# SOIL VAPOR EXTRACTION PILOT TEST REPORT

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# Executive Summary

A soil vapor extraction (SVE) pilot test was conducted in response to the United States Environmental Protection Agency (USEPA)'s Final Decision issued on February 26, 2008, for the Solutia Inc.'s (Solutia's) W.G. Krummrich Facility (site) in Sauget, Illinois. Per the Final Decision, SVE is to be applied to the unsaturated zone soils which are impacted with volatile organic compounds (VOCs), primarily benzene and chlorobenzenes. The following areas of the site were identified for SVE treatment: the Former Benzene and Chlorobenzene Storage area (Big Mo area), the Former Benzene Pipeline area, the North Tank Farm/Former Overhead Steamer Tank area, and the Near Little Mo area (refer to **Figure ES-1** for the locations of these treatment areas).

This *SVE Pilot Test Report* summarizes the results of SVE pilot testing conducted in the Big Mo area between January 2009 and July 2010. The results of the SVE pilot test were used to develop the *Work Plan for Full-Scale SVE* (November 2010), submitted to USEPA in a separate report.

**<u>Pilot Test Objectives</u>**

The primary objectives of the SVE pilot test were to:

- Demonstrate constituent of concern (benzene and chlorobenzene; [COC]) mass reduction and estimate the COC mass removal rates achievable with SVE technology.
- Determine the most effective operational configuration using a combination of SVE and air injection (AI) wells.
- Develop full-scale SVE design parameters, including well-to-well spacing, wellhead flow rates and vacuums/pressures, etc.

## Overview of Pilot Test Area

Three major soil units were identified in the pilot test area. Test wells were installed within each of the following geological units:

- Sandy fill/upper silty sand layer (from ground surface to approximately 10 feet below ground surface [feet bgs]).
- Intermediate silty clay layer (approximately 10 to 12 feet bgs).
- Lower silty sand layer (approximately 12 to 15 feet bgs).

The Big Mo area was chosen for the pilot test because this area exhibited the most elevated COC concentrations (historical borings S0607 and SB-A01 at 2,400 milligrams per kilograms [mg/kg] and 13,000 mg/kg benzene, respectively). The Big Mo area is also geologically similar to the other treatment areas. The SVE pilot test layout is shown in **Figure ES-2**. The pilot test encompassed an area of 60 feet by 80 feet (4,800 square feet).

## Summary of Pilot Test Program

The pilot testing program included the following key elements:

- Parameter Evaluation Testing (PET): The PET program was performed on individual SVE/AI wellheads, and also using multi-well test configurations. The PET was designed to:
    - Evaluate individual wellhead flow characteristics (i.e., flow rate vs. vacuum/pressure response at a well).
    - Evaluate the well field air flow distribution (i.e., vacuum/pressure response in the surrounding well field).

- Evaluate multi-well configurations using combinations of vapor extraction/air injection wells to determine the optimal configuration for the duration of pilot testing.

- Performance Evaluation (PE): The extended PE test was conducted to evaluate the overall COC mass reduction that could be achieved over an extended operation period.

- Soil Sampling: Soil sampling was incorporated into the test program to evaluate the COC mass reduction performance at various stages of the pilot test. It was desired to achieve at least 30% COC mass reduction during the pilot test so that typical soil sampling data variability would not obscure the SVE performance.

- Data Evaluation and Air Flow Modeling: A subsurface air flow computer model was used to estimate Radius of Influence (ROI) and Pore Volume (PV) exchange rates (PV/year) from the PET test data. The ROI and PV exchange rate are used to determine the full-scale SVE well spacing. The computer model was also used to develop intrinsic soil permeability estimates.

**Pilot Test Results Summary**

*PET and Extended PE Results*

- The sandy fill/upper silty sand and lower silty sand units appear to be more permeable than anticipated. Wellhead air flows ranged from 5.4 standard cubic feet per minute (scfm) at 25 inches of water (in. $H_2O$) to 34 scfm at 50 in. $H_2O$ for vapor extraction. The air injection flow rates ranged from 5 scfm at 40 in. $H_2O$ to 116 scfm at 50 in. $H_2O$.
- A relatively uniform vacuum/pressure influence was observed throughout the well field during the PET in most test scenarios. This indicated that adequate air flow distribution was occurring in response to the SVE/AI application.

- The flow field configuration testing demonstrated that the optimal configuration for the extended PE test was a combination of SVE and AI wells. The AI wells improved air flow through the target soils and increased the achievable COC mass removal rates.
- The PE test confirmed that a significant amount of COC mass could be removed from the sandy fill/upper silty sand layer using SVE. A total of 15,600 pounds (lbs) of benzene was removed based on monitoring of the air effluent of the pilot system. The average mass removal rate observed from the full SVE pilot test area was approximately 7.4 lbs per hour and approximately 1.0 lbs per hour from the sub-area. The mass removal performance is presented on **Figures ES-3A and ES-3B**.
- Water table fluctuations interfered with SVE performance in the sandy fill/shallow silty sand zone. The COC mass removal rate would likely have remained higher if water table elevations had not partially blocked the SVE well screens.
- The intermediate silty clay layer was briefly tested and the test indicated that SVE is not likely to be effective for treating this unit, as no measurable air flow rate could be achieved.
- SVE wells in the lower silty sand layer exhibited very similar wellhead air flow/vacuum relationships as compared to the sandy fill/upper silty sand layer SVE wells. Therefore, air flow characteristics estimated during the pilot test are expected to be reasonably applicable to the lower silty sand layer for the purposes of the full-scale design.

*COC Mass Reduction / Soil Sampling Results*

- COC (benzene) mass reduction estimates are presented on **Table ES-1**.
- The pre-pilot baseline COC mass estimate indicated that up to 79,000 lbs of benzene was present in the sandy fill/upper silty sand layer.
- The intermediate soil sampling event indicated approximately 17,000 lbs of benzene had been removed, demonstrating a 21% mass reduction after approximately six weeks of operation. The COC mass reduction observed from the soil data is generally consistent with that estimated from the vapor discharge of the SVE system.

- The sub-area baseline soil sampling indicated that up to 1,600 lbs of benzene was remaining in the sandy fill/upper silty sand layer. The final sub-area soil sampling event indicated approximately 500 lbs of benzene had been removed, demonstrating a 31% mass reduction after approximately seven weeks of system operation in the sub-area configuration. The COC mass reduction observed from the soil data is generally consistent with that estimated from the vapor discharge of the SVE system.

*ROI and Pore Volume Exchange Rate Modeling*

The SVE air flow performance characteristics were estimated from the pilot test data.

- A PV exchange rate of 500 to 1,000 PV per year can be achieved with a SVE well ROI of 20 to 25 feet (at wellhead flow rates of 25 to 30 scfm). For the types of COCs at the site, a minimum of approximately 500 to 1,000 PV exchanges per year is typically required.
- Model simulations provided an estimate of the intrinsic soil permeability (in both the radial and vertical directions, or $K_r$ and $K_z$ respectively). Soil permeability was estimated at $K_r = K_z = 3.94 \times 10^{-7}$ square centimeters ($cm^2$).

**Conclusions and Applicability of Results to Full-Scale Design**

The pilot test objectives were achieved, demonstrating that SVE can be an effective technology for reducing COC mass in the unsaturated zone soils (with the exception of the intermediate silty clay layer) at Solutia's W. G. Krummrich Facility. The following findings will be incorporated into the full-scale design:

- Because the wellhead performance (flow and vacuum response) was similar between the sandy fill/upper silty sand and lower silty sand layers during the pilot test, intrinsic soil permeability and pore volume exchange rates determined during the pilot test should be applicable to both layers.

- These results are also applicable to the other target areas based on prior testing that indicated these areas have similar soil characteristics as the Big Mo area.
- Air flow and vacuum/pressure data collected during the individual wellhead and multi-well testing component of the PET will be used to develop the wellhead performance specifications for the full-scale design.
- The well-to-well spacing will be based upon the ROI and PV exchange rates determined using the 2-D computer model analysis.
- The extended PE test COC mass removal rates will be used to estimate the potential COC mass reduction in the full-scale application.
- Water table fluctuations in the area may interrupt the application of SVE to the lower silty sand layer. However, historical water level records over the past several years indicate that sufficient periods of dry conditions occur which will allow for SVE operation at these depths.

# 1.0 INTRODUCTION

On February 26, 2008, the United States Environmental Protection Agency (USEPA) issued a Final Decision requiring Solutia Inc. (Solutia) to implement Soil Vapor Extraction (SVE) at the W.G. Krummrich Facility (site). Per the Final Decision, SVE is to be applied to the unsaturated zone soils which are impacted with volatile organic compounds (VOCs), primarily benzene and chlorobenzenes. The following areas of the site were identified for SVE treatment: the Former Benzene and Chlorobenzene Storage area (Big Mo area), the Former Benzene Pipeline area, the North Tank Farm/Former Overhead Steamer Tank area, and the Near Little Mo area (refer to **Figure 1** for the locations of these treatment areas).

A *SVE Pilot Testing Work Plan* (*Work Plan*) was submitted to USEPA in December, 2008. The *Work Plan* contained the proposed scope of work to conduct the SVE pilot test within the Big Mo treatment area. The Big Mo treatment area was selected for pilot testing because it had the most elevated VOCs concentrations and a soil profile generally consistent to the other treatment areas.

This *SVE Pilot Test Report* summarizes the results of SVE pilot testing conducted in the Big Mo area between January 2009 and July 2010. The results of the SVE pilot test were used to develop the *Work Plan for Full-Scale SVE* (November 2010), submitted to USEPA in a separate report.

## 1.1 SITE BACKGROUND

The W.G. Krummrich Facility is a 314-acre facility located at 500 Monsanto Avenue, Sauget, Illinois. The site is approximately one mile east, and in the floodplain, of the Mississippi River. The site is located in a heavily industrialized area, and has a history of approximately 100 years of industrial operations.

Prior to the SVE pilot test in the Big Mo area, pre-pilot test data collection activities were conducted in all of the proposed treatment areas to aid in the design of the pilot testing program. Pre-pilot test data collection activities were conducted between June 23 and July 3, 2008, and included:

- Soil boring installation to refine the geology and the vertical distribution of soil impacts within the unsaturated soils for each of the treatment areas.
- Vapor probe installation and point permeability testing (PPT) to obtain preliminary air flow characteristic data for the soil units within each of the treatment areas.

Key results of the pre-pilot test data collection event are summarized in **Section 5.3** of this report.

## 1.2 PILOT TEST OBJECTIVES

The primary objectives of the pilot test were to:

1. Develop Full-Scale SVE Design Parameters: The SVE pilot test was designed to determine key design and operational parameters, including air flow performance characteristics of the wells, vapor-phase VOC treatment requirements, and air moisture/condensate handling requirements. These parameters are required to design the SVE process equipment and layout/spacing of the SVE wells. Another goal of the testing was to verify operational strategies, including vapor extraction and air injection configurations to enhance SVE performance.

2. Demonstrate Constituent of Concern (COC) Mass Reduction: The SVE pilot test was also designed to determine the level of mass reduction that could be achieved in the unsaturated zone soils over a given timeframe.

## 1.3 PILOT TEST AREA OVERVIEW

The Big Mo treatment area was selected for pilot testing because it had the most elevated VOCs concentrations and a soil profile generally consistent to the other treatment areas. Therefore, the pilot test results in the Big Mo area are considered applicable for the full-scale SVE design in all the treatment areas. See **Figure 2** for the pilot area.

### *1.3.1 PILOT TEST AREA GEOLOGICAL CROSS-SECTION*

A geologic cross-section of the Big Mo treatment area is presented in **Figure 3**. As shown in the cross-section, a sandy fill and upper silty sand (sandy fill/upper silty sand) layer exists from the surface gravel cover to approximately 9 to 12 feet below ground surface (ft bgs). A lower silty sand layer, which is geologically similar to the upper silty sand layer, begins at depths ranging from 9 to 12 ft bgs and is present to a depth of approximately 16 ft bgs. A silty clay layer approximately 1-foot thick was found to be discontinuous in the pilot test area and occurred below the sandy fill/upper silty sand layer and above or imbedded in the lower silty sand layer.

The nature of the geology in the Big Mo area (particularly the presence of the gravel surface cover and intermediate silty clay layer) influenced the design of the SVE pilot test system, as discussed in **Section 1.4.3** of this report.

### *1.3.2 PILOT TEST AREA SOIL CONCENTRATIONS*

Baseline soil concentrations were collected in the Big Mo pilot test area in January 2009. Soil sampling results are presented in **Section 4.3**. Benzene was the primary COC detected in the Big Mo area, with a maximum benzene concentration of 47,000 milligrams per kilogram (mg/kg) at baseline boring location SS-09S. Historical soil borings S0607 and SB-A01 were previously the most impacted locations in the Big Mo area (at 2,400 mg/kg and 13,000 mg/kg benzene, respectively). Field observations also indicated the potential for non-aqueous phase liquids (NAPLs) to exist in the Big Mo area.

#### *1.3.3 TARGET COC MASS IN PILOT TEST AREA*

Based on baseline soil sampling conducted within the pilot test area in January 2009, the benzene mass was estimated to be approximately 79,000 lbs within the upper silty sand layer (prior to start-up of the pilot test). This mass estimate was based upon the average soil concentrations in the upper silty sands and assuming an average NAPL saturation of 10%. Methods used to develop the initial benzene mass estimate are described in **Section 5.2** of this report.

### 1.4 OVERVIEW OF PILOT TESTING APPROACH

To achieve the pilot test objectives described in **Section 1.2**, the SVE pilot test was conducted in two distinct phases:

- Parameter Evaluation Testing (PET).
- Extended Performance Evaluation (PE).

#### *1.4.1 PARAMETER EVALUATION TESTING*

The PET included testing of individual and multi-well configurations (including vapor extraction, air injection, or a combination of extraction/injection), to assess air flow performance characteristics of the site soils, and wellhead airflow vacuum/pressure responses. Refer to **Section 3.0** of this report for a detailed account of the PET activities.

### *1.4.2 EXTENDED PERFORMANCE EVALUATION*

Following the PET, an extended PE test was conducted. The PE test was intended to be operated for approximately three months, using the optimal vapor extraction/air injection well configuration determined during the PET.

The PE testing was designed to evaluate the potential target COC mass reduction that could be achieved over time. Soil sampling was incorporated into the PE test program to evaluate the COC mass reduction performance. Refer to **Section 3.0** of this report for a detailed account of the PE testing activities.

### *1.4.3 AIR INJECTION WELLS TO ENHANCE SVE PERFORMANCE*

Air injection (AI) wells were included in the test program to enhance the performance of the SVE wells. The AI wells were designed to address the following issues:

- The presence of the intermediate silty clay layer could have an effect on the performance of SVE within the lower silty sand layer. During SVE, air infiltrates from the atmosphere through the ground surface, in response to the application of vacuum at the SVE wells. If an overlying low-permeability layer (i.e., intermediate silty clay layer) substantially interferes with the infiltration of air from the atmosphere, this could limit subsurface air movement and affect the efficiency of the SVE process. AI wells were therefore designed to supply air to the lower silty sand layer in the event that the intermediate silty clay layer prevented sufficient air from entering this layer.
- The presence of the surface gravel cover in the pilot area could have potentially allowed excessive near-well surface air leakage, which can reduce the lateral movement of air (and reduce the radius of influence of the well). AI wells promote horizontal air flow when coupled with SVE wells. Also, the addition of a lower-permeability surface cover over the surface gravel layer, in conjunction with air injection, could further improve the

lateral distribution of air within the target layer. Therefore, an asphalt pavement cover was installed in the pilot test area to enhance performance in the upper silty sand layer.

- A source of air (i.e. through surface infiltration and/or through active air injection) is necessary for SVE to be effective. Due to the high levels of soil impacts and presence of NAPL in the pilot test area, air moving through the subsurface target intervals could quickly become saturated with VOCs. Supplying additional air through AI wells can provide more air for volatile contaminants to partition into, thereby increasing the SVE removal efficiency.

### *1.4.4 PILOT TEST OPERATIONAL PARAMETERS*

Per the *Work Plan*, the air flow rate of each SVE well in the upper and lower silty sand layers was anticipated to be 8 to 15 standard cubic feet per minute (scfm), with a wellhead vacuum of 5 to 12 inches of mercury (in. Hg; or 68 to 163 inches of water [in. $H_2O$]). Similarly, the design airflow rate per well in the intermediate clay layer was estimated to be 1 to 2.5 scfm with a vacuum at the individual wellheads of approximately 23 in. Hg (312 in. $H_2O$). A two-dimensional analytical airflow model was used along with the pre-pilot test PPT data (see **Sections 5.3 and 5.4** for details of these modeling efforts) to develop the anticipated air flow characteristics.

Actual operational parameters (i.e., flow and vacuum/pressure at individual wellheads) were determined during the PET/PE testing (refer to **Section 3.0** of this report). In general, the pilot test results confirmed that the sandy fill/upper silty sand layer was similar in permeability as compared to the pre-pilot test PPT results. However, the pilot test results suggested that the intermediate silty clay layer was lower in permeability than was suggested by the initial PPT results[1].

## 1.5 DOCUMENTATION OF CHANGES TO SVE PILOT TEST WORK PLAN

In general, the SVE pilot testing was conducted in accordance with the *Work Plan.* USEPA was notified in writing of the major deviations from the *Work Plan* and schedule changes, which included:

1. After the pilot system was installed and equipment start-up/shakedown activities were completed, rising water table elevations in the pilot test area prevented start-up of the PET. USEPA was notified on June 12, 2009, via electronic mail (e-mail) of the delay in the PET start due to adverse conditions.
2. USEPA was notified of initiation of a groundwater level monitoring program to assess when water levels would recede sufficiently to allow restart of the pilot testing activities (via e-mail dated June 17, 2009). When water levels declined to a minimum of 10 feet bgs, and remained at or below that level for two weeks, PET in the sandy fill/upper silty sand layer would resume.
3. USEPA was notified (via e-mail dated July 27, 2009) that water levels were recovering very slowly, and that groundwater monitoring was anticipated to continue until conditions were amenable for pilot testing.
4. USEPA was notified (via e-mail dated November 2, 2009) that water levels had declined sufficiently to allow restart of the PET in the sandy fill/upper silty sand layer. The

[1] As discussed in the *Section 2.2.1* of the *Work Plan*, short-circuiting of air flow between the intermediate silty clay layer and adjacent silty sand layers may have impacted PPT testing results, resulting in an overestimate of the intrinsic permeability for the silty clay layer.

proposed PET was then initiated in early November 2009. Testing was not possible in the lower silty sand layer due to elevated water table conditions.

5. The extended PE testing was briefly conducted in the sandy fill/upper silty sand layer beginning on November 13, 2009, after completion of the PET program. However, rising water levels resulted in a shut-down of the PE testing on December 4, 2009. USEPA was notified via e-mail on December 7, 2009, that the system was shut off and that groundwater monitoring would be conducted in anticipation of a restart when water table elevations would allow.

6. A memorandum describing the restart procedures of the PE testing was submitted to USEPA via e-mail on February 11, 2010. The memorandum indicated that the PE test would be restarted the week of February 15, 2010, and would be focused on the sandy fill/upper silty sand layer. In addition, the SVE wells screened within the lower silty sand layer would be used, as possible, to prevent groundwater from re-entering the upper silty sand layer, in an attempt to prevent another shutdown of the testing activities. The PE test operated for approximately three months in this configuration (until May 2010).

7. A memorandum recommending an extension of the PE testing was submitted to USEPA via e-mail on May 12, 2010. The recommendation was to extend the duration of the PE test for up to an additional three months, and to reconfigure the PE test to focus on a smaller sub-area of the pilot test area. The PE test was reconfigured to the smaller sub-area, and was operated in this configuration until July 2010.

8. Extended PE testing in the sub-area was shut down on July 16, 2010, in response to rising groundwater elevations. USEPA was notified of the shutdown via e-mail dated July 19, 2010.

# 2.0 PILOT STUDY EQUIPMENT AND INSTALLATION

This section provides a description of the pilot study well layout and equipment design, including specification and installation of:

- Twenty-six (26) pilot test wells.
- Twenty-five (25) vapor probes.
- SVE/AI wellhead construction details.
- SVE/AI manifold piping construction details.
- Process equipment (including SVE blowers, AI blowers, and ancillary equipment).
- External air/water treatment equipment (including a thermal oxidizer for vapor treatment and a shallow-tray air stripper for water/condensate treatment).
- Miscellaneous equipment.

## 2.1 PILOT TEST AREA LAYOUT

The as-built SVE pilot test layout is shown in **Figure 2**. The overall pilot test area encompassed an area of 60 feet long by 80 feet wide (4,800 square feet). Historical soil borings S0607 and SB-A01 were the most impacted locations in the Big Mo area (at 2,400 mg/kg and 13,000 mg/kg benzene, respectively), and therefore, an area surrounding these two borings was selected for the SVE pilot test. In addition, a 10-feet-long by 10-feet-wide area was planned for pilot testing in the intermediate silty clay layer.

A low-permeability cover, consisting of asphalt paving, was installed over the pilot test area in October 2008. The objective of the cover was to prevent precipitation infiltration during the pilot testing. In addition, the asphalt cover was also intended to have some benefit in improving the airflow through the sandy fill/upper silty sand layers (previously discussed in **Section 1.4.3**).

## 2.2 TEST WELLS AND VAPOR PROBES

### *2.2.1 SVE/AIR INJECTION WELL INSTALLATION*

A total of twenty-six (26) pilot wells were installed in February 2009 by Boart Longyear Company (Boart Longyear) of Indianapolis, Indiana, using sonic drilling technology.

- Sandy Fill/Upper Silty Sand and Lower Silty Sand Layer Wells: A total of 22 SVE well screens were designed to target the higher-permeability soil layers. Wells SVE-01 through SVE-11 are nested SVE wells[2]. Spacing between the SVE well nests in the sandy fill/upper silty sand and lower silty sand layers ranged from 10 feet to 30 feet.

- Combination SVE/Air Injection Wells: Five of the SVE wells in the sandy fill/upper silty sand layer (SVE-04AD, SVE-05AD, SVE-06AD, SVE-07AD, and SVE-08AD), and five of the SVE wells in the lower silty sand layer (SVE-04BD, SVE-05BD, SVE-06BD, SVE-07BD, SVE-08BD), were constructed to be used as both SVE and AI wells.

- Intermediate Silty Clay Layer Wells: The remaining four SVE wells (SVE-12 through SVE-15) were installed in a 10-foot by 10-foot area at spacing of approximately 5 feet on center.

The SVE/AI well locations are shown in **Figure 2**. Typical SVE well construction cross-sections are shown in **Figure 4** and the as-built SVE/AI well construction details are presented in **Table 1**.

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[2] Wells SVE-01 through SVE-11are nested SVE wells which contain two well screens in a single borehole. The shallow (A) well screen is installed in the sandy fill/upper silty sand layer, and the deep (B) screen is installed in the lower silty sand layer.

The combination SVE/AI wells were constructed of 2-inch internal diameter (ID) Schedule 80 chlorinated polyvinyl chloride (CPVC) with 10-slot screens. The remaining wells were constructed of 2-inch ID Schedule 40 polyvinyl chloride (PVC) with 10-slot screens. A #2 filter sand pack was set around the well screens and the annular space above the well screens was sealed with hydrated bentonite chips. The wells were completed to surface with solid CPVC (SVE/AI wells) or PVC (SVE wells) riser and hydrated bentonite, and sealed at the surface with a cement bentonite-grout mixture within a flush-mounted road box.

### *2.2.2 VAPOR PROBE INSTALLATION*

A total of nineteen (19) vapor probes were installed by Roberts Environmental Drilling, Inc. of Millstadt, Illinois (REDI) between February 2009 and April 2009 using direct push technology. Vapor probe locations are shown on **Figure 2**. Vapor probes VP-01 through VP-11 were installed as follows:

- Eight (8) vapor probes in the upper silty sand layer (labeled as Shallow – S).
- Eight (8) vapor probes in the lower silty sand layer (labeled as Deep – D).
- Three (3) vapor probes in the intermediate silty clay layer (labeled as Intermediate - I).

Six (6) vapor probes installed during the pre-pilot test data collection event (see **Section 1.1**) were also used during the pilot test.

All vapor probes are constructed of a 6-inch screened stainless steel direct push permanent implant with 3/16-inch by 1/4-inch Teflon tubing to above surface grade. A typical vapor probe construction cross-section is presented in **Figure 4** and the as-built vapor probe construction details are presented in **Table 2**.

## 2.3 PIPING MANIFOLD SYSTEM

The system manifold consisted of four aboveground main manifold lines that connected the wells to the main process equipment (**Figure 5**). Each SVE or SVE/AI wellhead was connected to a specific main manifold line and equipped with individual valves to control flow rates.

Two of the main manifold lines were dedicated to the SVE wells in the upper silty sand and the lower silty sand layer. A third main manifold line was connected to the SVE wells in the intermediate silty clay layer. The fourth main manifold line was used for air injection, and was connected to the combination SVE/AI wells (SVE-04AD/BD, SVE-05AD/BD, SVE-06AD/BD, SVE-07AD/BD, SVE-08AD/BD).

Wellhead controls located at each SVE and/or air injection well included a flow control gate valve and sample port for flow meter and pressure/vacuum gauge measurements. At the ten combination SVE/AI wells, two gate valves were fitted to allow the operator to change the well from extraction to injection mode, as necessary.

## 2.4 SVE/AI PROCESS EQUIPMENT

The main SVE process equipment consisted of two vacuum blowers (low and high vacuum systems), one injection blower, an oil-water separator, two air-moisture separators, a water collection tank, shallow tray air stripper, and a thermal oxidizer (ThermOx) unit. System piping and instrumentation diagrams (P&ID) are presented in **Figures 6A and 6B**. This section provides a brief overview of the pilot test equipment.

### *2.4.1 PROCESS EQUIPMENT*

Two separate SVE vacuum blowers were used:

- A low-vacuum blower system was used for the sandy fill/upper silty sand and lower silty sand layers. This rotary lobe, positive displacement blower system was designed to provide a capacity of 495 scfm at 16 inches of mercury vacuum at the inlet.
- A high-vacuum blower system was used for the intermediate silty clay layer, consisting of a rotary claw pump with a capacity of 15 scfm at 23 inches of mercury vacuum.

A single air injection blower was provided for the AI wells. A rotary vane blower with a capacity of 125 scfm at 13 lbs per square inch (psi) outlet line was used.

### *2.4.2 Vapor Discharge Treatment*

The SVE effluent was treated using the ThermOx. The ThermOx was designed to handle approximately 500 scfm at 40% of the lower explosive level (LEL) for benzene (approximately 4,800 parts per million by volume [ppmv]). The ThermOx unit was provided by Intellishare, Inc. (Intellishare).

### *2.4.3 Air Moisture/Condensate Removal and Treatment*

- Two air-moisture separators in series were connected to the main manifold lines for the upper and lower silty sand layers and designed to remove entrained water from the air stream. A third air-moisture separator was dedicated to the high-vacuum system for the intermediate silty clay layer.
- The air-moisture separators were designed to discharge to an oil-water separator (OWS) to remove any NAPL entrained within the condensate. NAPL could then be coalesced and transferred to a NAPL storage drum for disposal.
- An equalization tank was used to collect the condensate prior to treatment and discharge.
- A BISCO Environmental, Inc./NEEP Systems shallow tray air stripper (supplied by Schrader Environmental, Inc.) was used to treat the condensate water prior to discharge. VOC-impacted air from the air stripper was treated via the ThermOx unit.

- Treated condensate water was discharged to the site sewer and then to the American Bottoms wastewater treatment plant.

### *2.4.4 EQUIPMENT FREEZE PROTECTION*

Freeze-protection (i.e., heat trace/insulation on the manifold piping and heated enclosures for external process equipment) was added to the system in October/November 2009. In the December 2008 *Work Plan*, the SVE pilot test was planned to be conducted during warmer periods of the year. Due to rising water levels delaying the test schedule, freeze-protection equipment was added in anticipation of operation of the pilot test over the winter months.

# 3.0 PILOT TEST ACTIVITIES

This section summarizes the SVE pilot test operation and monitoring/sampling activities. The pilot test activities were in general accordance with the *Work Plan*. However, modifications to the *Work Plan* were required as a result of rising water table elevations in the Big Mo pilot test area. Therefore, the majority of pilot test activities were focused in the sandy fill/upper silty sand layer and the intermediate silty clay layer.

## 3.1 NARRATIVE OF PILOT TEST CHRONOLOGY

This section provides a brief overview of the chronology of the SVE pilot test. In addition, a brief explanation of the objective of each phase of the test, along with the rationale for any changes that were made to the scope of work, is provided.

Baseline soil sampling was conducted in the pilot test area in January 2009. The SVE pilot test system (including the SVE wells, vapor probes, and all mechanical equipment) was installed between February and May 2009.

Initial start-up and shakedown activities were conducted in May 2009, but were halted in early June 2009 due to rising water levels in the pilot test area. Water levels were monitored closely to determine the next opportunity to restart the pilot test. The pilot test system was winterized (heat-traced and insulated) in October and November 2009 in anticipation of potential resumed test operation over the winter months.

When water levels receded sufficiently, the PET, per *Section 4.0* of the *Work Plan*, was conducted in November 2009. During the PET, individual SVE wellhead testing and multi-SVE well configuration testing was conducted to determine general air flow performance characteristics of the SVE wells, and to determine the most efficient operating configuration for the upcoming extended PE test. At the completion of the PET, PE testing was briefly initiated. However, the pilot area water levels rose again which required shutdown of the PE testing.

The extended PE test (per *Section 4.2* of the *Work Plan*) was eventually restarted and performed between February and July 2010. The objective of the PE test was to determine the level of COC mass reduction that could be achieved over several months of operation. Assessment of target COC mass reduction was to be based upon comparison of baseline soil concentration data (January 2009) and two subsequent soil sampling events (per *Section 4.3.1* of the *Work Plan*) to be conducted at the mid-point and end-point of the PE test.

The proposed mid-test soil sampling event was conducted as planned in March 2010, following approximately six weeks of SVE operation in the sandy fill/upper silty sand layer. Based on the mid-test soil results, and the fact that water table elevations were again rising and beginning to interfere with the SVE performance, the SVE system was re-focused to operate on a smaller sub-area within the pilot test area. This was done with the intent of ensuring that a measurable COC mass reduction could be achieved in a sub-area (desired to be at least 30% mass reduction so typical soil sampling data variability would not obscure the SVE system performance).

The SVE system was therefore reconfigured in May 2010 to focus on the smaller sub-area. A soil sampling event was conducted within the sub-area immediately prior to system reconfiguration, in order to establish a refined baseline COC mass within the sub-area.

The PE test operated in the sub-area configuration from May to July 2010. During operation of the sub-area configuration, water levels continued to rise and it was determined that the SVE system had reached an asymptotic condition in terms of COC mass reduction. A final soil sampling event was conducted within the sub-area in June 2010 to evaluate the final mass reduction within the sub-area. The SVE system was shut-down in early July 2010 as it was determined that the SVE pilot objectives had been achieved.

## 3.2 PILOT TEST START-UP ACTIVITIES

Details of the pilot test area layout, equipment, and installation were previously provided in **Section 2.0**. Pilot test equipment and piping manifold construction activities were initiated in February 2009 and completed in May 2009.

### *3.2.1 BASELINE SOIL VAPOR SAMPLING*

In accordance with *Appendix D* of the *Work Plan* (*Sampling and Analysis Plan [SAP]*), baseline soil vapor samples were collected from all shallow SVE wells and vapor probes in April 2009 to establish conditions prior to pilot test startup. A total of twenty-two (22) soil vapor samples were collected from the shallow SVE wells (11) and vapor monitoring probes (11) for field screening of total VOCs using a Photoionization Detector (PID). A representative soil vapor sample was collected for laboratory analysis from the SVE well and vapor probe exhibiting the maximum PID reading. The soil vapor samples were collected into dedicated Tedlar bags and submitted to TestAmerica, Inc (TestAmerica, Knoxville, Tennessee) for analytical analysis of VOCs by USEPA Method TO-15.

### *3.2.2 INITIAL SYSTEM SHAKEDOWN*

Initial system start-up, shakedown, and trouble-shooting operations commenced on May 8, 2009, and continued through June 3, 2009, including:

- Shakedown and testing of each pilot test system component.
- Testing of safety alarm conditions and equipment interlock shutdowns.
- Process monitoring including flow, vacuum, pressure, and total VOCs.
- Brief testing of the operation and performance of the shallow, intermediate, and deep pilot test systems (high-flow and low-flow conditions).

Significant rainfall events and rising Mississippi River levels in May 2009 caused a dramatic increase in groundwater levels, preventing system operation. The system was shut down on June 4, 2009.

## 3.3 GROUNDWATER ELEVATION MONITORING

Groundwater in the pilot test area was gauged regularly following the June 2009 system shutdown to determine when levels had receded enough to expose the well screens. By late October 2009, groundwater levels had receded enough (to approximately 10 feet bgs) to expose the shallow SVE/AI well screens in the upper silty sand layer. Groundwater level monitoring data is presented on **Figure 7**. USEPA was notified via e-mail on November 2, 2009, that water levels had declined sufficiently to allow restart of the PET in the sandy fill/upper silty sand layer.

## 3.4 PARAMETER EVALUATION TESTING

The purpose of the PET was to evaluate air/vapor flow characteristics (i.e., well spacing, achievable airflow, and vacuum/pressure, etc.) in each of the unsaturated geological layers. Due to elevated groundwater levels, the majority of PET activities were conducted in the shallow SVE wells targeting the upper silty sand layer.

### *3.4.1 INDIVIDUAL WELLHEAD TESTING*

In early November 2009, the PET was completed for the upper silty sand layer in accordance with *Section 4.1* of the *Work Plan*. SVE wellhead testing was conducted at wells SVE-02A, SVE-04A, SVE-06A, SVE-08A, and SVE-10A, and AI wellhead testing was conducted at wells SVE-05A and SVE-07A.

SVE wellhead testing included applying a minimum of two different vacuums at each well while measuring the changes in vacuum and the corresponding vapor flow rate at the test well. Air injection wellhead testing included applying pressure while measuring the corresponding airflow at the test well. During testing, vacuum/pressure measurements were collected at the test well and surrounding SVE wells/vapor probes in accordance with the *Work Plan*. This data was used for the SVE air flow modeling described in **Section 5.4**.

### *3.4.2 MULTI-WELL AND FLOW FIELD CONFIGURATION TESTING*

Multi-well flow field configuration testing was conducted per *Section 4.1.2* of the *Work Plan* to examine the air flow distribution under various well configurations. The multi-well configurations (#1 through #7) included combinations of several SVE/AI wells under extraction and extraction/injection. Configurations #12 and #13 were tested to determine the preferred configuration for the PE phase of testing (i.e., the configuration that results in the maximum total vapor flow rate from the test area and the highest mass removal rate). Multi-well configurations are shown in **Figures 8A and 8B**.

Multi-well configurations #1 through #7 were run for approximately two to three hours. Configurations #12 and #13 were run for approximately 19 hours and 23 hours, respectively. During the testing of different well-field configurations, vapor flow rates and vacuum/pressure distribution in the test wells and surrounding SVE wells and vapor monitoring probes was monitored.

## 3.5 PERFORMANCE EVALUATION TESTING

Based on the design PET flow field configuration testing, Configuration #13 was selected as the preferred configuration for the extended PE test, because this configuration achieved the maximum COC mass removal rate (results of testing described in detail in **Section 4.1)**.

The PE test was briefly initiated between November 13, 2009 and December 4, 2009. Rapidly rising water levels resulted in a shut-down of the PE testing (USEPA was notified of this shut down via e-mail on December 7, 2009). Groundwater level monitoring (as discussed in **Section 3.3**) was conducted during the shutdown period to determine when the PE testing could resume. Groundwater monitoring data is presented on **Figure 7**.

Groundwater levels receded sufficiently by February 2010 to allow restart of the PE testing. The extended PE test was restarted in Configuration #13 (see **Figure 8B**). Note that, for the purposes of this *SVE Pilot Test Report*, the PE was assumed to officially start in February 2010 and the brief initial operation between November and December 2009 was not included in the evaluations.

Assessment of target COC mass reduction was proposed to be based upon comparison of baseline soil concentration data collected in January 2009 and two subsequent soil sampling events (proposed per *Section 4.3.1* of the *Work Plan* to be conducted at the mid-point and end-point of the PE test). The proposed intermediate soil sampling event was conducted as planned in March 2010, following approximately six weeks of SVE operation in the sandy fill/upper silty sand layer (refer to **Section 3.7.2**).

System operation and performance monitoring was conducted in accordance with *Section 4.3* of the *Work Plan* and included:

- SVE/AI system operational flow rate and vacuum/pressure monitoring.
- SVE/AI wellhead operational flow rate, vacuum/pressure monitoring.
- Vacuum/pressure distribution monitoring at vapor monitoring probes.
- Soil vapor sampling (at the individual wellheads and various points along the pilot system).

- Collection of soil vapor samples from the SVE main line for analytical laboratory analysis of VOCs via USEPA Method TO-15.
- Sampling of air and water discharge streams from the ThermOx and the air stripper, respectively, for compliance monitoring.

Other operational parameter monitoring included:

- Groundwater condensate collection rates.
- Air stripper performance (i.e., water discharge rate and system vacuum/pressure).
- ThermOx performance (i.e., inlet/outlet vapor concentrations and COC destruction efficiency).
- NAPL accumulation.
- Gauging of water elevation in available SVE wells.

### 3.6 SUB-AREA PERFORMANCE EVALUATION TESTING

The SVE system was re-focused to operate on a smaller sub-area within the pilot test area on May 13, 2010, due to increasing groundwater table elevations. This was done with the intent of ensuring that a measurable COC mass reduction could be achieved in a sub-area (desired to be at least 30% mass reduction so that typical soil sampling data variability would not obscure the SVE system performance).

A soil sampling event was conducted within the sub-area, immediately prior to the system reconfiguration (refer to **Section 3.7.3**), in order to establish a refined baseline COC mass within the sub-area.

The PE test operated in the sub-area configuration from May 13 to July 16, 2010. During operation of the sub-area configuration, water levels continued to rise and it was eventually determined that the SVE system had reached a point of diminishing return in terms of COC mass reduction (i.e., COC mass removal rates had declined to very low levels due to submergence of the SVE well screens and target soil interval).

A final soil sampling event was conducted in June 2010 to evaluate the final mass reduction within the sub-area (refer to **Section 3.7.4**). The pilot system was decommissioned between July 16, 2010, and July 21, 2010.

System performance monitoring continued during the sub-area PE testing using the same protocols described in **Section 3.5,** in general accordance with *Section 4.3* of the *Work Plan*.

## 3.7 SOIL SAMPLING

### *3.7.1 Baseline Soil Sampling Event*

Baseline soil sampling was conducted in the upper silty sand layer in January 2009 to establish pre-pilot test contaminant distribution and a baseline soil contaminant mass estimate. A total of eleven (11) soil borings were advanced by REDI into the upper silty sand layer using direct push technology. Soil samples were collected in accordance with the SAP (*Appendix D* of the *Work Plan*). The baseline soil sampling locations are shown on **Figure 2**. A summary of the sample locations and depth intervals is presented on **Table 3A**.

Soil samples were collected in dedicated Geoprobe® acetate liners. Each 6-inch soil interval was characterized and field-screened for total VOCs using a PID. A representative grab sample from each location was collected using Terra-core sampling devices for laboratory analysis of VOCs from the interval with the maximum PID reading. Soil samples were submitted to TestAmerica (Savannah, Georgia) and analyzed for VOCs via USEPA Method 8260B.

### *3.7.2 INTERMEDIATE SOIL SAMPLING EVENT*

The intermediate soil sampling event was conducted in March 2010 after approximately six weeks of operation of the PE test. As described in *SAP (Appendix D* of the *Work Plan)*, the intermediate soil samples were proposed to be collected from the same location and depth interval as the baseline soil samples. However, at several locations, the intermediate soil samples had to be collected from depths that were shallower than the baseline soil samples (at 7.0 to 7.5 ft bgs or 7.5 to 8.0 ft bgs). This was required because the water table elevation was above the depth of the baseline soil samples. A summary of the sample locations and depth intervals is presented on **Table 3A**.

A total of eleven (11) soil borings were advanced using a Geoprobe® and samples were collected into dedicated acetate liners (similar protocols as the baseline sampling as described in **Section 3.7.1**). Each 6-inch interval was screened in the field for total VOCs using a PID and soil samples were collected and submitted to TestAmerica (Savannah, Georgia) for laboratory analysis of VOCs via USEPA Method 8260B.

### *3.7.3 SUB-AREA BASELINE SOIL SAMPLING EVENT*

Prior to the system reconfiguration, a sub-area baseline soil sampling event was conducted in order to establish a refined baseline COC mass estimate for the sub-area in the vicinity of SVE-05A. A total of five (5) soil samples were collected from borings SS-03S, SS-101S, SS-102S, and two from SS-08S. The sub-area baseline soil sampling locations are shown on **Figure 2**. A summary of the sample locations and depth intervals is presented on **Table 3B**.

Soil borings were advanced using a Geoprobe® and samples were collected into dedicated acetate liners (similar protocols as the baseline sampling as described in **Section 3.7.1**). Each 6-inch interval was screened in the field for total VOCs using a PID and select soil samples were submitted to TestAmerica (Savannah, Georgia) for laboratory analysis of VOCs via USEPA Method 8260B.

### *3.7.4 SUB-AREA FINAL SOIL SAMPLING EVENT*

The final soil sampling event was conducted in June 2010 after approximately seven weeks of operation of the sub-area PE test. As described in the *SAP (Appendix D* of the *Work Plan*), the final soil samples were collected for laboratory analysis from the same location and interval as the sub-area baseline soil samples. A total of four (4) soil samples were collected from borings SS-03S, SS-08S, SS-101S, and SS-102S. A summary of the sample locations and depth intervals is presented on **Table 3B**.

Soil borings were advanced using a Geoprobe® and samples were collected into dedicated acetate liners (similar protocols as the baseline sampling as described in **Section 3.7.1**). Select soil intervals were screened in the field for total VOCs using a PID and soil samples were collected and submitted to TestAmerica for laboratory analysis of VOCs via USEPA Method 8260B.

## 3.8 VAPOR DISCHARGE TREATMENT MONITORING

Vapor discharge treatment monitoring was conducted in accordance with Illinois Environmental Protection Agency (IEPA) Construction Permit No. 08120014 issued to Solutia on January 9, 2009, and revised on October 26, 2009, and May 26, 2010 (permit). Operation monitoring parameters included quarterly influent and effluent vapor sampling and continuous ThermOx operation temperature monitoring. Quarterly influent/effluent vapor samples were collected into Tedlar® bags and shipped to TestAmerica (Knoxville, Tennessee). Vapors in the Tedlar® bags were transferred to Summa® canisters at the laboratory within 72 hours of sampling. These samples were analyzed for VOCs via USEPA Method TO-15.

Permit conditions required that the operating temperature of the ThermOx be recorded by an automated data recording device and that the ThermOx must operate at a temperature of 1400°F. Compliance monitoring for these conditions included:

- Continuous temperature monitoring with a two-pen circular Honeywell chart recorder that continuously records the combustion chamber temperature.
- Monitoring of the outlet temperature of the ThermOx with a programmable logic controller that triggered a shutdown if the system temperature decreased below 1450°F.

All vapor discharge and permit requirements were met during the pilot testing.

### 3.9 WATER DISCHARGE TREATMENT MONITORING

Treated groundwater discharge (effluent) from the air stripper was monitored in accordance with the American Bottoms Regional Wastewater Discharge Permit issued to Solutia on March 30, 2009, as a “Modification to Discharge Permit No.: 04C-105”. Once per month, if the air stripper was operated, effluent samples were collected by American Bottoms personnel and Solutia personnel for analysis of VOCs and semi-VOCs (SVOCs) via USEPA Methods 624 and 625, respectively. Results of all air stripper effluent samples indicated system operation was in accordance with permit requirements.

# 4.0 PILOT TESTING RESULTS

This section provides a summary of the pilot test results, including:

- General air flow/vacuum/pressure performance data from the PET (including individual and multi-well configuration testing data).
- General air flow/vacuum/pressure performance data from the PE test (including the sub-area reconfiguration data).
- Soil gas sampling results from the SVE wellheads and vapor probes.
- SVE system vapor concentration and mass removal data.
- Soil sampling results (baseline, mid-test sampling, sub-area baseline, and sub-area final sampling).

## 4.1 PARAMETER EVALUATION TESTING RESULTS

The PET was intended to develop SVE wellhead air flow performance characteristics, including:

- Individual SVE wellhead air flow/vacuum response (or pressure response in the case of air injection tests). This data is required to evaluate the vacuum (or pressure) required to achieve a desired air flow rate at a well, which is essential for optimization of pilot test operation and important for the full-scale design equipment/mechanical specifications.
- Provide wellhead air flow performance characteristics (air flow/vacuum response) and well field vacuum response data (i.e., vapor probe response) to evaluate the resulting air flow field distribution during SVE application. This data is required to evaluate soil permeability and full-scale SVE well placement/spacing.
- Multi-well configuration testing to evaluate the most efficient system operation configuration (i.e., vapor extraction or combination of vapor extraction/air injection) to achieve effective air flow distribution in the subsurface and maximum COC mass

removal. This data was used to select the long-term PE testing configuration, and will also be used for developing operational strategies for a conceptual full-scale application.

#### *4.1.1 Individual Wellhead Performance Results*

As described in **Section 3.4.1**, individual wellhead testing was conducted at shallow wells SVE-02A, SVE-04A, SVE-06A, SVE08A, and SVE-10A as vapor extraction and at shallow wells SVE-05A and SVE-07A as air injection. A low- and high-flow condition was tested at each well with the exception of SVE-02A, which triggered the lower explosive limit (LEL) alarm on the ThermOx when the flow was increased. A summary of the individual well design PET is presented on **Table 4**. Refer to **Appendix A** for the comprehensive monitoring data tables.

Wellhead flows ranged from 5.4 scfm at 25 in. $H_2O$ to 33.6 scfm at 50 in. $H_2O$ for vapor extraction. The air injection flow rates ranged from 5.3 scfm at 40 in. $H_2O$ to 116 scfm at 50 in. $H_2O$.

Generally, the well field responded linearly to changes in flow at the test wells. For example, at SVE-10A, the flow rate increased from 12.4 scfm to 24.7 scfm (doubled) and the response at nearby and far monitoring points also doubled. This general trend was also observed at SVE-04A, SVE-06A, and SVE-08A.

#### *4.1.2 Multi-Well Configuration Performance Results*

As described in **Section 3.4.2**, multi-well and flow field configuration testing included combinations of several wells operating under vapor extraction or vapor extraction/air injection.

The first phase of the multi-well configuration testing included Configurations #1 through #7 (refer to **Figure 8A**). The second phase of multi-well configuration testing included Configurations #12 and #13 (refer to **Figure 8B**). These configurations were tested in the upper silty sand layer only. A summary of the multi-well design PET data is presented in **Tables 5 and 6**. Refer to **Appendix B** for the comprehensive monitoring data tables.

Configurations #1 through #7: Testing of Configurations #1, #2, and #4 through #7 indicated that measurable vacuum/pressure distribution was observed at a radius greater than 15 feet from the test wells. The vapor extraction/air injection combination well configurations allowed for slightly higher vacuums and flow rates at the vapor extraction test wells by introducing clean air into the soil. **Table 5** provides a summary of the test data for these configurations.

When the system was operating in Configuration #3, vacuum influence was not observed at nearby monitoring points. The vacuum was increased at the SVE-07A wellhead to 100 in. $H_2O$ in an attempt to achieve some vacuum influence at surrounding monitoring points, but no vacuum influence was observed. However, when using SVE-07A as an AI well during the testing of Configuration #7, a low air flow rate was achieved.

Configurations #12 and #13: The second phase of testing was to run the system in Configurations #12 and #13 to determine the preferred configuration for the extended PE test. Testing of Configurations #12 and #13 was conducted for 19 and 23 hours, respectively.

Configuration #12 yielded a mass removal rate of 21 lbs benzene per hour at a total system flow rate of approximately 570 scfm (**Table 6**). Configuration #13 achieved a higher total system flow rate of approximately 600 scfm and a greater mass removal rate of 40 lbs benzene per hour (**Table 6**). Based on this testing, Configuration #13 was selected for the extended PE test.

As shown on **Table 6**, slightly higher flows and vacuum were achievable with the system set in Configuration #13. Individual wellhead extraction rates ranged from 1.8 scfm to 12.5 scfm in Configuration #12, and from 1.8 scfm to 16.7 scfm in Configuration #13.

Both configurations demonstrated satisfactory airflow distribution throughout the pilot area as measured at the vapor monitoring points. Vacuum/pressure influence in the pilot area ranged from 0 in. $H_2O$ to -0.85 in $H_2O$ in Configuration #12, and from -0.22 in. $H_2O$ to +0.7 in $H_2O$ (pressure) in Configuration #13.

### *4.1.3 TESTING IN INTERMEDIATE SILTY CLAY AND LOWER SILTY SAND LAYERS*

Testing was conducted in the intermediate silty clay and lower silty sand layer during the initial start-up and shakedown of the pilot system equipment (refer to **Section 3.2.2**). Minimal testing was possible in these layers due to the rise in the water table elevation in the test area. However, the brief testing yielded the following observations:

- No measurable air flow could be achieved within the intermediate silty clay unit at the maximum vacuum capacity of the available equipment.
- Wellhead performance (i.e., air flow rate and vacuum response) of SVE wells in the lower silty sand layer was similar to the upper silty sand layer. This is consistent with the findings of the pre-pilot test data collection event (refer to **Section 1.1** and **Section 5.3**)

Based on these observations, the upper silty sand layer PET/PE results can be used for the design of the lower silty sand layer SVE system. However, SVE is not likely to be an effective process for the intermediate silty clay layer. Based on preliminary COC mass distribution estimates for the treatment areas, the COC mass within the intermediate clay layer appears to be a small fraction of the overall COC mass (this will be discussed in more detail in the *Work Plan for Full-Scale SVE*; refer to **Section 6.0**).

## 4.2 PERFORMANCE EVALUATION RESULTS

The objective of the extended PE testing was to determine the achievable level of COC mass reduction on the soils. The design PET multi-well configurations discussed in **Section 4.1** were used to select the PE testing configuration.

In general, it was desired to achieve at least 30% mass reduction on the soils over the duration of the extended PE test (originally anticipated to be 3 months per *Section 4.2* of the *Work Plan*). The rationale for this mass reduction target was to prevent typical soil sampling variability (i.e., due to natural soil heterogeneity and non-uniform COC distribution) from potentially obscuring the actual SVE mass removal performance.

### *4.2.1 MASS REMOVAL RATE PERFORMANCE RESULTS*

The SVE pilot test performance was monitored as described in **Section 3.6**. The key results are summarized below (and are also shown in **Table 7**).

Full Area PE Results:

- The full SVE pilot test area operated continuously for a total twelve weeks (86 days) from February 16, 2010, to May 13, 2010.
- The average mass removal rate was 7.4 lbs benzene per hour and ranged from 0.2 to 20 lbs benzene per hour.
- The total estimated mass removed was 14,000 lbs benzene (based on vapor removal). As discussed in **Sections 5.1 and 5.2** of this report, the overall COC mass removal estimated from the vapor phase sampling is consistent with the COC mass removal estimated from the soil sampling data.

Sub-Area PE Results:

- The SVE pilot test operated in the sub-area for a total of nine weeks (64 days) from May 13, 2010 to July 16, 2010.
- The average mass removal rate was 1.0 lbs benzene per hour and ranged from 0.03 to 2.3 lbs benzene per hour.
- The total estimated mass removed was 1,600 lbs benzene (based on vapor removal) during the sub-area operation. Note that additional SVE wells located outside the sub-area were operated intermittently during the extended sub-area operation to aid in removing water from the sub-area. Therefore, the total of 1,600 lbs of benzene includes COC vapor mass that was removed from the overall pilot test area. It was estimated from the individual wellhead concentration data (i.e., SVE-05A and SVE-07A) that approximately 730 lbs of benzene was removed from within the sub-area boundaries.
- As discussed in **Section 5.2** of this report, the overall COC mass removal estimated from the vapor phase sampling is generally consistent with the COC mass removal estimated from the soil sampling data.

A summary of the PE results is presented on **Table 7**. Wellhead performance data is summarized in **Tables 8A and 8B**. Comprehensive system monitoring and performance data tables are presented in **Appendix C**.

Charts of the cumulative mass removed and benzene concentration for the full SVE pilot area and sub-area are presented on **Figures 9A and 9B**. .

### *4.2.2 SOIL VAPOR SAMPLING RESULTS*

Refer to **Table 9** for a summary of the baseline soil vapor sampling results (April 2009). Baseline soil vapor field PID screening results of the shallow SVE wellheads ranged from 158 ppmv at well SVE-01A to greater than 15,000 ppmv (which was the upper detection limit of the

PID that was used for the baseline sampling) at SVE-04A. Baseline soil vapor field screening results of the vapor monitoring probes ranged from 172 ppmv at VP-A03S to greater than 15,000 ppmv at VP-A01S.

Soil vapor samples were collected from SVE-04A and vapor probe VP-09S for laboratory analytical analysis of VOCs via USEPA Method TO-15. Vapor probe VP-09S was selected for analysis because it had the highest field PID screening result of the newer vapor probes installed as part of the *Work Plan* implementation (14,878 ppmv). The resulting baseline soil vapor benzene concentration at SVE-04A was 22,000 ppmv and at VP-09S was 54,000 ppmv. The soil vapor laboratory analytical report is presented in **Appendix D**.

<u>General Changes in Soil Vapor Concentrations During SVE Testing Duration</u>: Soil vapor concentrations were measured periodically at the SVE wellheads and at vapor monitoring probes during the PE testing. Sampling was performed using a PID, and results are presented in **Appendix C**.

As expected, vapor concentrations at SVE wells and vapor monitoring probes generally declined in response to the SVE testing, with the exception of VP-02S (which remained greater than 9,999 ppmv, which was the upper detection limit for the PID used for the duration of testing). It should be noted that rising water table elevations may have interfered with the vapor concentration measurements taken at some locations (due to submergence of the vapor probe screens or impacted soil intervals, etc.).

## 4.3 SOIL SAMPLING RESULTS

### *4.3.1 SVE FULL PILOT AREA – BASELINE AND INTERMEDIATE SOIL SAMPLING RESULTS*

Baseline and intermediate soil sampling events were conducted in the full SVE pilot area as described in **Sections 3.7.1 and 3.7.2**, respectively. Soil sampling analytical results for the baseline and intermediate soil sampling events are presented on **Table 3A** and the laboratory analytical reports are presented in **Appendix D**.

During the baseline soil sampling event, the concentration of benzene ranged from 210 mg/kg at location SS-01S to 47,000 mg/kg at location SS-09S. Field observations indicated that NAPL was present in the sandy fill/upper silty sand layer at varying depths.

During the intermediate soil sampling event, the concentration of benzene ranged from 290 mg/kg at location SS-03S to 5,600 mg/kg at location SS-02S. As was the case for the baseline event, NAPL was observed at several of the sampling locations.

### *4.3.2 Sub-Area – Baseline and Final Soil Sampling Results*

Baseline and final soil sampling events were conducted in the SVE Sub-Area pilot area as described in **Sections 3.7.3 and 3.7.4**, respectively. Soil sampling analytical results for the baseline and final soil sampling events are presented on **Table 3B** and the laboratory analytical reports are presented in **Appendix D**.

During the baseline soil sampling event, the concentration of benzene ranged from 20 mg/kg at location SS-08S to 6,500 mg/kg at location SS-101S. Field observations of sheen and product staining indicated that some NAPL may be present in the fill/upper silty sand layer.

During the final soil sampling event, the concentration of benzene ranged from 34 mg/Kg at location SS-102S to 1,300 mg/Kg at location SS-03S.

# 5.0 DISCUSSION OF RESULTS

This section provides an analysis of the key results of the pilot test, including:

- An analysis of the vapor mass removal rates achieved by the SVE system.
- An analysis of the COC mass reduction achieved in the upper silty sand layer.
- A review of the pre-pilot PPT results, and a comparison of air flow characteristics between the sandy fill/upper silty sand layers and the lower silty sand layer in Big Mo and other treatment areas of the site.
- Air flow characteristic modeling of the SVE pilot test results.

## 5.1 VOC VAPOR MASS REMOVAL ANALYSIS

SVE systems typically achieve the majority of VOC mass removal from soils within two to three years of operation. Following an initial period of high mass removal rates, the mass removal rate will decrease to asymptotic levels, which is typically based on soil mass transfer limitations in the subsurface. At one point in the test, the mass removal rates declined to a low of 0.03 lbs per hour (refer to **Appendix C, Table C-2**). However, it is likely that this reduction in mass removal rate was a result of the SVE well screens and target soil interval being partially submerged, due to fluctuating water table elevations. It is unlikely that mass removal rates had reached a mass transfer limited/asymptotic condition during the pilot test.

As presented in **Section 4.2.1** and **Table 7** of this report, a maximum initial mass removal rate of 20 lbs of benzene per hour was achieved at the start-up of the PE test in February 2010. This initial high mass removal rate is a function of the theoretical vapor saturation limit of benzene (discussed in more detail below) and some level of contact inefficiency between the flushing air and the soil contaminant distribution.

The vapor saturation limit represents the theoretical maximum concentration in air (or soil pore spaces) that can occur due to chemical-to-vapor equilibrium partitioning. The vapor saturation concentration[3] for benzene is 200 grams per cubic meter ($g/m^3$) at 12 degrees Celsius. This is equivalent to approximately 62,000 ppmv.

Evidence of residual NAPL was observed in the Big Mo pilot test area. Baseline TO-15 soil vapor samples from the vapor probes (refer to **Table 9**) indicated that the maximum vapor concentration was 54,000 ppmv benzene (at VP-09S) under static conditions. This is lower than the theoretical vapor saturation limit, but is overall in relative agreement with the theory.

During SVE, air enters the subsurface from the atmosphere (or air injection wells) in response to the vacuum gradient created by the SVE wells. The air sweeps through the soil pore spaces and chemical-to-vapor partitioning and/or soil desorption will occur. Depending on the level of soil impacts, chemical partitioning rates, and air flushing rates, the air that is eventually extracted from the subsurface will have reached some level of vapor saturation (measured as a vapor concentration in ppmv at the wellhead, or SVE system effluent).

The ratio of the vapor saturation limit to the actual wellhead or SVE system effluent concentration represents an overall dilution factor. This dilution factor is a dynamic, changing value as the SVE treatment continues, due to clean-up of soils within the air flow pathways. For example, if residual NAPL is present, the free-phase chemicals may be volatilized more quickly (resulting in lower dilution factors). As the NAPL is removed, and soil desorption/mass transfer limitations begin to dominate, the dilution factor will increase.

In practice, the effective dilution factor can range from 2 to 10 during initial operation in highly impacted soils. Over time, the dilution factor increases as the soil COC concentrations in the

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[3] Verschueren, K. Handbook of Environmental Data on Organic Chemicals, 3rd Edition. Van Nostrand Reinhld Co., New York: 1996.

subsurface decreases. Based on the vapor theoretical saturation concentration of benzene (62,000 ppmv) and the actual initial vapor concentration from the well field based on SVE Line A TO-15 analytical data (5,100 ppmv; refer to **Appendix D** for the laboratory analytical report and **Appendix E** for a summary of the analytical results), an average initial SVE dilution factor of 12 was calculated. This dilution factor can be used in the full-scale conceptual design to evaluate the initial mass removal rates that may be achieved in treatment areas with similar levels of COC impacts and soil characteristics.

## 5.2 SOIL COC MASS REDUCTION ANALYSIS

One of the primary objectives of the SVE pilot test was to determine the mass reduction that could be achieved over an extended duration (PE test). Because the PE test was conducted for approximately twelve weeks in the entire area, and was then reconfigured to a sub-area for an additional nine weeks, a COC mass reduction was estimated for both portions of the test.

The following sections provide an evaluation of the estimated mass reduction of COCs that was achieved in the pilot test area and sub-area configurations.

### *5.2.1 PILOT TEST AREA COC MASS ESTIMATE*

The results of the baseline soil sampling event (January 2009) and intermediate soil sampling event (March 2010) are presented in **Table 3A**. As shown in **Table 10**, the COC mass in the pilot test area was estimated based on the baseline and intermediate soil sampling data.

The mass calculation was based on an arithmetic average of the soil data, which was assumed to be uniformly distributed throughout the upper silty sand layer. In addition, an average 10% NAPL saturation was assumed for this layer, based on actual field observations of residual free-phase product during the soil sampling events.

The COC mass was reduced from 79,000 lbs of benzene at the baseline event, to 62,000 lbs of benzene at the intermediate soil sampling event. Based on the soil data, approximately 17,000 lbs of COC mass was removed (approximately 21%), after six weeks of SVE treatment (i.e., six weeks of SVE operation had elapsed at the time when the intermediate soil sampling was conducted).

For comparison, approximately 14,000 lbs of benzene was estimated to be removed based on vapor monitoring of the SVE discharge (as previously discussed in **Section 4.2.1)**. The vapor phase mass removal estimate is in general agreement with the mass removal estimate based on the soil data.

### *5.2.2 Sub-Area COC Mass Estimate*

The results of the baseline sub-area soil sampling event (May 2010) and final sub-area soil sampling event (June 2010) are presented in **Table 3B**. As shown in **Table 10**, the COC mass in the pilot test sub-area was estimated based on these soil sampling events.

As for the full test area, the mass calculation was based on an arithmetic average of the soil data, which was assumed to be uniformly distributed throughout the upper silty sand layer. In addition, an average 1% NAPL saturation was assumed for this layer, based on field observations of residual free-phase product (which was minimal at this stage of the test).

The COC mass was reduced from approximately 1,600 lbs of benzene at the sub-area baseline event to 1,100 lbs of benzene as of the final sub-area soil sampling event. Based on the soil data, approximately 500 lbs of benzene of the COC mass (approximately 31%) remaining in the sub-area, was removed after an additional seven weeks of SVE treatment (i.e., seven weeks of SVE operation had elapsed at the time when the final sub-area soil sampling was conducted).

For comparison purposes, the estimated mass removed based on vapor phase monitoring of the SVE discharge was 1,600 lbs of benzene during the extended sub-area operation (previously discussed in **Section 4.2.1**). However, it should be noted that additional SVE wells which were located outside the sub-area were operated intermittently during this phase of testing to aid in removing water from the sub-area. Therefore, the total of 1,600 lbs of benzene removed during this phase of testing reflects COC vapor mass that was removed from the entire pilot test area. It was estimated from the individual wellhead concentration data (i.e., SVE-05A and SVE-07A) that approximately 730 lbs of benzene was removed from within the sub-area boundaries. This vapor phase mass removal estimate is in agreement with the mass removal based on the soil data.

## 5.3 SUMMARY OF PRE-PILOT TEST POINT PERMEABILITY RESULTS

As discussed in **Section 1.1** of this report, point permeability testing was conducted in all treatment areas at the site between June 30 and July 3, 2008, as part of the pre-*Work Plan* data collection event (refer to *Appendix B* of the *Work Plan*). The following average relative air permeabilities were determined for the soil layers within the treatment areas:

- Sandy fill layer: $1.9 \times 10^{-8}$ centimeter squared ($cm^2$)
- Upper silty sand layer: $1.8 \times 10^{-8}$ $cm^2$
- Intermediate silty clay layer[4]: $3.9 \times 10^{-9}$ $cm^2$
- Lower silty sand layer: $2.1 \times 10^{-8}$ $cm^2$

Based on the above point permeability data, the sandy fill, upper silty sand, and lower silty sand layers would be expected to show similar air flow characteristics. In addition, the soil types, permeability, and air flow characteristics are similar in the Former Benzene and Chlorobenzene

[4] Field observations indicate that the intermediate silty clay layer is highly plastic and of low intrinsic permeability. However, the PPT and modeling results for this layer yielded a higher permeability than anticipated. This higher estimated permeability is likely due to short-circuiting of air flow between the silty clay layer and the upper and lower silty sand layers.

Storage (Big Mo), Former Benzene Pipeline, North Tank Farm/Former Overhead Steamer Tank, and Near Little Mo areas.

## 5.4 SVE AIR FLOW MODELING

The pilot test results were analyzed using a two-dimensional (2-D) analytical SVE air flow model[5] to estimate the following air flow performance characteristics of the SVE wells, for use in the full-scale conceptual SVE design:

- Intrinsic Soil Permeability: Model simulations provide an estimated intrinsic soil permeability (in both the radial and vertical directions, or $K_r$ and $K_z$ respectively). The estimated permeability is based on the actual wellhead performance (i.e., measured flow rate and vacuum response at the SVE test wells) and the observed vacuum distribution within the vapor probes at various radii from the extraction well.

  The resulting permeability data can then be used in the model to simulate the wellhead vacuum required to achieve various design air flow rates from the SVE well. These results are then used to specify the design wellhead vacuum required to achieve a desired flow rate from the well, which is then used to specify the full-scale blower equipment specifications.

- Radius of Influence: The radius of influence (ROI) is the radial distance from a SVE well where the minimum target number of pore volume exchanges will occur (a definition of pore volume exchange rate is provided in **Section 5.4.1**). From a full-scale design standpoint, the center-to-center spacing of the SVE wells is based on this ROI.

[5] Baehr, A.L. and Joss, C.J. 1995. "An updated model of induced air flow in the unsaturated zone," Water Resources Research Vol 31, n 2, pp 417-421.

### 5.4.1 *DEFINITION OF TARGET PORE VOLUME EXCHANGE RATE*

When a volumetric flow rate of air is extracted from a SVE well, the resulting pore air velocities are highest near the well. The pore air velocity decreases exponentially with distance from the well. The pore air velocity at each distance can be converted into a volumetric pore air flushing rate. The pore air flushing rate represents the number of times the air volume within each soil pore is removed over a given period of time (usually expressed as a pore volume [PV] exchange rate per year, or PV/year). Based on this, typically the soils located at the midpoint between SVE wells will have fewer PV exchanges per year.

The PV exchange rate is a key full-scale SVE design parameter. This is because there is a theoretical minimum volume of air that must be flushed through each cubic yard of soil to volatilize and remove the target COC mass. The time it takes to flush the theoretical minimum volume of air through the soils located between the SVE wells controls the overall remediation timeframe.

The PV exchange rate required to achieve a desired level of mass reduction is a complex function of several factors, but it is generally related to the volatility of the target COCs, efficiency of air flow/contaminant contact, and the level of COC impacts within the soils. In practice, the required PV exchange rate is an empirically derived value, and is based on field experience in similar settings. For the types of COCs at the site, a minimum of approximately 500 to 1,000 pore volume exchanges per year is typically required.

### 5.4.2 *PILOT TEST MODELING RESULTS*

The results of the SVE modeling are summarized in **Table 11** and **Appendix F.** The general SVE air flow performance characteristics are as follows:

Intrinsic Soil Permeability:

- Sandy fill/upper silty sand layer $K_r = K_z = 3.94x10^{-7}$ cm$^2$ (isotropic conditions).
- The effective surface cover permeability, $K_c/B_c$[6], was estimated at $3.58x10^{-10}$ cm$^2$.
- The modeling results indicate that the soil permeability is higher than estimated using the previous point permeability testing (discussed in **Section 5.3** of this report).

Radius of Influence:

Using the soil permeability results, two flow conditions, 25 scfm and 30 scfm, were modeled to develop full-scale design parameters including PV exchange rates and ROI. To achieve the target PV exchange rate range of 500 PV/year to 1,000 PV/year, the model estimated the following range of ROI:

- At a 25 scfm flow rate at the SVE wellhead:
    - Approximately 1,000 PV/year is achieved at an ROI of 20 feet.
    - Approximately 500 PV/year is achieved at an ROI of 25 feet.
- At a 30 scfm flow rate at the SVE wellhead:
    - Approximately 1,000 PV/year is achieved at an ROI of 21 feet.
    - Approximately 500 PV/year is achieved at an ROI of 27 feet.

Note that the above PV exchange rates are for a single well. Overlapping of the ROI in multi-well configurations would affect the overall pore volume exchanges.

[6] The computer model assumes that the surface cover is 10 cm thick (represented by $B_c$), and the overall permeability of this surface cover is a function of its thickness (i.e., $K_c/B_c$).

## 6.0 CONCLUSIONS

The objectives of the SVE pilot test were to demonstrate that SVE could achieve reduction of COC mass in the unsaturated zone soils, and to develop design parameters for a full-scale SVE application.

The findings of the SVE pilot test study were:

- SVE can be an effective technology for reducing COC mass in the unsaturated soils, including the sandy fill, upper silty sand, and the lower silty sand layers.
- SVE is not likely to be effective for treating the intermediate silty clay layer. No measurable air flow could be achieved in this layer using the maximum vacuum capacity of the test equipment. Based on preliminary COC mass distribution estimates, the COC mass within the intermediate clay layer represents a small fraction of the overall COC mass in the unsaturated zone (i.e., sandy fill/upper silty sand and lower silty sand layers. This is discussed in more detail in the *Work Plan for Full-Scale SVE*).
- Based on soil sampling data, approximately 17,000 lbs of COC mass (as benzene) was removed from the sandy fill and upper silty sand layers. An additional 500 lbs of COC mass (as benzene) was removed from the sub-area after extending the test operation.
- An estimated COC mass reduction of 21% was achieved in the pilot test area, and 31% reduction was achieved in the sub-area, based on soil sampling data.
- Based on vapor monitoring data, approximately 15,600 lbs of COC mass (as benzene) was removed during the SVE pilot test. This COC mass removal is generally consistent with the COC mass reduction observed on the soils in the pilot test area.
- The average COC mass removal rates were 7.4 lbs per hour and 1.0 lb per hour (as benzene) from the full SVE pilot area and from the sub-area, respectively. COC mass removal rates ranged from 0.03 to 20 lbs per hour (as benzene). Mass removal rates declined as the test proceeded, but this was likely attributable to rising water table elevations rather than achieving asymptotic mass removal conditions.

- SVE air flow performance characteristics were estimated from the pilot test data. A PV exchange rate of 500 to 1,000 PV per year can be achieved with a SVE well ROI of 20 to 25 feet (at wellhead flow rates of 25 to 30 scfm). This is based on the testing results within the sandy fill/upper silty sand layer within the Big Mo area. However, because the SVE wellhead performance (flow and vacuum response) was similar between the sandy fill/upper silty sand layer and the lower silty sand layer during this pilot test, this is also likely to be applicable to the lower silty sand layer. These results are also applicable to the other treatment areas (including the Former Benzene Pipeline, North Tank Farm, and Near Little Mo areas), based on prior point permeability testing in these areas that indicate that they have similar soil permeabilities.
- Soil permeabilities of the sandy fill/upper silty sand layer was estimated at $K_r = K_z = 3.94 \times 10^{-7}$ $cm^2$ (isotropic soil conditions) using the SVE air flow model. These estimates are higher than what was indicated by the point permeability testing conducted at the site prior to the SVE pilot test.

A *Work Plan for Full-Scale SVE* was prepared (November 2010) using the findings of this *SVE Pilot Test Report*. The following considerations were incorporated into the full-scale conceptual SVE design:

- <u>SVE Well Spacing Design</u>: Selection of the SVE well spacing for full-scale application will be based upon the ROI analysis. In this *SVE Pilot Test Report*, a range of potential ROI values for the SVE wells was determined using a computer model and the air flow/vacuum responses measured at the individual SVE wellheads and vapor probes (refer to **Section 5.4**).

- <u>Applicability of Pilot Test Results to Other Areas/Soil Layers</u>: Soil conditions that were encountered in the Big Mo pilot test area are geologically similar to the other potential target areas on site (Former Benzene Pipeline, North Tank Farm, and Near Little Mo areas). This was verified based on the prior point permeability testing (discussed in

**Section 5.3**). Therefore, the SVE design parameters developed in this *SVE Pilot Test Report* are considered applicable to all of the specified treatment areas.

Also, due to high water table elevations encountered during the SVE pilot test, the majority of pilot testing was conducted within the sandy fill and upper silty sand layers. SVE was conducted briefly within the lower silty sand layer during the initial test start-up, prior to the increase in the water table elevation. Based on the brief testing, wellhead air flow and vacuum response in the lower silty sand layer was similar to the response observed in the upper silty sand layer. Therefore, the same design parameters generated for the sandy fill/upper silty sand layer (i.e., wellhead flow/vacuum performance and design ROI) can be applied to the lower silty sand layer for full-scale design purposes.

- Water Table Fluctuations: Water table level fluctuations in the area may interrupt the application of SVE to the lower silty sand layer. However, historical water level records indicate that sufficient periods of dry conditions occur which will allow for SVE operation at these depths. The historical water level data and these trends will be discussed in the *Work Plan for Full-Scale SVE*, but historical data shows that the water table is deeper than 15 feet bgs during drier periods (water levels were this deep immediately prior to the system shakedown period).

- Target Area Mass Estimates: The COC mass in each of the target areas of the site (i.e., Former Benzene and Chlorobenzene Storage area (Big Mo area), the Former Benzene Pipeline area, the North Tank Farm/Former Overhead Steamer Tank area, and the Near Little Mo area) will be estimated based upon the available site characterization data. This information will be compared to the anticipated SVE mass removal rates to assess performance of a full-scale system.

**TABLES**

**FIGURES**

# Appendix A

# Individual Well Parameter Evaluation Testing Data

# Appendix B

# Multi-Well Parameter Evaluation Testing Data

# Appendix C

# Performance Evaluation Data

# Appendix D

# Laboratory Analytical Reports

# Appendix E

# Summary of Analytical Results for Vapor Samples

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# Air Flow Modeling

# EXECUTIVE SUMMARY TABLE

# EXECUTIVE SUMMARY FIGURES