# INTERIM REMEDIAL ACTION TREATABILITY STUDY RESULTS USING INTERNAL COMBUSTION ENGINE SOIL VAPOR EXTRACTION TECHNOLOGY


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## EXECUTIVE SUMMARY

The primary purpose for performing the interim remedial action (IRA) treatability study using the internal combustion engine (ICE) soil vapor extraction (SVE) system was to further evaluate the applicability of the ICE-based SVE technology and collect additional extended SVE operational data to properly design a full-scale remediation system. The ICE SVE technology was used to remediate gasoline-contaminated soils associated with the aboveground storage tank systems .

The site layout for the IRA study included a single vapor extraction well (VEW) (previously installed), seven vapor monitoring points (VMPs), and a Remediation Service, International (RSI) Model V4 dual-engine ICE SVE system. During the IRA period, vapor extraction flow rates, soil gas concentrations, and other system parameters were monitored and adjusted (as necessary) to maintain optimal vapor extraction mass removal rates and treatment efficiency. A radius of influence (ROI) vacuum response test was conducted at the conclusion of the IRA study period in order to estimate a maximum ROI achievable under sustained, long-term ICE SVE operations.

Prior to, and upon completion of, the IRA study, initial and final soil gas chemistry data were collected, including oxygen ($O_2$), carbon dioxide ($CO_2$), and total volatile hydrocarbons (TVH) concentrations. Initial (baseline) and final soil gas data were collected from each of the seven VMPs (VMPs-1, 3, 4, 5, 6, 7, and 8). Changes in soil gas chemistry were used in conjunction with the vacuum response data to support the conclusion made regarding the effective ROI observed during the IRA period.

The ICE SVE system used during the IRA proved to be a reliable and effective vapor treatment technology for the subject site. Daily TVH mass removal rates ranged from 508 to 647 pounds per day (lb/day) total hydrocarbons, averaging approximately 595 lb/day. The ICE's destruction removal efficiency (DRE) observed during the same period ranged from 98.93 to 99.96 percent destruction of the extracted hydrocarbon vapors, resulting in an average DRE of 99.58 percent. Results from the vacuum response test indicated a radius of influence (ROI) of up to 300 feet from the extraction well. The effective ROI within the source area soils (containing residual fuel hydrocarbon mass) was estimated to be 150 feet from the VEW, while the ROI for soils containing only vapor-phase contamination (no residual fuel) extended up to 300 feet from the VEW. For purposes of this report and full-scale design parameters, the effective ROI used was 150 feet.

On the basis of the positive results from the IRA study at the FBTS, RSI recommends a full-scale ICE SVE remedial design. The recommended full-scale design would include the addition of 2 VEWs, 10 multi-interval VMPs, and 2 additional dual-engine ICE systems. This recommendation is based on a target cleanup time frame of approximately 5 years, or less (for the vadose zone, source area soils at the FBTS). Optional full-scale remediation approaches using the ICE technology are also discussed in this report. Once a target cleanup time frame is established for this site, the appropriate number of ICE SVE systems needed to meet that goal can then be determined.

# 1. INTRODUCTION

An interim remedial action (IRA) treatability study using internal combustion engine (ICE) soil vapor extraction (SVE) technology was performed at One primary purpose of the IRA study was to evaluate the effectiveness of the ICE-based SVE technology at remediating gasoline-contaminated soils associated with former aboveground storage tank systems. On the basis of results from a previous 5-day ICE SVE pilot test conducted in July 2000, the need to conduct an extended IRA treatability study using a larger dual-engine ICE SVE system was recommended. The recommended IRA period (approximately 6 months) would provide the time necessary for this site, and the ICE system, to reach a more realistic "steady-state" condition (i.e. hydrocarbon mass removal and vapor extraction flow rates). The extended operating period would allow time for several soil gas "pore volume" exchanges to occur within the source area, thus providing a more accurate assessment of the effective radius of influenece (ROI) and hydrocarbon mass removal rates.
. The rationale for selecting the dual-engine ICE SVE system was due primarily to the high influent (extracted vapor) concentrations of total volatile hydrocarbons (TVH) [initially, greater than 60,000 parts per million by volume (ppmv)] and large areal extent of residual fuel hydrocarbon contamination. Two key areas where the ICE SVE technology has an advantage over more traditional treatment technologies (e.g. thermal or catalytic oxidation) are: (1) a greater hydrocarbon ppmv mass removal capacity (typically 4 to 5 times) per cubic foot of vapor treated; and (2) no external power is required.

# 2. OBJECTIVES

The primary objectives of the IRA treatability study were to

- Evaluate the efficacy of the ICE-based SVE technology as a final remedy component
- Establish a full-scale, steady-state operating condition in both the extracted vapor flow rate and concentration, and in the vacuum induced to the subsurface in order to more accurately estimate the maximum effective ROI from a single vapor extraction well (VEW).
- Collect sufficient data to properly assess the remaining TVH mass within the vadose zone, in order to more effectively design a full-scale remediation system.

# 3. DESCRIPTION OF ICE SVE TECHNOLOGY

The following sections describe the ICE SVE technology and system capabilities.

## 3.1. Internal Combustion Engine Technology

Vapor extraction and combustion is an innovative technology that uses an internal combustion engine (ICE) with advanced emission controls to extract and burn nonchlorinated hydrocarbon vapors from the vadose (unsaturated) zone. Vapors are extracted from the subsurface by the intake manifold vacuum of the engine via vapor extraction wells (VEWs) screened within contaminated intervals. The extracted vapors are then burned as fuel to run the engine. The ICE exhaust gases then pass through a standard automotive catalytic converter for complete oxidation before being discharged to the atmosphere.

### 3.2. ICE System Capabilities

Remediation Service, International (RSI) of Ventura, California, has developed a Model V4 ICE unit that uses two Ford Motor Company™ 460-cubic-inch-displacement (CID) engine blocks, heads, and accessories along with onboard computer controlled systems that monitor the performance of both engines. The intake manifold of each engine provides the vacuum source, up to 20 inches of mercury or approximately 270 inches of water. Typical extraction flow rates for the Model V4 (dual-engine system) range from 50 to 120 standard cubic feet per minute (scfm), depending on soil conditions and the TVH, oxygen, and carbon dioxide concentrations in the extracted soil gas. RSI manufactures ICE units in two sizes; a single-engine Model V3 and a dual-engine Model V4.

The on-board computerized system provides the necessary monitoring for maximum system efficiency. The data acquisition system includes constant monitoring of several system parameters, including the engine oil pressure, coolant temperature, exhaust temperature, exhaust percent oxygen, engine speed, and operation (flow rates, inches of well vacuum, supplemental fuel usage, air/fuel ratio, and engine hours). Continuously monitored by the on-board computer, the system shuts down automatically if one or more of the following conditions exists: engine overspeed, high coolant temperature, high exhaust temperature, low oil pressure, fire, or high water level in the well gas filter assembly. The system is programmed to store and report the reason for the automatic shutdown.

Supplemental fuel (propane or natural gas) is used to provide smooth operation of the engine as the extracted soil gas vapor concentrations fluctuate. Supplemental fuel consumption can be eliminated if the extracted soil gas vapor concentrations provide sufficient fuel to sustain combustion and smooth engine operation. Depending on the percent oxygen (generally >15% required) and British thermal unit (BTU) value of the influent soil gas, soil vapor hydrocarbon concentrations in excess of 30,000 to 40,000 ppmv are generally sufficient to sustain engine operation without the need for supplemental fuel. The computer (Phoenix 1000 controller) regulates the fuel requirements of the engine through a patented carburetor system. The controller makes adjustments in the supplemental fuel flow to compensate for the changing influent hydrocarbon concentrations and to maintain the proper stoichiometric air/fuel ratio. When the proper air/fuel ratio is maintained, the total hydrocarbon destruction removal efficiency (DRE) typically exceeds 99 percent.

The RSI systems are equipped with a flame arrestor to protect the ICE unit from "flashback" from the engine. An on-board fire control system equipped with a dry chemical extinguisher is provided, and it will automatically discharge in the event of a fire.

External electrical power is not required. The electronic ignition system is battery-powered (12-volt) and adjusts automatically in response to commands from the computer. The RSI ICE systems can also be equipped with a modem for remote monitoring and remote adjusting (as necessary) of well vacuum, well flow, and engine speed (i.e. RPM) in order to optimize system performance and minimize supplemental fuel consumption. The remote monitoring capability also allows for adjustments to be made while the system is running.

### 3.3. Regulatory Acceptance

The regulatory acceptance of this technology for treatment of hydrocarbon vapors in soil gas has been widespread. The states where ICE units have been tested and/or are currently operating are as follows:

| Permitted | 1- to 5-Day Pilot Testing |
|---|---|
| Arizona | Alabama |
| California | Colorado |
| Florida | Georgia |
| Hawaii | Kansas |
| Idaho | Louisiana |
| Illinois | Oklahoma |
| Massachusetts | Michigan |
| New Jersey | Missouri |
| New Mexico | Montana |
| New York | Nevada |
| Ohio | North Carolina |
| Oregon | Tennessee |
| Pennsylvania | Utah |
| Texas | Alberta, Canada |
| Washington | |
| Ontario, Canada | |
| Mexico | |
| Argentina | |

## 4. IRA ACTIVITIES

This section describes the IRA activities. Included are descriptions of the treatability study area site layout, test procedures, and ICE system testing.

### 4.1. Site Layout

This section provides information regarding locations and design of the vapor extraction well (VEW), vapor monitoring points (VMPs), and the ICE SVE system layout.

### 4.1.1. Vapor Extraction Well and Vapor Monitoring Point Installations

The VEW constructed as part of the previous SVE pilot test consists of one 2-inch diameter Schedule 40 PVC well with 20 feet of 0.040-inch slotted well screen located between 69.5 and 89.5 feet below ground surface (bgs). The annular space above the screened interval was sealed with bentonite to prevent disruption of air flow from upper soil intervals. A total of eight vapor monitoring points (VMP-1 through VMP-8) were installed at varying distances from the VEW as part of the pilot test and IRA activities. Each VMP was constructed in the same manner, with either three or four vapor probe intervals at each location. Each VMP interval consisted of one 1-foot-long, 0.75-inch-diameter, 0.02-inch-slotted PVC well screen placed in the center of a 3-foot interval of coarse aquarium graded sand. Each vapor probe screened interval is separated from adjacent intervals with bentonite seals. Each probe interval is connected to the ground surface with an separate 0.75-inch solid PVC casing and equipped with individual 1/4-inch ball valves and 3/16-inch hose barb connections. The surface restoration consists of a flush-mounted traffic-rated well box and cover. A 500-gallon propane tank was located approximately 20 feet from the ICE unit. The tank was clearly labeled to indicate its contents.

### 4.1.2. Test Component Layout

Figure 4-1 is the site layout and shows locations of the VEW, VMPs, and ICE unit. A single pipe header, equipped with well flow measurement and soil gas sampling points, was connected to the ICE unit with a combination of 2-inch, Schedule 40 PVC pipe and 2-inch flexible hose. A 500-gallon propane tank was positioned next to the ICE unit to provide supplemental fuel when needed.

## 4.2. ICE System Testing

The testing performed during start-up and throughout the extended IRA study period are summarized below.

### 4.2.1. Start-up Testing and System Optimization

Following installation of the RSI Model V4 ICE unit, initial start-up testing was performed to ensure that the ICE vapor treatment system was operating properly. Before system start-up, initial "baseline" soil gas samples were collected from VMPs (1, 3, 4, 5, 6, 7, and 8). The VMPs were field screened for oxygen ($O_2$), carbon dioxide ($CO_2$), and total volatile hydrocarbon (TVH) concentrations by using an Horiba™ multigas direct reading instrument. Before sample collection, the Horiba™ instrument was calibrated according to the manufacturer's instructions. The baseline *in situ* soil gas results were later compared with final sampling results to evaluate changes in soil gas chemistry ($O_2$, $CO_2$, and TVH) and the overall effectiveness of the ICE SVE system.

During the IRA study period, a total of 23 1-liter Summa™ canister samples were collected (9-influent, 14-effluent) and submitted to Air Toxics Limited, a State of Arizona certified air analytical laboratory located in Folsom, California. Vapor samples were analyzed for benzene, toluene, ethyl benzene, and total xylenes (BTEX), and total petroleum hydrocarbon (TPH) content using U.S. Environmental Protection Agency (USEPA) Method TO-3. One additional influent vapor sample was collected during the IRA start-up period and analyzed using USEPA Method TO-14. The additional TO-14 vapor sample was required for compliance with the approved air permit to determine if any chlorinated or other regulated compounds were present in the vapor stream. On the basis of the results of the TO-14 analysis, no other compounds of concern were detected (except for those previously mentioned and typically found in gasoline). In addition to laboratory analyses, field TVH, $O_2$, and $CO_2$ concentrations were measured in the extracted soil gas with an Horiba™ multigas emission analyzer. TVH results from both laboratory analyses and field measurements were used to determine the overall DRE of the ICE unit.

During the initial start-up and optimization period, vapor extraction flow rates and other system parameters were adjusted to optimize the TVH mass removal rate and DRE of the ICE unit, while minimizing or eliminating the need for supplemental fuel.

### 4.2.2. Extended IRA Treatability Study Activities

The extended IRA study period was conducted to further evaluate the effectiveness of the ICE technology (using a larger RSI Model V-4 dual-engine system) and to determine initial full-scale TVH mass removal rates and effective ROI from a single VEW. Additionally, *in situ* soil gas data collected before and upon completion of the IRA study (from various VMP locations) were used to confirm the ROI and to assist in evaluating a full-scale ICE SVE remedial system design for the entire site.

### 4.2.3. ICE SVE System Monitoring

During the initial and extended portions of the IRA study period, several system parameters were monitored and recorded. These parameters included:

- Vapor extraction flow rates and influent TVH concentrations,
- Changes in baseline soil gas concentrations at both the VEW and VMPs,
- Destruction efficiency of the ICE unit; and
- ROI vacuum response (ROI) testing.

# 5. IRA TREATABILITY STUDY RESULTS

The following sections provide the results from the IRA treatability study testing.

## 5.1. Observed Performance of the ICE SVE System

During the IRA study, RSI personnel conducted several field and laboratory sampling events that included periodic monitoring and collection of influent and effluent vapor samples from the ICE system and initial and final *in situ* soil gas samples from multiple VMPs with an Horiba™ field instrument. Sampling results were used to evaluate the overall performance of the ICE system, estimate the effective ROI from a single VEW, and evaluate the applicability of a full-scale ICE SVE remedial system(s) design.

The ICE SVE dual-engine system operated from August 30, 2001, through May 21, 2002, as part of the IRA treatability study. During the 263-day period, 22 days of system downtime occurred because of air permit/regulatory issues outside of RSI's control. Additionally, 10.5 and 25.5 days of ICE system operation were lost on engines 1 and 2, respectively, because of excessive condensate/water collection in the ICE unit's moisture separator. The excessive condensate caused the system to automatically shut down to avoid engine damage, and these events were also out of RSI's control. Therefore, the total number of days possible for ICE system operation was 230.5 and 215.5 for engines 1 and 2, respectively. The approximate total number of actual days of ICE system operation was 221 (5,301 hours) for engine 1 and 181 (4,348 hours) for engine 2. Comparing the total actual days of system operation (based on the recorded engine operating hours) to the total possible days of operation, the overall operating time (based on continuous 24/7 operation) was approximately 95 and 84 percent for engines 1 and 2, respectively. The actual run time percentages also included the downtime for routine system maintenance (every 2 weeks). The reason for the differences in the engine run times was due primarily to a problem with an electronic component in the control system on engine 2. Once the component was replaced, the system ran at 100 percent.

### 5.1.1. Hydrocarbon Mass Removal Rates

The TVH mass removal rates observed during the IRA study ranged from 508 to 647 pounds per day (lb/day), averaging approximately 595 lb/day. Table 5-1 shows the influent TVH concentrations and extraction flow rates during each of the nine laboratory sampling events. Using a combined (both engines operating) average daily hydrocarbon mass removal rate of 595 lb/day (or approximately 297.5 lb/day per engine) over a total of 9,649 hours (total combined engine hours, or 402 single engine days), an overall total of approximately 119,595 pounds (or approximately 19,932 gallons, assuming 6 pounds per gallon) of fuel hydrocarbons (i.e., gasoline) was removed during the IRA study period.

### 5.1.2. Hydrocarbon Destruction/Removal Efficiencies

Destruction/removal efficiencies (DREs) for the ICE system were calculated with the following equation:

$$\text{DRE} = \frac{\text{Total Pounds TVH Influent - Total Pounds TVH Effluent}}{\text{Total Pounds TVH Influent}} \times 100\%$$

During the IRA study period, both influent and effluent TVH concentrations were monitored by collecting 1-liter Summa™ canister samples for laboratory analysis, and by using an Horiba™ hydrocarbon emission analyzer. Laboratory results showed that influent TVH concentrations ranged from 37,000 to 62,000 ppmv and that during the same period effluent samples ranged from 3.9 to 160 ppmv. The Horiba™ meter indicated that influent and effluent TVH concentrations ranged from 42,480 to 73,800 ppmv and from 20 to 80 ppmv, respectively.

On the basis of results from all nine laboratory sampling events, DREs ranged from 98.93 to 99.96 percent, averaging 99.58 percent over the entire IRA study period.

**Table 5-1 - Influent TVH Concentrations and Flow Rates**

| Date/Time | Location | TVH (ppmv) | TVH (µg/L) | Flow Rate (scfm) |
|---|---|---|---|---|
| 9/13/01 1100 | Influent to ICE System | 58,000 | 240,000 | 29 |
| 10/25/01 1430 | Influent to ICE System | 60,000 | 250,000 | 27 |
| 11/8/01 0930 | Influent to ICE System | 62,000 | 260,000 | 27 |
| 11/21/01 1030 | Influent to ICE System | 51,000 | 210,000 | 27 |
| 12/13/01 1100 | Influent to ICE System | 48,000 | 200,000 | 30 |
| 1/9/02 1550 | Influent to ICE System | 47,000 | 200,000 | 31 |
| 2/26/02 1400 | Influent to ICE System | 46,000 | 190,000 | 38 |
| 4/24/02 1004 | Influent to ICE System | 39,000 | 160,000 | 41a/ |
| 5/21/02 0900 | Influent to ICE System | 37,000 | 160,000 | 41 |

TVH = Laboratory results for total volatile hydrocarbons using EPA Method TO-3.
ppmv = parts per million by volume.
µg/L = micrograms per liter.
scfm = standard cubic feet per minute.
a/ = Flow rate measured in the field on 4/24/02 was incorrect because of faulty instrumentation. Corrected flow rate shown on Table 5-1 (41 scfm) is based on actual system parameters (i.e, RPM, engine manifold vacuum, well vacuum, and engine breathing efficiency).

### 5.1.3. Radius of Influence

The ROI was estimated on the basis of the vacuum response and soil gas chemistry data collected from various VMPs across the site. The ICE system operated for a sufficiently extended period to allow multiple soil gas "pore volume" (PV) exchanges to occur within the affected subsurface soils area. The extended IRA ICE operation also allowed time for both the system and the site to reach a steady-state, fill-scale operating condition from a single VEW. Comparisons between the initial and final soil gas concentrations collected from the VMPs were used to ensure that soil gas chemistry was affected at the various radii and vacuums measured. The vacuum data were collected at all the VMPs with Magnehelic (brand name) pressure gauges, and responses were recorded in inches of water column (inches $H_2O$) vacuum.

Since the majority of the hydrocarbon contamination existed at the deepest of the VMP intervals (~90 feet), the vacuum response and soil gas data collected at the 88- to 91-foot depth interval from each VMP was used to estimate the "effective" ROI.

In addition to the collection of vacuum response and soil gas chemistry data, a subsurface PV exchange rate calculation was also used to estimate the removal rate of the *in situ* soil gas at varying radii from the VEW. As a rule-of-thumb, a minimum daily PV exchange rate (air-filled porosity of the soil) of about 0.5 PV/day is usually required to ensure timely and effective progress during remediation. This rule-of-thumb applies primarily to the vadose zone soils within the source area, which would typically contain significant amounts of residual fuel contamination. It should be noted that for soils outside the source area, affected with only vapor-phase (soil gas) contamination (and not additional residual fuel contamination), effective remediation can usually occur at a daily PV exchange rate far less than 0.5 PV/day (typically, 0.1 to 0.01 PV/day).

A site-specific PV exchange rate should be determined for each site. The optimum PV rate is based on several factors, including the evaluation of changes of *in situ* soil gas chemistry over time, ROI vacuum response testing, the overall volumetric size and relative soil gas concentrations within the source area, and the expected and/or acceptable cleanup timeframe.

The estimated PV exchange rate was calculated on the basis of the following assumptions:

- Current vapor extraction flow rate of 41 scfm (with a system capacity of up to approximately 100 to 120 scfm), once the extracted vapor concentrations decrease to around 15,000 ppmv or less, and oxygen and carbon dioxide concentrations are above 18 and below 2 percent, respectively.
- Estimated ROI of 150 feet within the source area (containing residual contamination); and up to 300 feet within areas of only vapor-phase contamination.
- Average vadose zone thickness being affected is 50 feet.
- Soil porosity of 30 percent.

The formula used to calculate the time to remove one PV is:

$$T_p = V_p / Q = \phi R^2 \pi H / Q$$

$T_p$ = time to remove one pore volume (minutes)
$V_p$ = one pore volume (cubic feet)
Q = volumetric vapor flow rate (cubic feet per minute)
$\phi$ = air-filled void fraction in soil (soil porosity)
R = radius of influence (in feet)
H = vertical thickness of contamination (in feet)
$\pi$ = pi (3.141592)

By using the above assumptions and formula, at the current extraction rate of 41 scfm, the current PV exchange rate would be approximately 0.056 PV/day at a 150-foot radius and 0.014 PV/day at a 300-foot radius. After concentrations drop and the system reaches a greater capacity flow rate of approximately 100 scfm, a PV exchange rate of 0.136 PV/day at a 150-foot radius and 0.034 PV/day at a 300-foot radius would be achieved.

Although the PV exchange rates calculated during the IRA were below the ideal minimum of 0.5 PV/day as stated earlier, the overall effectiveness that the ICE system had on reducing the soil gas hydrocarbon concentrations throughout the study area was significant. Therefore, based primarily on the changes in soil gas chemistry and vacuum response testing data, the effective ROI determined during the IRA was approximately 150 feet within the source area (with soils containing residual fuel contamination), and up to 300 feet in areas containing only vapor-phase contamination.

At a system operating condition of 16 inches $H_2O$ wellhead vacuum, the vacuum response test data (at 90 feet bgs) showed a relative vacuum response of approximately 1.3 inches $H_2O$ at 150 feet (based on linear interpolation of measured vacuums at 113 and 200 feet), and a measured vacuum of ~0.65 inch $H_2O$ at 300 feet from the VEW. Table 5-2 shows the corresponding vacuum response at each vapor monitoring point location at varying distances from the VEW.

**Table 5-2 - Radius of Influence Vacuum Response Test**

| Date/Time | Distance from VEW (feet) | Location | Depth Interval (feet) | Initial Vacuum (inches H2O) | Final Vacuum (inches H2O) | Actual Vacuum (inches H2O) |
|---|---|---|---|---|---|---|
| 5/21/02 1000 | 13 | VMP-1 | 90 | 4.00 | 0.00 | 4.00 |
| 5/21/02 1000 | 45 | VMP-3 | 88 | 2.55 | 0.00 | 2.55 |
| 5/21/02 1000 | 113 | VMP-4 | 90 | 1.55 | 0.00 | 1.55 |
| 5/21/02 1000 | 200 | VMP-5 | 91 | 1.00 | 0.00 | 1.00 |
| 5/21/02 1000 | 300 | VMP-6 | 91 | 0.65 | 0.00 | 0.65 |
| 5/21/02 1000 | 15 | VMP-7 | 91 | 3.80 | 0.00 | 3.80 |
| 5/21/02 1000 | 45 | VMP-8 | 90.5 | 2.80 | 0.00 | 2.80 |

## 5.2. Changes in Site-Wide Contaminant Concentrations

Typically, at sites contaminated with fuel hydrocarbons (i.e., gasoline), initial TVH vapor concentrations will be very high (greater than 10,000 ppmv), while $O_2$ and $CO_2$ levels will tend to exhibit low or depleted $O_2$ and elevated $CO_2$ levels,

### 5.2.1. Monitoring Progress

To properly evaluate both the progress of the remedial action and the performance of the remedial system, "baseline" measurements of *in situ* soil gas chemistry (i.e., TVH, $O_2$, and $CO_2$) should be collected from multiple locations and depths across the site before remedial action begins. Then as remediation progresses, these same parameters should be periodically monitored at the same locations and depths and the results compared with the previous measurements.

### 5.2.2. Initial and Final Soil Gas Concentrations

As part of the IRA activities, initial (baseline) and final soil gas concentrations at the VEW and various VMPs across the site were compared. The results indicatboth increases and decreases in soil gas TVH, $O_2$ and $CO_2$ concentrations over the IRA study period. According to sampling results from previous investigations, the “source area” covers an area much larger than that influenced from the single VEW (VW-9) used during the IRA. The increases and decreases in soil gas concentrations resulted primarily from (1) an increasing ROI over time, and (2) the numerous PV exchanges that occurred within the study area over the IRA period.

The laboratory results showed an overall decrease of 40.3 percent (from 62,000 to 37,000 ppmv) in the extracted TVH vapor concentrations at the VEW during the IRA. During the same period, extracted $O_2$ and $CO_2$ levels at the VEW increased by 141 percent and decreased by 18.4 percent, respectively. Table 5-3 shows the results between initial and final soil gas concentrations for $O_2$, $CO_2$, and TVH and the percent change for each parameter over the IRA period.

**Table 5-3 - Initial and Final Soil Gas Concentrations**

| Date/ Time | Location | Sampling Depth (feet) | Oxygen (percent) | Carbon Dioxide (percent) | Horiba TVH (ppmV) | Laboratory TVH (ppmV) |
|---|---|---|---|---|---|---|
| 8/30/01 1600 | VEW (VW-9) | 69.5 - 89.5 | 4.80 | 7.13 | 73,800 | Not Sampled |
| 9/13/01 1030 | VEW (VW-9) | 69.5 - 89.5 | 5.30 | 7.35 | 59,760 | 58,000 |
| 10/3/01 1115 | VEW (VW-9) | 69.5 - 89.5 | 6.10 | 6.82 | 70,200 | Not Sampled |
| 10/25/01 1430 | VEW (VW-9) | 69.5 - 89.5 | 6.30 | 6.25 | 61,200 | 60,000 |
| 11/8/01 0900 | VEW (VW-9) | 69.5 - 89.5 | 7.60 | 6.55 | 73,800 | 62,000 |
| 11/21/01 0900 | VEW (VW-9) | 69.5 - 89.5 | 7.90 | 6.53 | 70,020 | 51,000 |
| 12/5/01 1300 | VEW (VW-9) | 69.5 - 89.5 | 12.50 | 4.42 | 40,320 | Not Sampled |
| 12/13/01 1030 | VEW (VW-9) | 69.5 - 89.5 | 9.20 | 6.18 | 70,560 | 48,000 |
| 1/9/02 1530 | VEW (VW-9) | 69.5 - 89.5 | 9.00 | 5.60 | 60,660 | 47,000 |
| 1/29/02 1230 | VEW (VW-9) | 69.5 - 89.5 | 10.10 | 6.32 | 75,600 | Not Sampled |
| 2/26/02 1330 | VEW (VW-9) | 69.5 - 89.5 | 11.30 | 5.00 | 53,100 | 46,000 |
| 3/19/02 1100 | VEW (VW-9) | 69.5 - 89.5 | 11.40 | 5.20 | 52,200 | Not Sampled |
| 4/24/02 1000 | VEW (VW-9) | 69.5 - 89.5 | 10.50 | 6.16 | 47,600 | 39,000 |
| 5/21/02 0750 | VEW (VW-9) | 69.5 - 89.5 | 11.56 | 5.82 | 42,480 | 37,000 |
| **Percent Change** | **VEW (VW-9)** | **69.5 - 89.5** | **(+)141%** | **(-)18.4%** | **(-)42.4%** | **(-)36.2%** |
| 8/13/01 0710 | VMP-1 | 72 | 4.50 | 7.42 | 68,400 | Not Sampled |
| 5/22/02 1110 | VMP-1 | 72 | 15.16 | 2.90 | 53,640 | Not Sampled |
| **Percent Change** | **VMP-1** | **72** | **(+)337%** | **(-)60.9%** | **(-)21.6%** | **Not Sampled** |
| 8/13/01 0735 | VMP-1 | 80.5 | 3.90 | 7.50 | 72,000 | Not Sampled |
| 5/22/02 1125 | VMP-1 | 80.5 | 13.12 | 4.25 | 58,500 | Not Sampled |
| **Percent Change** | **VMP-1** | **80.5** | **(+)236%** | **(-)39.7%** | **(-)18.8%** | **Not Sampled** |
| 8/13/01 0755 | VMP-1 | 90 | 3.60 | 7.10 | 85,500 | Not Sampled |
| 5/22/02 0755 | VMP-1 | 90 | 10.20 | 6.14 | 72,000 | Not Sampled |
| **Percent Change** | **VMP-1** | **90** | **(+)183%** | **(-)13.5%** | **(-)15.8%** | **Not Sampled** |

**Table 5-3 - Initial and Final Soil Gas Concentrations (continued)**

| Date/ Time | Location | Sampling Depth (feet) | Oxygen (percent) | Carbon Dioxide (percent) | Horiba TVH (ppmV) | Laboratory TVH (ppmV) |
|---|---|---|---|---|---|---|
| 8/13/01 0820 | VMP-3 | 71 | 2.40 | 9.13 | 63,000 | Not Sampled |
| 5/22/02 1022 | VMP-3 | 71 | 16.00 | 2.94 | 45,180 | Not Sampled |
| **Percent Change** | **VMP-3** | **71** | **(+)567%** | **(-)67.8%** | **(-)28.3%** | **Not Sampled** |
| 8/13/01 0840 | VMP-3 | 80 | 2.20 | 8.62 | 68,400 | Not Sampled |
| 5/22/02 1035 | VMP-3 | 80 | 14.20 | 3.60 | 54,360 | Not Sampled |
| **Percent Change** | **VMP-3** | **80** | **(+)545%** | **(-)58.2%** | **(-)20.5%** | **Not Sampled** |
| 8/13/01 0855 | VMP-3 | 88 | 2.30 | 7.50 | 83,160 | Not Sampled |
| 5/22/02 1051 | VMP-3 | 88 | 11.08 | 5.60 | 69,840 | Not Sampled |
| **Percent Change** | **VMP-3** | **88** | **(+)382%** | **(-)25.3%** | **(-)16.0%** | **Not Sampled** |
| 8/13/01 0915 | VMP-4 | 71.5 | 3.20 | 9.25 | 60,300 | Not Sampled |
| 5/22/02 0917 | VMP-4 | 71.5 | 14.64 | 3.56 | 52,200 | Not Sampled |
| **Percent Change** | **VMP-4** | **71.5** | **(+)358%** | **(-)61.5%** | **(-)13.4%** | **Not Sampled** |
| 8/13/01 0935 | VMP-4 | 80 | 3.40 | 8.14 | 62,100 | Not Sampled |
| 5/22/02 0939 | VMP-4 | 80 | 13.68 | 4.04 | 58,680 | Not Sampled |
| **Percent Change** | **VMP-4** | **80** | **(+)302%** | **(-)50.4%** | **(-)5.5%** | **Not Sampled** |
| 8/13/01 0955 | VMP-4 | 90 | 3.00 | 7.46 | 77,400 | Not Sampled |
| 5/22/02 0956 | VMP-4 | 90 | 10.54 | 5.82 | 76,140 | Not Sampled |
| **Percent Change** | **VMP-4** | **90** | **(+)251%** | **(-)22.0%** | **(-)1.6%** | **Not Sampled** |
| 8/13/01 1035 | VMP-5 | 71.5 | 5.50 | 9.50 | 33,030 | Not Sampled |
| 5/22/02 0840 | VMP-5 | 71.5 | 13.74 | 7.56 | 1,335 | Not Sampled |
| **Percent Change** | **VMP-5** | **71.5** | **(+)150%** | **(-)20.4%** | **(-)96.0%** | **Not Sampled** |
| 8/13/01 1100 | VMP-5 | 80 | 4.70 | 9.55 | 38,700 | Not Sampled |
| 5/22/02 0851 | VMP-5 | 80 | 11.12 | 9.88 | 2,370 | Not Sampled |
| **Percent Change** | **VMP-5** | **80** | **(+)137%** | **(+)3.5%** | **(-)93.9%** | **Not Sampled** |

**Table 5-3 - Initial and Final Soil Gas Concentrations (continued)**

| Date/ Time | Location | Sampling Depth (feet) | Oxygen (percent) | Carbon Dioxide (percent) | Horiba TVH (ppmV) | Laboratory TVH (ppmV) |
|---|---|---|---|---|---|---|
| 8/13/01 1110 | VMP-5 | 91 | 4.30 | 9.33 | 42,300 | Not Sampled |
| 5/22/02 0900 | VMP-5 | 91 | 9.42 | 11.26 | 3,450 | Not Sampled |
| **Percent Change** | **VMP-5** | **91** | **(+)119%** | **(+)20.7%** | **(-)91.8%** | **Not Sampled** |
| 8/13/01 1135 | VMP-6 | 71.5 | 6.00 | 11.43 | 12,600 | Not Sampled |
| 5/22/02 0810 | VMP-6 | 71.5 | 11.42 | 9.60 | 4,260 | Not Sampled |
| **Percent Change** | **VMP-6** | **71.5** | **(+)90.3%** | **(-)16.0%** | **(-)66.2%** | **Not Sampled** |
| 8/13/01 1155 | VMP-6 | 81 | 5.50 | 11.82 | 13,500 | Not Sampled |
| 5/22/02 0820 | VMP-6 | 81 | 10.10 | 11.00 | 4,680 | Not Sampled |
| **Percent Change** | **VMP-6** | **81** | **(+)83.6%** | **(-)6.9%** | **(-)65.3%** | **Not Sampled** |
| 8/13/01 1205 | VMP-6 | 91 | 4.10 | 12.85 | 14,400 | Not Sampled |
| 5/22/02 0830 | VMP-6 | 91 | 6.88 | 13.68 | 3,900 | Not Sampled |
| **Percent Change** | **VMP-6** | **91** | **(+)67.8%** | **(+)6.5%** | **(-)73.0%** | **Not Sampled** |
| 8/13/01 1230 | VMP-7 | 30.5 | 18.40 | 2.40 | 2,230 | Not Sampled |
| 5/22/02 1203 | VMP-7 | 30.5 | 20.30 | 0.36 | 229 | Not Sampled |
| **Percent Change** | **VMP-7** | **30.5** | **(+)10.3%** | **(-)85.0%** | **(-)89.7%** | **Not Sampled** |
| 8/13/2001 240 | VMP-7 | 72 | 6.00 | 7.87 | 48,600 | Not Sampled |
| 5/22/02 1208 | VMP-7 | 72 | 17.46 | 3.70 | 3,890 | Not Sampled |
| **Percent Change** | **VMP-7** | **72** | **(+)191%** | **(-)53.0%** | **(-)92.0%** | **Not Sampled** |
| 8/13/01 1255 | VMP-7 | 81 | 5.40 | 7.50 | 52,200 | Not Sampled |
| 5/22/02 1217 | VMP-7 | 81 | 17.24 | 3.94 | 4,860 | Not Sampled |
| **Percent Change** | **VMP-7** | **81** | **(+)219%** | **(-)47.5%** | **(-)90.7%** | **Not Sampled** |
| 8/13/01 1315 | VMP-7 | 91 | 3.80 | 6.85 | 66,600 | Not Sampled |
| 5/22/02 1232 | VMP-7 | 91 | 15.04 | 5.62 | 11,760 | Not Sampled |
| **Percent Change** | **VMP-7** | **91** | **(+)296%** | **(+)18.0%** | **(-)82.3%** | **Not Sampled** |

**Table 5-3 - Initial and Final Soil Gas Concentrations (continued)**

| Date/ Time | Location | Sampling Depth (feet) | Oxygen (percent) | Carbon Dioxide (percent) | Horiba TVH (ppmV) | Laboratory TVH (ppmV) |
|---|---|---|---|---|---|---|
| 8/13/01 1330 | VMP-8 | 30 | 18.40 | 1.95 | 1,870 | Not Sampled |
| 5/22/02 1248 | VMP-8 | 30 | 20.20 | 0.44 | 105 | Not Sampled |
| **Percent Change** | **VMP-8** | **30** | **(+)9.8%** | **(-)77.4%** | **(-)94.4%** | **Not Sampled** |
| 8/13/01 1350 | VMP-8 | 70.5 | 5.90 | 7.40 | 43,200 | Not Sampled |
| 5/22/02 1255 | VMP-8 | 70.5 | 17.04 | 3.90 | 4,260 | Not Sampled |
| **Percent Change** | **VMP-8** | **70.5** | **(+)189%** | **(-)47.3%** | **(-)90.1%** | **Not Sampled** |
| 8/13/01 1410 | VMP-8 | 81 | 5.30 | 7.70 | 46,800 | Not Sampled |
| 5/22/02 1305 | VMP-8 | 81 | 17.04 | 4.10 | 5,040 | Not Sampled |
| **Percent Change** | **VMP-8** | **81** | **(+)222%** | **(-)46.8%** | **(-)89.2%** | **Not Sampled** |
| 8/13/01 1420 | VMP-8 | 90.5 | 4.00 | 7.20 | 66,600 | Not Sampled |
| 5/22/02 1315 | VMP-8 | 90.5 | 15.54 | 5.24 | 7,980 | Not Sampled |
| **Percent Change** | **VMP-8** | **90.5** | **(+)289%** | **(-)27.2%** | **(-)88.0%** | **Not Sampled** |

# 6. CONCLUSIONS AND RECOMMENDATIONS

On the bases of RSI's understanding of the extent of soil contamination at the site and results from the ICE SVE pilot test and IRA treatability study, the following conclusions and recommendations are provided.

## 6.1. ICE Technology Performance

The ICE SVE system used during this pilot test proved to be a reliable and effective vapor treatment technology. The DREs observed during the IRA study ranged from 98.93 to 99.96 percent destruction of the extracted TVH vapors, averaging 99.58 percent. Based on the total operating hours possible during the IRA period (excluding the air permit approval process and excessive condensate collection that resulted in system downtime), the overall operating time (based on continuous 24/7 operation) for the ICE unit was approximately 95 and 84 percent for engines 1 and 2, respectively. The average system (both engines combined) operating time of approximately 90 percent also included downtime (every two weeks) to conduct routine engine maintenance.

Results from the vacuum response and from initial and final *in situ* soil gas testing indicated an effective ROI of approximately 150 feet from the VEW within the source area (soils containing residual fuel contamination) and up to 300 feet in areas where only vapor-phase contamination exists. As TVH concentrations decrease, an increase in oxygen and decrease in carbon dioxide levels will also occur. These changes in soil gas chemistry will allow for greater ICE extraction flow rates over time, which could provide an increase from the current rate of approximately 41 scfm to around 100 to 120 scfm. As extraction flow rates increase, the effective ROI and the PV exchange rate will also increase.

The TVH mass removal rates observed during the IRA ranged from 508 to 647 lb/day, averaging approximately 595 lb/day (or approximately 297.5 lb/day per engine). An overall total of approximately 119,595 pounds of TVH (or approximately 19,932 gallons, assuming 6 lb/gallon for gasoline) was removed and treated using the ICE system.

### 6.2. Full-Scale Remedial Action Recommendation

The results of the IRA indicate that, the vadose zone (unsaturated) "source area" soil contamination extends beyond the IRA study area. In order to effectively treat the remaining area with soil contamination above the "human health risk screening levels"), a minimum of 2 additional VEWs and up to 10 additional multi-interval VMPs are recommended. On the basis of the information provided from previous investigations, the locations for the additional VEWs would be to the southeast and southwest of the existing VEW (VW-9). The additional VMPs should be located at approximately 100, 150 and 200 feet from each of the VEWs. Using a 150-foot ROI (within the source area), the three VEWs (one existing and two proposed) should be spaced between 250 and 300 feet apart (in a triangular fashion) to provide sufficient coverage and overlap of the ROIs (typically, 10 to 20 percent). Figure 6-1 shows the recommended locations of the proposed VEWs and VMPs as part of the full-scale design. Figures 6-2 and 6-3 illustrate the approximate ROI coverage areas of the proposed full-scale design at 150 and 300 feet, respectively.

The assumptions used to make these recommendations were based on the site-specific IRA results, which may or may not extend into the proposed areas. Variations in soil gas chemistry and subsurface geology within the proposed locations could affect the ROI, number of additional wells needed and optimal well spacing. The dual-engine ICE system used during the IRA operated at a maximum TVH mass removal rate throughout the study period. On the basis of the overall TVH concentration reductions measured at the VEW and VMPs during the IRA, the current dual-engine ICE unit could probably operate at the existing VEW (VW-9) an additional year (assuming 24/7 operation) with little or no supplemental fuel requirement. Then, following the first year, the ICE system could probably continue to operate cost-effectively [using less than 50 percent supplemental fuel (i.e. propane)], for up to 2 additional years at the same location.

If the remaining area contains similar TVH concentrations and mass as those within the IRA study area, up to two additional dual-engine ICE systems would be needed to significantly reduce (up to 80 percent or greater) the remaining fuel contamination at this site over the next 4 to 5 years. If vadose zone remediation at this site could be extended beyond 5 years, then perhaps only one additional dual-engine ICE system might be required. However, attempting to estimate a cleanup time frame at a site with less than a full-scale design [i.e. 2 vs. 3 dual-engine systems (total) to cover the entire source area] is not realistic at this time.

For example, one proposed remedial action approach may be to use only one or two ICE systems (instead of three) to treat the source area. This approach could be accomplished by mobilizing the unit(s) from one extraction well to another for a period of time, or by alternating the extracted well flow between VEWs using individual hose/manifold piping to each VEW from a central ICE location(s) on the site.

Using this scenario (2 vs. 3 systems), due primarily to the overall reduction in TVH mass removed per day, the cleanup time frame would obviously be extended. Additionally, a subsurface soil gas “rebound” effect (increased TVH and $CO_2$, and decreased $O_2$) would occur once the system/well flow is removed from a given well location. Upon return to this location (weeks or months later), the ICE unit would need to overcome the negative impact caused by the downtime (i.e., rebound period). The “rebound period” causes changes in the soil gas chemistry (due to the oxygen utilization of indigenous bacteria and volatilization of residual fuel hydrocarbons), which temporarily impacts the ICE system’s process capacity (i.e., reduced well flow rates and ROI) due to the changes in TVH, $O_2$, and $CO_2$ concentrations. The temporary impact could take weeks to recover (depending on the PV exchange rate), before the system reached its previously established “steady-state” well flow rate and maximum effective ROI. On the basis of these and other site uncertainties, the most reliable method to reasonably estimate a cleanup time frame by using the recommended full-scale system design and implementation.

Any combination of dual-engine ICE SVE units (properly installed and operated), whether 1, 2, or 3 systems, would eventually clean up the site. RSI understands that the timetable set will determine the relative “level of effort” with respect to the full-scale remedial approach for this site. Once an approved cleanup schedule/time frame is determined, RSI could then recommend the “best fit” approach (i.e., number of systems necessary) for the site in order to meet that schedule.

On the basis of extensive studies by the U.S. Air Force Center for Environmental Excellence (AFCEE), Technology Transfer Division, at sites impacted with fuel (petroleum) hydrocarbon contamination, the ICE SVE technology is the most cost-effective remedial alternative when influent TVH vapor concentrations are above 5,000 to 10,000 ppmv (AFCEE,1998). The AFCEE study was conducted over several years at numerous sites throughout the United States. The study also compared the ICE technology to other more traditional technologies, such as thermal and catalytic oxidation.

Overall, based on RSI’s extensive experience with a variety of SVE and other remedial technologies, the ICE SVE technology is recommended as the most cost-effective and efficient method of remediating the vadose zone (unsaturated) soils.

## 7. LIMITATIONS

The environmental services described in this report have been conducted in general accordance with current regulatory guidelines and the standard-of-care exercised by other environmental professionals performing similar work. No other warranty, expressed or implied, is made regarding the professional opinions presented in this report. Variations in site conditions not observed or described in this report may be encountered during subsequent activities.

This document is intended to be used only in its entirety. No portion of the document, by itself, is designed to completely represent any aspect of the project described herein. RSI should be contacted if the reader requires any additional information, or has questions regarding content, interpretations presented, or completeness of this document.

RSI's opinions and recommendations regarding the environmental conditions, as presented in this report, are based on limited subsurface assessment and chemical analysis. The samples collected and used for testing, and the observations made, are believed to be representative of the area evaluated. Variations in soil conditions will exist beyond the points used in this evaluation.

The environmental interpretations and opinions contained in this report are based on the results of both field sampling and laboratory analyses intended to detect the presence and concentration of specific chemical constituents from the subject site. The laboratory testing and analyses have been conducted by an independent laboratory approved by the State of Arizona to conduct such tests. RSI's conclusions, recommendations, and opinions are based on an analysis of the observed site conditions. It should be understood that the conditions of the site could change with time as a result of natural processes or activities of man. In addition, changes to the applicable laws, regulations, codes, and standards of practice may occur due to government action or a broadening of knowledge. The findings of this report may, therefore, be invalidated over time, in part or in whole, by changes over which RSI has no control.

This report is intended exclusively for use by the client. Any use or reuse of the findings, conclusions, and/or recommendations of this report by parties other than the client is undertaken at said parties' sole risk.

## 8. REFERENCES

AFCEE, 1998. "Comprehensive Technical Report for the Evaluation of Soil Vapor Extraction and Treatment Using Internal Combustion Engine Technology," Including: Bolling, Davis-Monthan, Luke, and Williams Air Force Bases. July.

**TABLE OF CONTENTS**

## TABLE OF CONTENTS (CONTINUED)

**Tables**



**Figures**



**Appendicies**

# APPENDIX A

# ICE SVE FIELD DATA

# APPENDIX B

# LABORATORY ANALYTICAL RESULTS