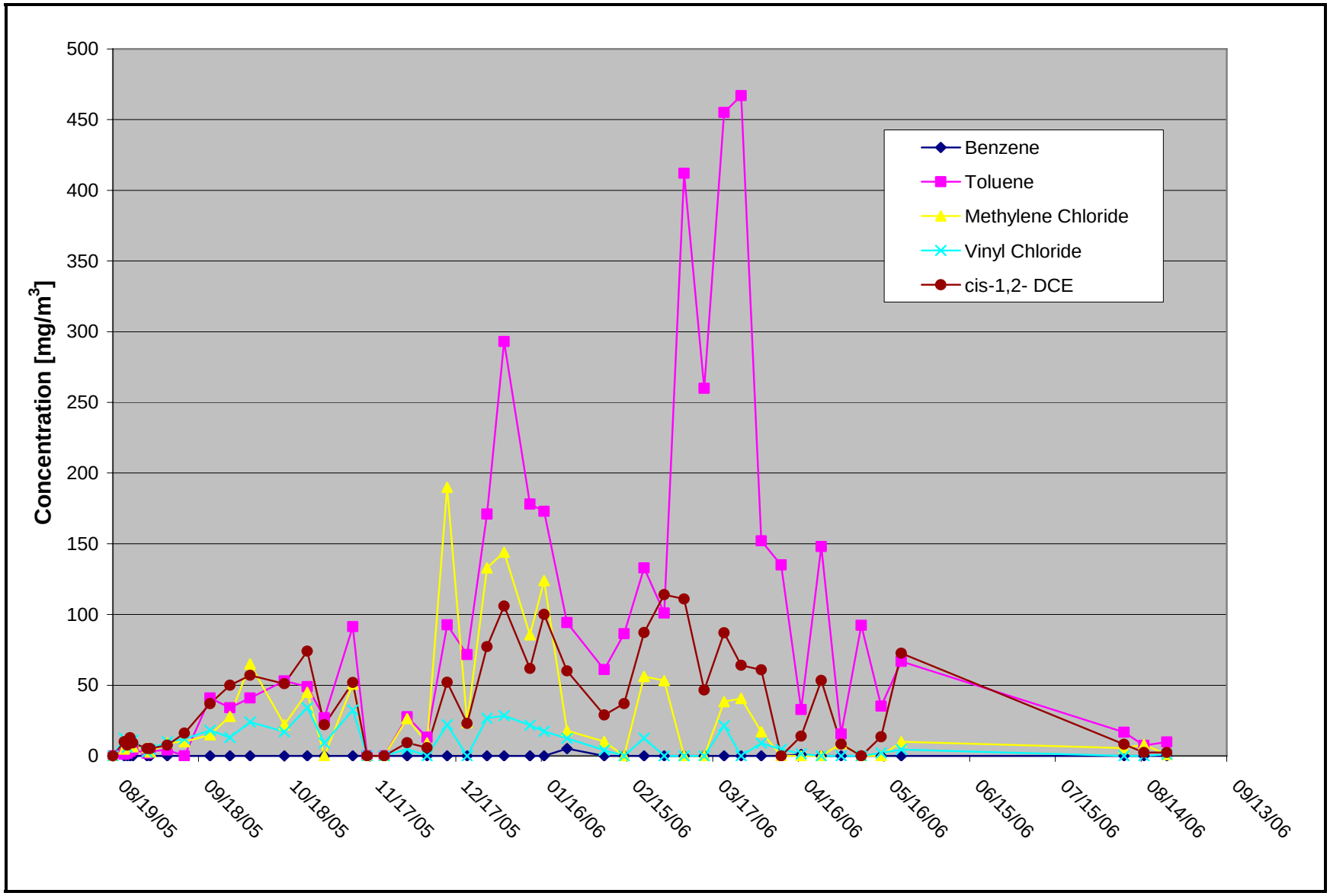

Figure 25. COC Vapor Influent Concentrations versus Time

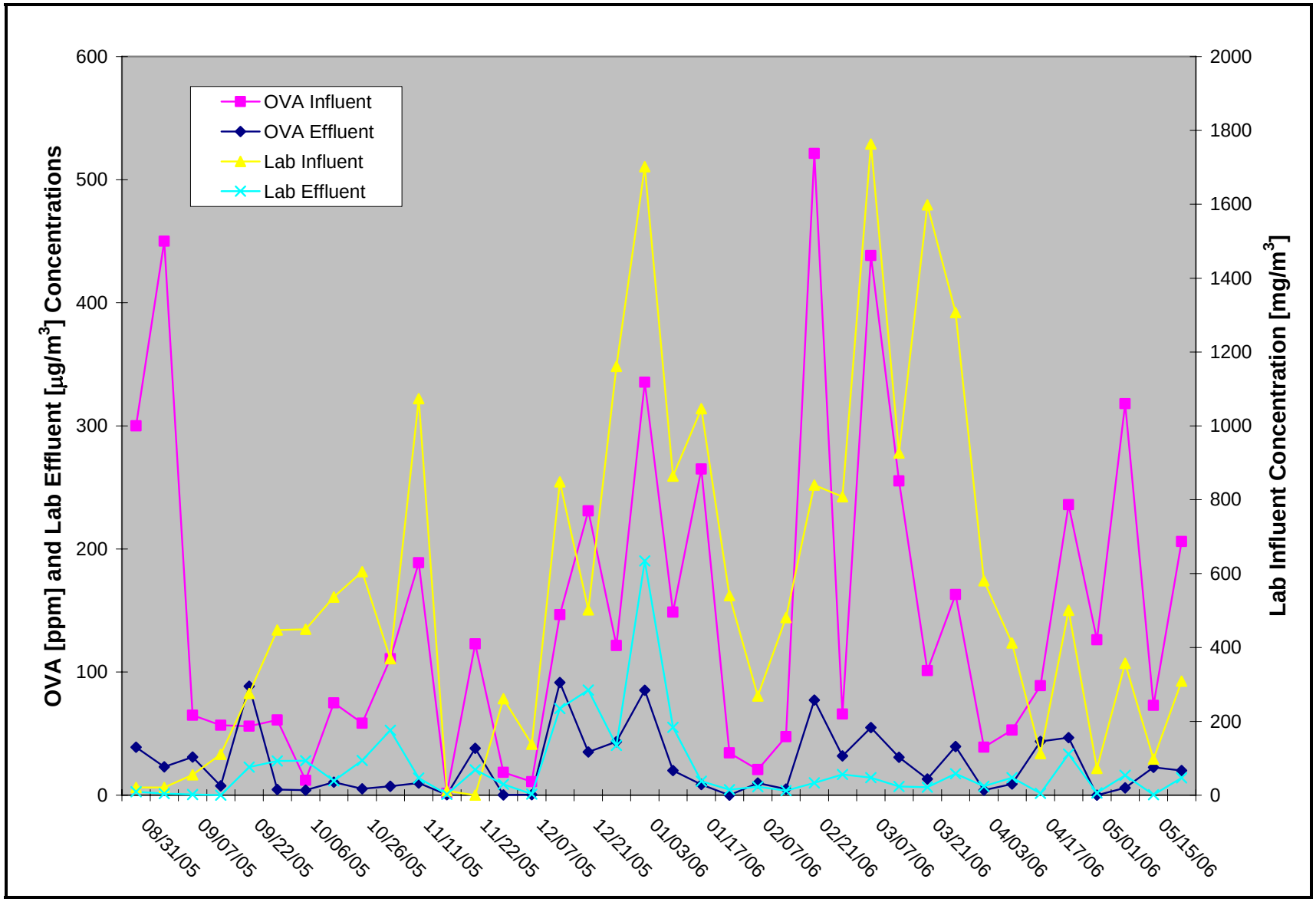

Figure 26. OVA and Laboratory Correlation

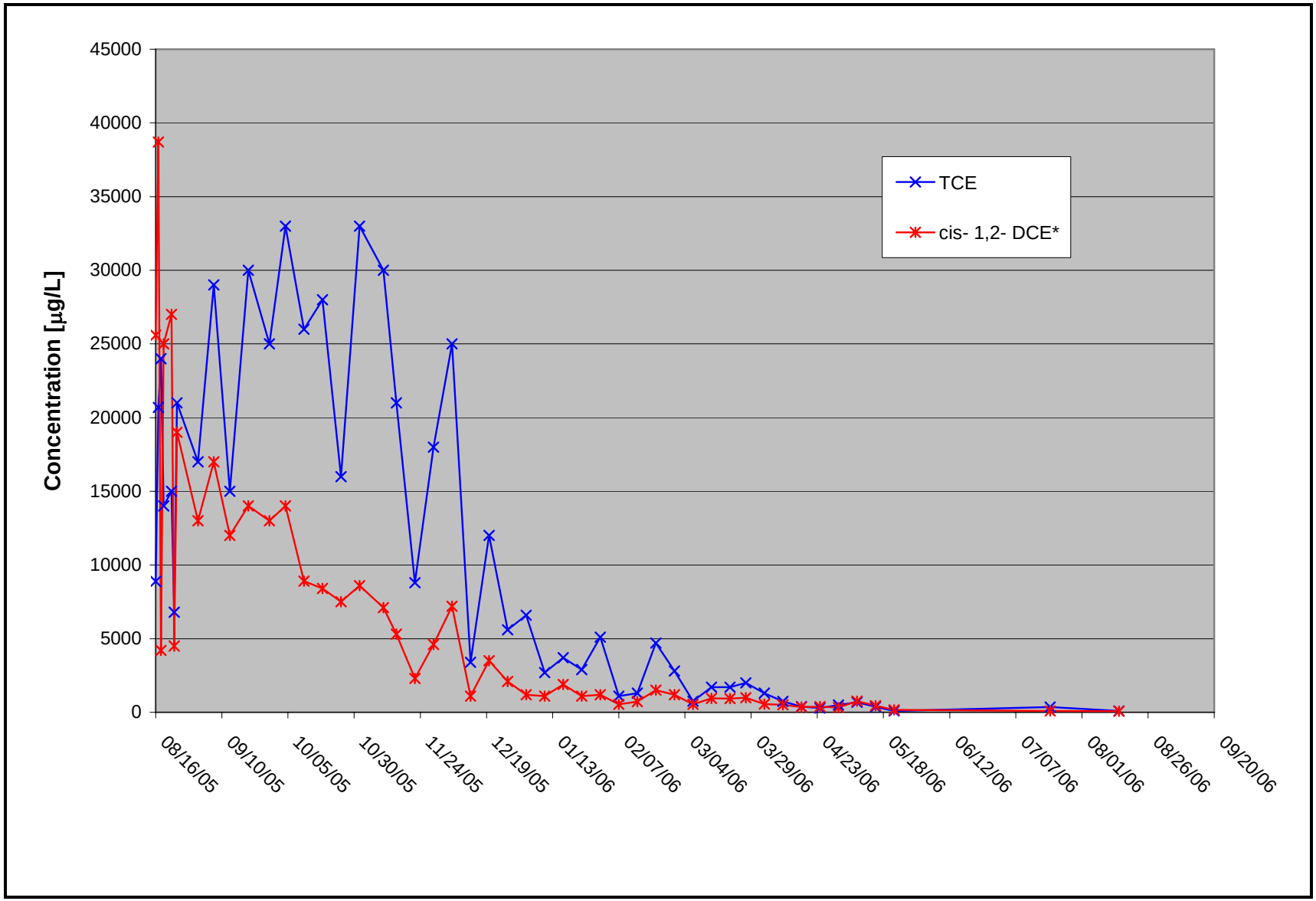

Figure 27. TCE and cDCE Ground Water Concentrations

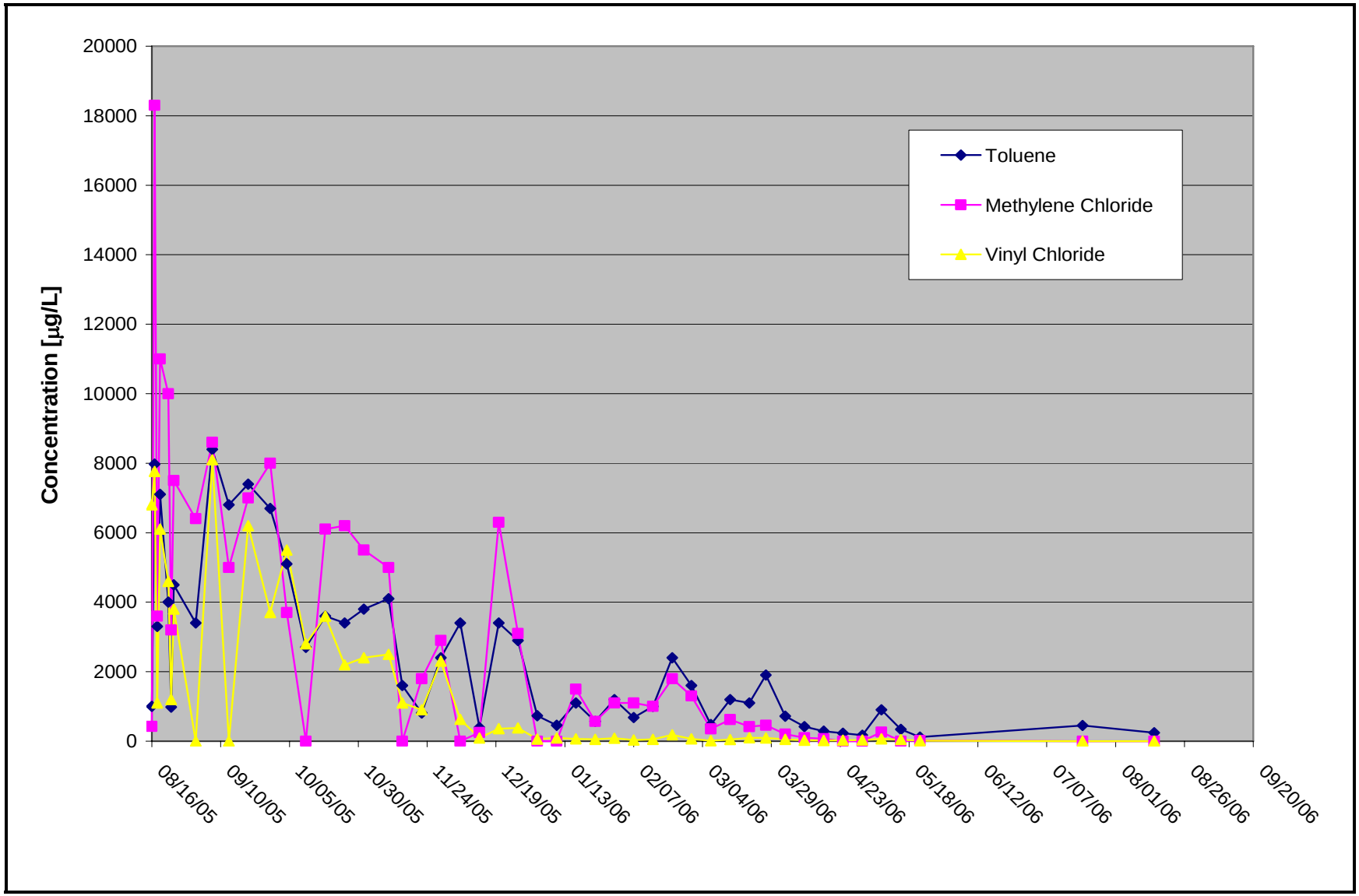

Figure 28. Toluene, Methylene Chloride, and VC Ground Water Concentrations

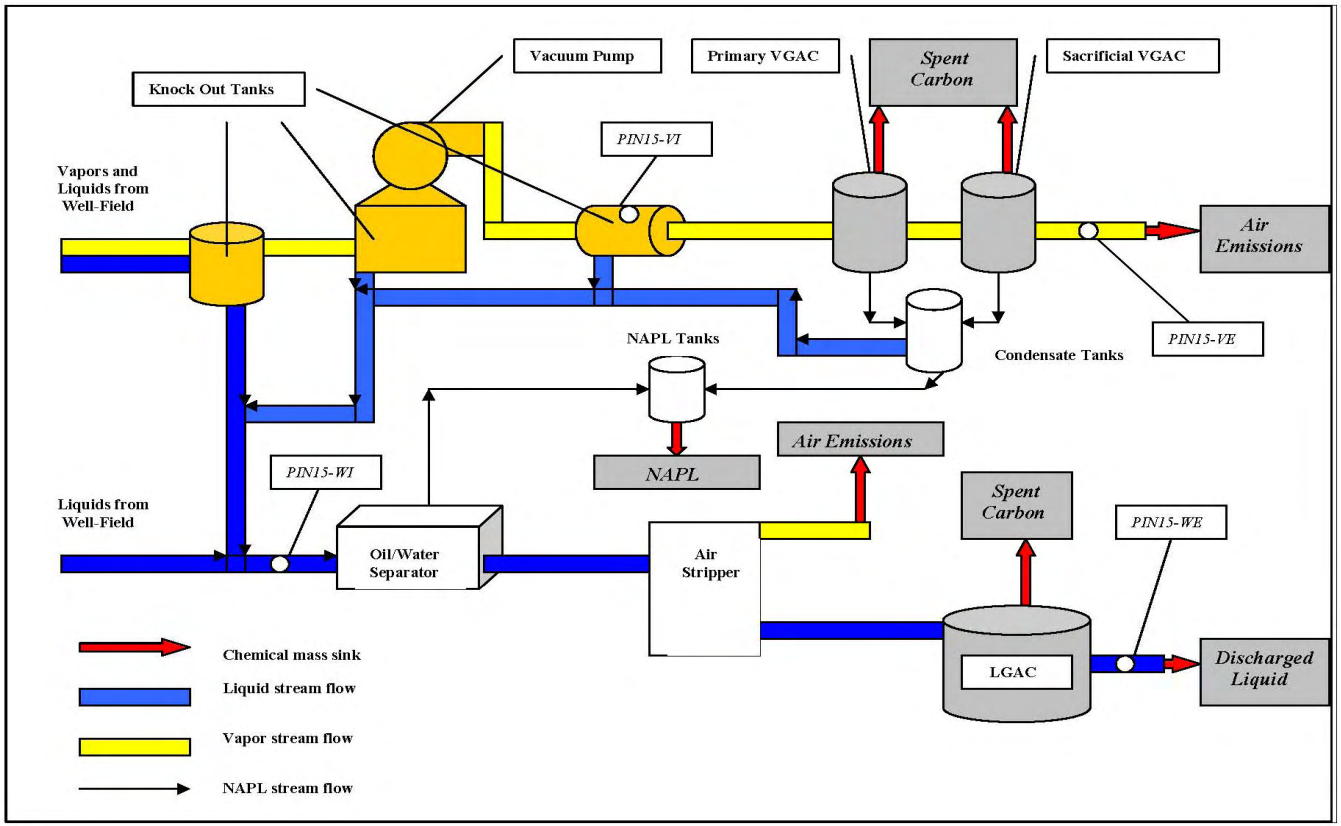

Figure 29. Conceptualized Process Flow Diagram Showing Chemical Sinks

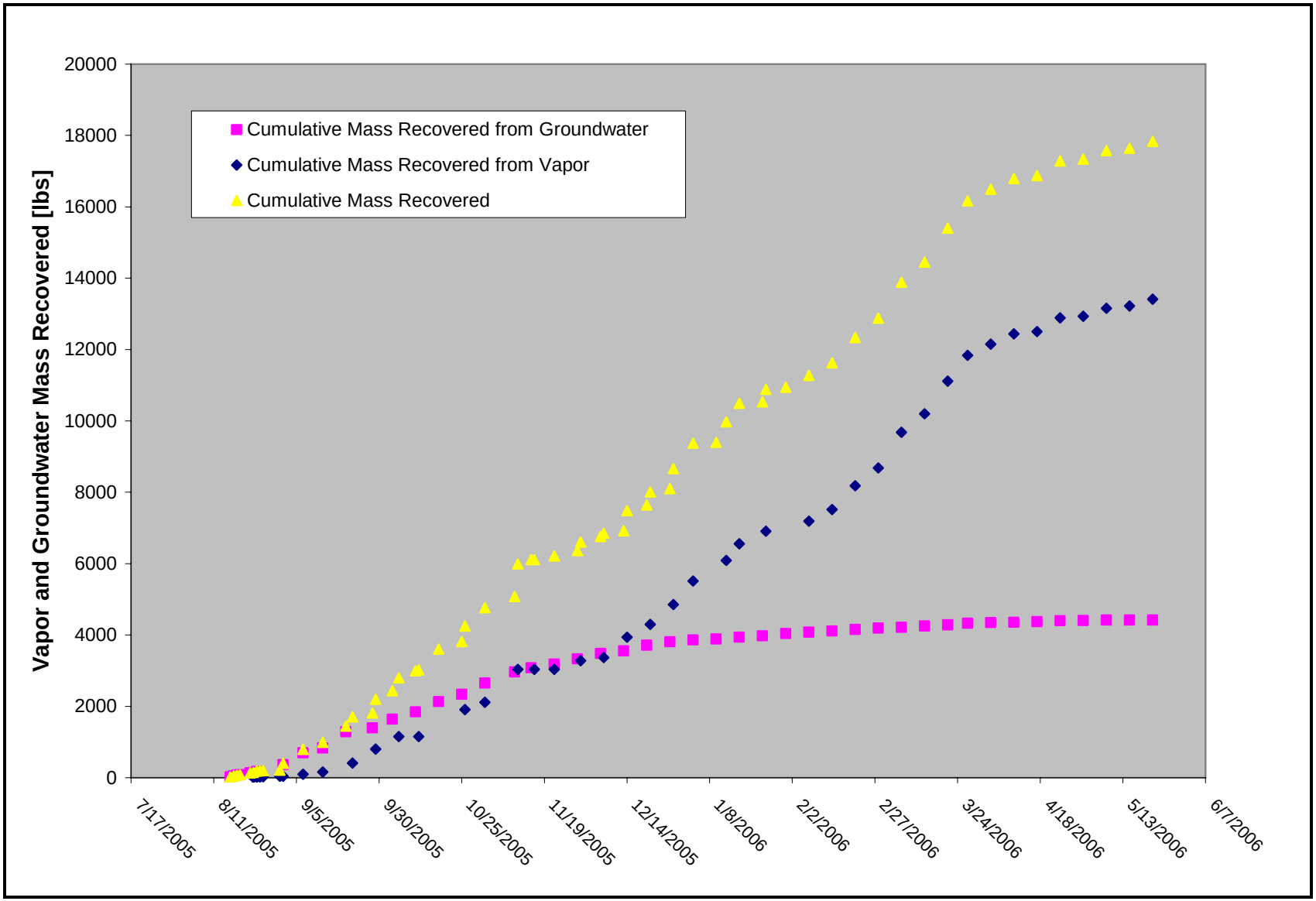

Figure 30. Cumulative Mass Recovered

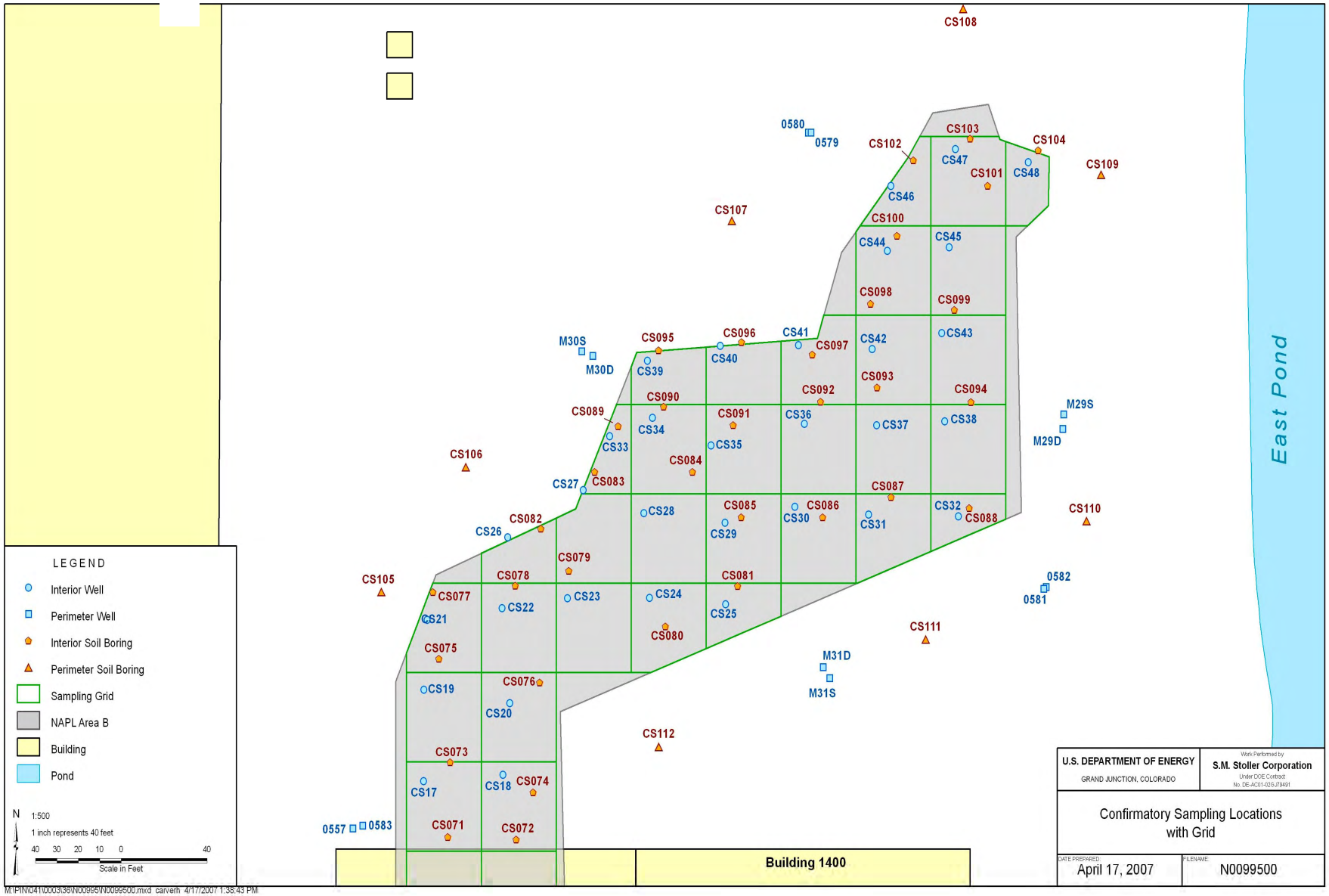

Figure 31. Confirmatory Sampling Locations

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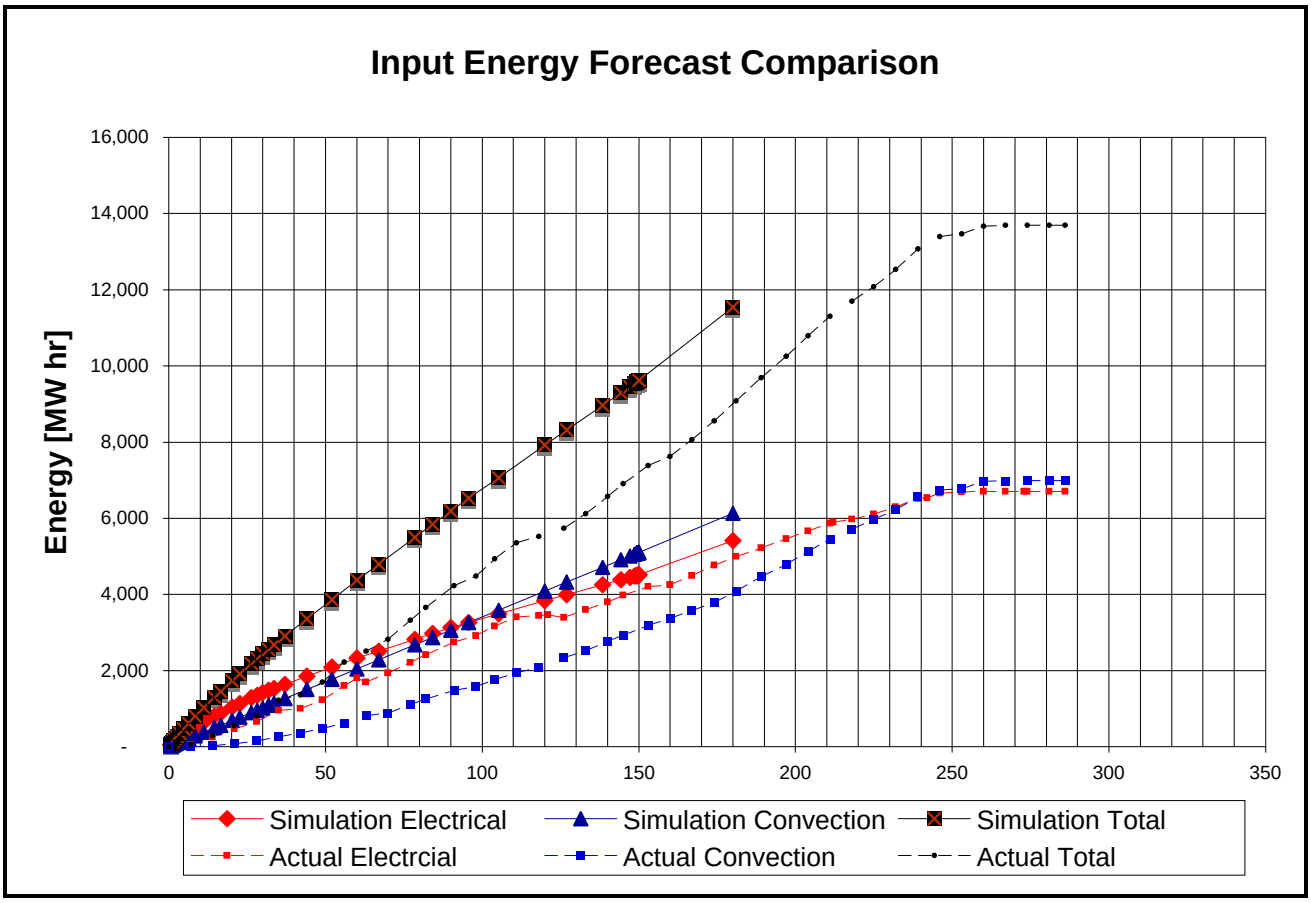

Figure 32. Input Energy Forecast Comparison

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Table 1. Remediation Goals

NAPL Component	Ground Water Cleanup Goals (µg/L)[a]	Soil Cleanup Goals (µg/kg)[b]
TCE	11,000	20,400
cDCE	50,000	71,000
Methylene Chloride	20,000	227,000
Toluene	5,500	15,000
Total Petroleum Hydrocarbons[c]	50,000	2,500,000

[a]µg/L = micrograms per liter
[b]µg/kg = micrograms per kilogram
[c]As measured by Method Florida-Petroleum Range Organics (FL-PRO)

Table 2. Project Cost

Project Phase	Cost
Planning and Design	$583,929
Construction (includes equipment)	$4,832,556
Operations	$2,439,272
Demobilization	$162,485
Final Report	$74,711
Total Project Cost	$8,092,953

Table 3. Project Summary Information

	Parameter	Units	Notes
Site Characteristics	Treatment Area	36,400 ft^2	Approximately
	Volume Treated	54,000 yd^3	Approximately
	Deep Extent of Treatment	40 ft bgs	Based on Stoller information
	Shallow Extent of Treatment	Surface	Based on Stoller information
	Depth to Ground water	1-6 ft bgs	Based on Stoller information
	Contaminants of Concern	Toluene; TCE, cDCE, Methylene chloride; TPH	LNAPLs; DNAPLs; Heavy Oils
	Soil Resistivity (Static)	30 Ω·meter	Based on site experience
Remedial Approach	Vapor Cap	40,000 ft^2	asphalt cap w/ 5 ft impermeable skirt
	ET-DSP™ Electrodes	185	Area B and Building 1,400 electrodes
	Electrode Boreholes	95	Staggered in two distinct layers, include slant electrodes Building 1,400
	ET-DSP™ PDS	10 x 400 kVA units	C/w computer and Internet control
	Temperature Sensors	~2,000	150 strings with 16 sensors per
	Pressure Sensors	30	Verify hydrodynamic control
	Distance Between Electrodes	~24'	Based on numerical simulation
	Depth to Bottom of Electrode	35-29 ft bgs	Heat transfer 3−6 ft below electrode
	Depth to Top of Electrode	14-8 ft bgs	Heat transfer 3−6 ft above electrode
	Steam Spears (in electrode borings)	29	Installed to 5 ft bgs in deeper electrode set (800,000 BTU/hr)
	Steam Spears	12	Installed in later stage of operations
	Target Temperature	~85 °C	Minimum temperature achieved within treatment volume
	Extraction Wells	25	Two header systems for separate vapor and ground water control
	Extraction Header/Piping	Above Grade	6-inch to 2-inch steel pipe
	Extraction System Water Treatment	Two High Vac, Multi Phase	~100 horsepower. One complete standby system
	Vapor Recovery Flow Rate	~1,000 scfm	Maximize contaminant recovery
	Vapor Treatment Method	Regenerative carbon	3,000 lbs GAC for polish
Summary Info	Electrical Power Input	1,218 kW	Average for project duration
	Total Energy Input	13,833,000 kW-Hr	Total energy input during operations
	Water Demand	60 gpm	Average, rate varied from 40 to 80 gpm
	Time to Target Temperature	120 days	Based on operations
	Duration of Operations	8 months	Sep 2005 to May 2006

Table 4. Thermal Remediation Equipment

Equipment	Rating	Manufacturer	Energy Type
Hot Water Heater (1)	6,000,000 BTU/hr	Quikwater™	Propane/gas fired
Steam Generator (1)	0.8 to 1.4 million BTU/hr	Electro-Steam BV-240	Electrical
Steam Generator (1)	3 million BTU/hr	Equipment rented	diesel
Power Delivery Systems (9)	400 kVA	Mc^2	Electrical
Electrode-Steam injection points	35 kW per electrode.	Mc^2	Electrical-steam
Water circulation system (10)	>10 gpm	Mc^2	Electrical

Table 5. Area B Project Activities Timeline

Design	
Project Kickoff Meeting	25 Feb 2004
Conceptual Design Complete	23 Mar 2004
Final Design Complete	29 Jun 2004
Construction	
Construction Readiness Review	29 Jun 2004
Construction mobilization	6 Jul 2004
Construction permitting finalized	8 Jul 2004
Vapor cap skirt installation completed	24 Jul 2004
Shut down for Hurricane Charlie	12 Aug 2004
Construction Progress Review	18 Aug 2004
Vapor cap paving & swale complete	24 Aug 2004
Drilling subcontractor mobilized	30 Aug 2004
Shut down for Hurricane Frances	1 Sep 2004
Drilling subcontractor remobilized	7 Sep 2004
Secured for Hurricane Ivan	9 Sep 2004
Construction Progress Review	22 Sep 2004
Shut down for Hurricane Jeanne	24 Sep 2004
Construction Progress Review	20 Oct 2004
Drilling/well installation complete	29 Nov 2004
Treatment area tent install complete	27 Jan 2005
Wellhead/piping complete	31 Mar 2005
Construction Progress Review	20 Apr 2005
Construction Progress Review	17 May 2005
Construction Progress Review	28 Jun 2005
Baseline sampling complete	29 Jul 2005
Operations	
Operations Readiness Review	9 Aug 2005
Treatment system startup	16 Aug 2005
Hydraulic & pneumatic control established; begin preheating	1 Sep 2005
Preheating complete; begin Ramp Up	23 Sep 2005
Initial Operations Progress Review	19 Oct 2005
Ramp-up complete; begin maintenance heating	15 Jan 2006
Mid-Pt Operations Progress Review	25 Jan 2006
Maintenance heating complete; begin extended heating	31 Mar 2006
Extended heating complete; begin cool down with Area III heating	28 Apr 2006
Area III heating complete; continue cool down	15 May 2006
Cool down complete	9 Jun 2006
System shut down	12 Jun 2006
Final Progress Review	14 Jun 2006

Confirmatory Sampling	
Confirmatory sampling commenced with perimeter soil sampling	30 May 2006
Round 1 ground water confirmatory sampling	14 Jul 2006
Allowable toluene levels exceeded - resume focused heating at western edge of Area III	18 Jul 2006
Focused heating complete	29 Aug 2006
Round 2 ground water confirmatory sampling complete – all samples below required levels	11 Sep 2006
Round 3 ground water confirmatory sampling complete	29 Sep 2006
Demobilization	
Demobilization activities started	6 Nov 2006
Site restoration complete	27 Dec 2006
Final Report	
Final Report Submittal to Stoller	10 Apr 2007
Final Report Presentation	12 Apr 2007

Table 6. Energy Usage

Electrical Energy Injected	6,844,000 kW-Hr
Hot Water Energy Injected	5,432,000 kW-Hr
Steam Energy Injected	1,558,000 kW-Hr
Total Injected Energy	13,833,000 kW-Hr
Energy per yd^3	249 kW-Hr/yd^3
Total Extracted Energy	4,036,000 kW-Hr

Table 7. Mass of Contaminants in the Vapor and Liquid Phases

Contaminant	Vapor Phase		Liquid Phase		Total
	Mass	% of Total	Mass	% of Total	
Toluene	2,528 lbs	86 %	419 lbs	14 %	2,947 lbs
Methylene Chloride	776 lbs	64 %	444 lbs	36 %	1,220 lbs
TCE	8,658 lbs	81 %	2,033 lbs	19 %	10,691 lbs
cDCE	1,068 lbs	56 %	828 lbs	44 %	1,896 lbs
Total	**13,030 lbs**	**78 %**	**3,724 lbs**	**22 %**	**16,754 lbs**

Table 8. Contaminant Mass Estimate Before Remediation

Contaminant	Mass (lbs)
TCE	10,500
Methylene chloride	1,490
Toluene	530
cDCE	690
Total for COCs	13,210
1,1,1-TCA	240
Vinyl chloride	300
Benzene	240
1,1-DCE	240
Ethylbenzene	240
o-Xylene	240
p-Xylene	250
TDCE	240
Total VOCs (including COCs)	**15,200**
Heavy oil compounds	50

Table 9. Mass Estimate After Remediation

Contaminant	Mass Removed	Mass After Remediation	Removal Efficiency
Toluene	2,947 lbs	50.4 lbs	98.3%
Methylene Chloride	1,220 lbs	7.3 lbs	99.4%
TCE	10,691 lbs	17.3 lbs	99.8%
cDCE	1,896 lbs	73.4 lbs	96.3 %
TPH	547 lbs	4.6 lbs	99.2%[a]
Total	17,301 lbs	153.0 lbs	99.1%

[a]The TPH removal efficiency does not take into account mass that may have been removed in the vapor stream, therefore the actual removal efficiency was likely higher than the reported value.

Table 10. Average Confirmatory Ground Water Results

Contaminant	Round 2 Average Concentration	Round 3 Average Concentration	Remediation Goal
TCE	135 µg/L	162 µg/L	11,000 µg/L
Toluene	177 µg/L	197 µg/L	5,500 µg/L
Methylene Chloride	12 µg/L	Not Detected	20,000 µg/L
cDCE	71 µg/L	146 µg/L	50,000 µg/L
FL-PRO	3 mg/L	3 mg/L	50 mg/L

Table 11. Predicted and Actual Total Energy

	Area B Predicted Energy (mW-Hr)	Area B Actual Energy (mW-Hr)	Building 1400 Energy (mW-Hr)	Extended Heating Energy (mW-Hr)	Total Energy Input (mW-Hr)
Electrical	5,419	5,919	282	643	6,844
Convective Energy					
Hot Water	6,126	4,725	114	593	5,432
Steam	0	1,002	0	556	1,558
Total Convective Energy	6,126	5,726	114	1,149	6,990
Total Energy	**11,545**	**11,645**	**396**	**1,792**	**13,833**
kW-Hr/yd^3	**214**	**216**	**264**	**33**	**249**

Notes:
Extended heating energy is the energy used during the extended operations in April 2006.
Building 1400 hot water energy based on 2.5 gpm of 80 ºC water injected to electrodes over 3 months

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