Final Report: In Situ Radio Frequency Heating Demonstration (U)

Westinghouse Savannah River Company
Savannah River Site
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Executive Summary

A field demonstration of in situ radio frequency heating was performed at the Savannah River Site (SRS) as part of the U.S. Department of Energy-Office of Technology Development's Integrated Demonstration. The objective of the demonstration was to investigate the effectiveness of in situ radio frequency (RF) heating as an enhancement to vacuum extraction of residual solvents (primarily trichloroethylene and perchloroethylene) held in vadose zone clay deposits. Conventional soil vacuum extraction techniques are mass transfer limited because of the low permeabilities of the clays. By selectively heating the clays to temperatures at or above 100°C, the release or transport of the solvent vapors will be enhanced as a result of several factors including an increase in the contaminant vapor pressure and diffusivity and an increase in the effective permeability of the formation with the release of water vapor. The demonstration team included participants from the Westinghouse Savannah River Technology Center (SRTC), the Westinghouse Science and Technology Center (Pittsburgh, PA), and KAI Technologies, Inc., the developers and operators of the patented borehole applicator.

The in situ heating demonstration integrated RF applicator technology and vacuum extraction from a single, horizontal well. The horizontal well was drilled through a shallow contaminated, subsurface clay layer at a depth of approximately 40 feet and was continuously screened over a 300-foot horizontal section. The applicator, approximately 17 feet long, operated at a maximum power output of 25 kW and a frequency of 13.56 MHz. The applicator was inserted to a location approximately 100 feet from the start of the screened zone to heat one section of the well. The vacuum extraction system consisted of a rotary lobe blower capable of providing a flow of approximately 150 cfm at 6 inches Hg vacuum. Offgases drawn from the well were destroyed with a skid-mounted, thermal-catalytic oxidation system. Several vertical boreholes were placed both in and adjacent to the expected heated zone and in a "cold" control zone to monitor temperatures, pressures, and soil gas concentrations.

The original test plan for the demonstration called for a cold pump test to establish a baseline removal rate, followed by three to four weeks of heating, and an approxi-

mately equal time span to monitor the cooldown period with continuous vacuum extraction. Offgas monitoring was used as the primary measure for confirmation of enhanced release of the solvents.

The heating stage of the test was conducted over a 34-day period with approximately 27 days of operation. Offgas concentrations from the well rose steadily during the initial stage (first 15 days) to levels ranging from 150 to 200 ppmv of perchloroethylene and from 20 to 30 ppmv of trichloroethylene. These levels were sustained over the latter half of the heating stage and appeared to correlate directly with periods of applicator power output. The maximum soil temperature at approximately 6 feet from the center of the applicator reached 63°C from an initial ambient temperature slightly below 20°C. The RF power output was controlled using commercial fiber optic temperature sensors located on the applicator and at the screen wall. The control temperatures ranged from 100 to 130°C. Power output was cycled to maintain temperatures within these control values established by the limitations of the well casing material (fiberglass reinforced epoxy). The maximum RF output per cycle ranged from 10 to 25 kW.

The radio frequency energy was coupled efficiently to the targeted clay layer from a horizontal borehole. The single RF applicator delivered over 95% of its available power to the surrounding contaminated clayey sediments. The applicator was tuned to the clay environment to present a voltage standing wave ratio of 1.75 at its underground feed point and further tuned at the surface to present a ratio of 1.05 to the generator. The entire RF system (RF generator to applicator output) was estimated to operate with an 80% delivered energy efficiency to the clay. Excellent impedance matching existed throughout the heating test illustrating the effectiveness of pretest studies conducted to determine the dielectric properties of the targeted sediments and modeling studies conducted to design the applicator. During the demonstration period, approximately 11,000 kilowatt-hours of RF energy were successfully coupled to the subsurface sediments and heated a soil volume of nearly 1500 cubic feet to temperatures greater than 60°C. The total volume heated to temperatures above ambient (approximately 20°C) was calculated at nearly 30,000 cubic feet. The radio frequency electric field detected at the surface was more than two orders of magnitude below the established threshold limit values and posed no hazard to operating personnel.

The original test plan was modified as a result of several findings and unexpected behavior of the integrated system encountered during the initial stages of the demonstration. These findings included well flooding from residual water or near saturated conditions near the screen and low vapor flow. The first problem was compounded by heavy rainfall encountered during the first half of the test period. Rates of water removal, performed with an air lift pump adapted to operate in a horizontal well alongside the RF transmission line, typically ranged from 5 to 10 gallons per day. During the first half of the test, the second problem, low vapor flow, was a direct result of the low permeability and high water content of the clay formation and negated attempts at establishing an ambient temperature baseline release rate. During the later stage of the heating period, the low flow was a direct effect of the single well design. A high pressure zone, or vapor lock, was created at the applicator when temperatures in this region approached and exceeded 100°C. This effect drastically reduced the zone of influence of the well vacuum on the formation and, consequently, the extraction rate of contaminants. Typical vapor flow rates varied from 5 to 15 scfm during heating and from 20 to 35 scfm during cooldown.

Over 170 kilograms of chlorinated solvents were successfully extracted from the sediments over the course of the demonstration. The thermal catalytic oxidation system destroyed the contaminants with an efficiency ranging from 80 to 95%. All discharges to the environment were well within the permissible guidelines required by the state of South Carolina.

Due to the problems encountered with the integration of RF heating using a borehole applicator combined with vacuum extraction from a single horizontal well, the results of the demonstration did not provide enough data to adequately assess the feasibility of applying the technology for thermally enhanced remediation of contaminated clays in the unsaturated zone. The demonstration provided a greater understanding of the important component and system designs, the critical operating parameters, and the essential site characterization requirements for in situ RF heating applications. The results and insights from this demonstration have also led to selecting specific solutions to address the problems encountered. The primary limitations resulted from the use of a relatively long, single horizontal well design screened within a low-permeable clay formation. A horizontal borehole application is advantageous for vadose zone remediation as the applicator can be moved through the well heating a progressively larger volume of the contaminated tabular clays. However, such an application must consider the proper choice of well completion materials that are compatible with the installation technique, RF electric fields, and the expected high temperatures. In addition, independent vertical extraction wells should be used and located within and in the perimeter of the expected heated zone to ensure adequate containment and sufficient extraction rates of both the solvent and water vapor generated by heating.

1.0 Introduction

1.1 Program Description

1.1.1 Background

As part of the Integrated Demonstration of in situ remediation technologies at the Savannah River Site (SRS), a demonstration was performed to investigate in situ radio frequency (RF) heating as a means of enhancing ambient vacuum extraction of volatile organic compounds from vadose zone clay deposits. The demonstration employed a single collinear-loaded-dipole RF applicator designed for borehole applications. The demonstration team included participants from Westinghouse Savannah River Technology Center (SRTC), Westinghouse Science and Technology Center (Pittsburgh, PA), and KAI Technologies, Inc., the developers of the borehole applicator.

The final processing system for this demonstration integrated four technologies:

- soil vacuum extraction (SVE)
- radio frequency heating
- horizontal well drilling
- thermal/catalytic treatment of offgases.

The demonstration area was a shallow clay layer (kaolinite) contaminated with chlorinated volatile organic compounds (CVOCs, primarily perchloroethylene [PCE] and trichloroethylene [TCE]). The clay layer is adjacent to an excavated leaky process sewer line that ran between the M-Area metal fabrication facility and its Resource Conservation and Recovery Act (RCRA) - closed seepage basin (see Figure 1-1). A more detailed description of the targeted site and its history is available in the field test plan for the SRS In Situ Radio Frequency Heating Demonstration (WSRC-RP-92-1428). Previous studies at the site (Eddy et al. 1991) show that a large fraction of the solvents that were released to the subsurface are held above the water table within these clay layers. Slow release of the residual solvents provides a long-term source of groundwater contamination. Because of the low permeabilities of the clays, conventional (ambient temperature) soil vacuum extraction techniques are mass transfer limited. By selectively heating the clays to temperatures at or above 100°C, the release and transport of PCE and TCE should be enhanced as a result of several factors:

- an increase in the solvent vapor pressures and diffusivities

- an increase in the sediment's effective permeability with the release of water vapor and residual solvent
- favorable shifts in liquid-solid and gas-solid adsorption equilibria
- enhanced removal from steam stripping by water vapor generated in situ.

Radio frequency energy heats the soils through a dielectric heating mechanism in which the applied electromagnetic field physically distorts the atomic or molecular structure of the material. The physical distortion is transferred into mechanical and then thermal energy. Pretest studies conducted to measure the dielectric properties of the sediments (Snyder, Harold, and Kasevich 1993) showed that the clays, because of higher water content, will preferentially capture the RF energy, focusing the applied power precisely in the zones that need to be heated. For this test, selecting the KAI RF applicator technology over competing heating techniques was driven by three issues:

- Because of its ability to penetrate and couple with the soil, RF heating is faster than conductive (e.g., ohmic or joule heating) heating mechanisms and does not require a continuous conductive path from the source to the targeted zone. Convective heating mechanisms (e.g., the injection of hot air or steam) are not considered effective because of the low permeability of the clays.
- Because the RF energy from the KAI applicator can be focused to the clays, its overall energy efficiency is higher than other RF designs.
- Because the KAI collinear applicator is compatible with horizontal well applications, its use results in an efficient integrated heating process.

1.1.2 Integrated System

The targeted clay-layer is located at a depth approximately 40 feet below the surface and varies in thickness to a maximum of about 10 feet. A horizontal well was drilled through the clay layer and completed with a screened fiberglass casing. Figure 1-2 illustrates the location of the horizontal well with respect to the seepage basin and other significant landmarks in the Integrated Demonstration (ID) site. Integrating the RF borehole applicator and horizontal well drilling technologies was chosen for the following reasons:

- The clay layers are tabular in extent and the horizontal configuration can, therefore, provide better access to and extend its zone of influence over a larger volume of the targeted contaminated sediments for vacuum extraction.

- The horizontal well permits placement of the applicator in a geometry that maximizes coupling the RF fields with the targeted clays.
- A single applicator can be moved through the well progressively heating a larger volume with a single borehole.

The same well was used to heat the formation and extract vapors. The process arrangement depicting the layout and integration of the four technologies is shown in Figure 1-3. Vacuum extraction was accomplished with a rotary lobe blower capable of providing 150 scfm at 6 inches Hg vacuum. Chlorinated solvent vapors were destroyed (to CO₂ and HCl) prior to atmospheric discharge by passing the offgas stream through a ceramic-supported monolith halo-carbon oxidation catalyst. Both the RF and SVE-catalytic oxidation systems were wholly contained portable units capable of being transported to other remediation sites.

1.1.2 Program Plan

Prior to the demonstration, both laboratory and field testing were performed to determine soil treatability (Snyder, Harold, and Kasevich 1993). Surrogates of the targeted sediment were analyzed in the laboratory to determine the dielectric properties as a function of frequency and water content. These properties were used as input to KAI's proprietary computer model that supported applicator design and predicted expected heating rates and temperature contours in the field (Kasevich and Benham 1992). This information was used to set the initial operating parameters of the field test unit. Onsite analyses of the test well were performed prior to heating to verify dielectric properties and to confirm applicator design. These pretest measurements were critical to RF process control and optimization to ensure that the applicator impedance is matched to the impedance of the soil load, which varies as a function of moisture, temperature, and, therefore, heating time.

The field demonstration was conducted in three stages chosen to adequately assess changes in vacuum extraction rates that could be attributed to RF heating (the listed time frames were those originally proposed):

1. Ambient temperature vacuum extraction (two weeks), conducted to establish a baseline removal rate
2. RF heating application (three to four weeks), conducted with continued vacuum extraction to heat one zone of the screened section of the horizontal well.
3. Cooldown with continued vacuum extraction (three to four weeks), conducted to monitor changes occurring as the subsurface temperatures return to ambient.

The primary variable monitored to determine the effects of RF heating was the CVOC concentration in the offgas, which was sampled several times daily to track the changes in extraction rates over time. In addition, several boreholes were placed within and surrounding the anticipated heated zone and within a "cold" control zone and completed with monitoring equipment to track changes in subsurface temperatures, pressures, and soil-gas concentrations. To supplement field monitoring, pretest and post-test characterization was performed on core samples to measure changes in the CVOC and water content. A detailed description of the characterization techniques and results can be found in Eddy-Dilek et al. (1993).

1.2 Program Participants, Relationships, and Organization

This program was a cooperative effort between the Environmental Sciences Section (ESS) of Savannah River Technology Center (SRTC) - Westinghouse Savannah River Company (WSRC), the Environmental Technologies Department of the Westinghouse Science and Technology Center (STC), and KAI Technologies of Woburn, MA. The overall organizational structure at the demonstration initiation is shown in Figure 1-4. The program was co-managed by Mr. T. L. Walton of SRTC and Dr. T. S. Snyder of STC. Mr. Walton managed the demonstration site preparation that included: horizontal well drilling, lining, and finishing; field temperature and pressure monitoring well drilling and fitting; offgas treatment system procurement and well interfacing; and analytical services. Dr. Snyder managed soil treatability testing and RF services and interfaces. KAI Technologies (Mr. R.S. Kasevich, President) supplied the RF hardware and operational services under subcontract to STC via partial order transfer to the Westinghouse Environmental Services Business Unit (ESBU).

Field operations were conducted by a cooperative effort between Mr. T. R. Jarosch of SRTC, Mr. R. J. Beleski of STC, and Mr. D. L. Faust of Eyring Corporation (subcontracted to KAI for RF equipment operations). Mr. Jarosch coordinated all non-RF site preparation, mobilization, and operational activities and was the field team leader. Mr. Faust coordinated the RF equipment mobilization and managed its operation. Mr. Beleski coordinated all SRS-

KAI interfaces and provided direct assistance with mobilization and operational activities of both SRS and KAI hardware.

1.3 Program Objectives

The four primary objectives and criteria for determining the success of this demonstration are summarized below:

- **Simple installation, start up, and trouble free operation of the integrated system.** It was important to demonstrate that the RF applicator technology provides controlled and efficient heating for the types and stratigraphy of sediments at SRS (i.e., interbedded clay and sand layers) and is compatible with use of a horizontal well drilled to target the contaminated lenses.
- **Accelerated volatilization of TCE and PCE from the contaminated soil.** The primary purpose for the addition of heat to the contaminated zones was to increase the volatilization rate significantly over that experienced with simple vapor extraction.
- **Reduced cost over comparable technologies.** It was important to demonstrate that the normalized cost of the RF-accelerated vapor extraction is competitive with alternative remediation technologies. Our goal was to demonstrate the cost savings from the projected reduced remediation time will, as a minimum, compensate for the added cost of the RF capital and operating costs.
- **Conformance of field performance with treatability studies and computer predictive modeling.** Confirmation of the ability to accurately assess soil treatability and model performance prior to equipment mobilization is essential for accurately scaling the process and determining costs prior to investment. The results of the actual field demonstration will be used to refine the treatability regimen and modeling codes.

Figure I-1. Savannah River Site Integrated Demonstration Project Area Location Map

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Figure 1-2. Horizontal Well Location at the SRS Integrated Demonstration Site

Figure 1-3. Schematic Diagram of RF-Enhanced Vacuum Extraction Process

Figure I-4. Project Organization for In Situ Radio Frequency Heating Demonstration

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2.0 Conclusions

2.1 General Summary

The performance of the individual components brought together for the in situ radio frequency (RF) heating demonstration all met or exceeded expectations. However, the integrated system (defined as the overall design incorporating the combination of vacuum extraction operations with the RF borehole applicator in a single horizontal well) did not perform optimally to result in definitive conclusions regarding the feasibility of RF as an in situ heating source for thermal enhanced remediation. Several problems encountered in the field were solved successfully while others were too difficult to approach or change in a short demonstration of this nature. The latter are hurdles that can be readily overcome. Solutions are discussed further in Chapter 3. A brief description of the performance and results with regard to meeting the four primary program objectives is listed below. The remainder of this chapter is a more detailed listing of the performance, results of the individual components, and the operations of the overall integrated design.

1. The difficulties that impacted the installation, start up, and operation of the demonstration were successfully solved or minimized in the field. The RF borehole applicator operated successfully in a horizontal well application delivering greater than 95% of its available power to the surrounding sediment while operating for approximately 500 hours at power outputs above 20 kW. Slightly more than 11 MWH of RF energy were coupled to the sediments over 27 days of operation, heating a volume of approximately 1500 cubic feet to temperatures above 60°C. Hardware modifications to the transmission line design were successfully made and accounted for the added thermal stresses encountered in a horizontal application. In addition, the computer control programs and diagnostic equipment integral to the KAI system were capable of sensing the onset of adverse conditions in the well and could power down the system in an orderly fashion to avoid unnecessary damage and, thereby minimize operating downtimes.
2. A gradual increasing trend of PCE and TCE concentrations in the offgas was observed that correlated to continued input of RF energy. Concentrations rose from levels of a few ppmv to levels ranging from 150 to 200 ppmv of PCE and from 20 to 30 ppmv of TCE. However, two significant factors related to the single well design restricted assigning these effects solely to RF heating:
 - Limited flow from the formation early in the demonstration resulting from the low permeability of the clays and compounded by high saturation levels. This effect negated attempts at obtaining baseline extraction data. A gradual increasing trend in solvent release rates may be characteristic of clays under extended periods of vacuum extraction with natural drying of the formation.
 - Formation of a vapor lock down hole at the applicator from steam generated by the RF energy. Once temperatures at the applicator approached 100°C, there was little or no vacuum in the well at the heated zone.
3. A breakdown of the costs for this demonstration and for a projected commercial operation are given in Chapter 5. The basis for these studies is a cost per hour or day of operation and cost per KW-hour of forward-coupled RF power. As a result of the flow and vacuum effects listed above, the extent of contaminant release from the heated volume under sufficient vacuum extraction could not be determined. In addition, the duty cycle of the applicator was significantly affected by the choice of casing material, thereby reducing the volume heated for a fixed operating period. Therefore, while this demonstration provided useful data on the cost of planning, mobilizing, and operating a remediation project, an accurate determination of the true cost per cubic yard of treated sediments is not available.
4. Pretest studies to measure the dielectric properties of the soil and modeling studies that incorporated these parameters to support the design of the applicator were successful. Excellent impedance matching of the applicator to the surrounding clayey sediments existed throughout the demonstration. However, pretest modeling to predict subsurface temperature contours was unsuccessful in predicting field results. This was due in part to the reduced duty cycle of the applicator required by the temperature limits of the well screen and in part to simplifying assumptions on the effects of water vaporization and mass transport. Improvements to the pretest modeling efforts are discussed further in Chapters 3 and 5.

2.2 Integrated System

While important insights were gained in the operation of the integrated system, the single well design and the site conditions limited the ability to effectively demonstrate field performance. A summary of these issues is presented in the sections that follow.

2.2.1 Single Well Operation

A number of complications were encountered by attempting to combine vacuum extraction with RF heat application in a single, horizontal well. Several of the effects from these complications played critical roles in the ability to meet the demonstration's objectives. The effects associated with the use of a single horizontal well were rooted in causes unique to the demonstration design and more generally, to a single well application, and impacted both vacuum extraction and RF applicator operations. The following is a list of the effects encountered in the demonstration:

- **Low air flow from the formation.** This was the first attempt at placing a vapor extraction well screened within a clay formation of low permeability. Results indicate that the clay formation near the well was close to saturation, further reducing the effective permeability. High saturation levels were due to excess water used in the well installation and completion and to the large rainfall levels in the months just preceding and during the initial stages of field activities. Figure 2-1 displays the daily and cumulative rainfall from January 1, 1993, through May 31, 1993. The low flow (typically less than 20 scfm) significantly impeded the initial cold pump test stage of the demonstration, and, therefore, limited attempts to obtain meaningful baseline data. In addition, it was difficult to determine the primary cause of changes in the zone of influence of the well vacuum and in the contaminant concentrations in the offgas. These changes could have been results induced by heating or by extended vacuum extraction with natural drying of the formation near the well screen.
- **Water infiltration into the well.** Vacuum applied to the well pulled in enough water as the vacuum levels within the well were sufficient to overcome capillary forces within the sediments adjacent to the well screen. This phenomena resulted in the following effects:
 - Blocked flow through the well.* The problems from water infiltration into the well were compounded by the well design. In particular, the low point or "sump" zone of the well was located near the entry point where it transitions from horizontal and rises to the surface. This was the same end of the well where the applicator was inserted and the vacuum extraction system connected. Figure 2-2 shows the

location of the well low point with respect to applicator position and flow direction. A sufficient influx of water occurred over a twenty-four hour period to physically block the well casing (approximately one cubic foot of water will fill 16 feet of casing or screen). Flow restrictions were detected by pressure changes in down hole piezometer tubes. Large pressure surges were observed when infiltration was sufficient to fill the screen, creating a manometer-like water plug. The problem was solved by adapting a commercial air-displacement pump that was modified to operate in a horizontal position (for a further description of the pump adaptations see Chapter 4). The pump was capable of removing water at a rate of 2 gph.

Periodic quenching of the RF applicator. Evidence of water infiltration upstream and surrounding the applicator was observed as rapid temperature depressions of the well screen temperature probe and the RF heating applicator detuning as sensed at the RF power generator. Initially, these events automatically lowered the driving RF power level or, as a protective measure, shut down the RF heating system completely. The system control program was modified to automatically sense the presence of the water and to restart the heating cycle at full power within minutes of the conclusion of the water flow. The net effect of the quenching events was to decrease the effective heating time of the system. The worst case events subtracted as much as 20 minutes of heating time out of a heating hour.

- **Steam formation in the well.** Water converted to steam by the absorption of RF energy created a vapor lock that dramatically reduced flow. This was the most critical effect of the single well design. Figure 2-3 schematically displays this concept. The effect of steam formation is evident by observing how well flow was inversely related to downhole temperatures at the applicator (see Figure 2-4). As the downhole wall temperature approached 100°C, the flow dropped rapidly to approximately one-third the original rate and responded only slightly to successive increases in the applied vacuum. This vapor lock effect was also observed in pressure measurements at the piezometers located at and upstream of the applicator. Vacuum levels decreased to near standard barometric pressure despite increases in the applied vacuum once temperatures at the applicator approached or exceeded 100°C (see Figure 2-5).
- **Logistical complexities.** The entire integrated system, including extraction operations, had to be interrupted to repair damaged or failed equipment in the well (RF application, water removal, or critical instrumentation).

Consequently, vacuum extraction data with the RF power off could not be taken while repairs and modifications were conducted. In addition, the operation and monitoring equipment and instrumentation was crowded, restricting delivery of an optimally sized water pump and complicating applicator insertion and retrieval. Figures 2-6 and 2-7 illustrate crowding at the horizontal well head.

- **RF energy application was controlled to protect the well screen.** The relatively low temperature rating of the fiberglass horizontal well screen (approximately 120°C) set a limit on the application time of the RF energy to the formation. The borehole wall temperature sensor was used to determine if the temperature limit was being approached. When the temperature reached a set point the RF heating system was turned off or shifted to a lower power level until air movement in the borehole cooled the borehole liner to a restart temperature, typically 10 degrees below the set point temperature. The net effect was to lower the average delivered power to the formation from nearly 25 kW to approximately 20 kW.

2.2.2 Vacuum Extraction Rates

As a result of high saturated conditions near the well screen, insufficient baseline extraction data were collected to adequately assess the effectiveness of RF heating on extracting contaminants from clay. The flow and contaminant release characteristics from clays will occur at a significantly slower rate relative to other, more permeable sediments. Figure 2.8 displays the wellhead TCE and PCE concentrations and well wall temperature (used as an indicator of RF "power on" conditions) over the course of the heating stage. There was some evidence that contaminant concentrations from the well showed positive response to RF energy delivery during the heating portion. The effects were evidenced as a gradual increasing trend in contaminant concentrations from the well with continual power output, and rapid, smaller variations in the concentrations that appeared to correlate to RF power on/off cycles. However, there was no conclusive evidence that the gradual trend was solely related to the application of RF heat. Because of insufficient data on CVOC extraction from clays and insufficient ambient extraction baseline data, one cannot rule out that the observed general trend may have simply been the unique release characteristics of clay, independent of heat application. For instance, following each of the first four heating cycles depicted in Figure 2-8, vacuum extraction was halted and the well was opened continuously over periods ranging from one to three days. The coincident rise in offgas concentration with renewed power output from the applicator may be

due in part to transient mass transfer effects characteristic of the clays.

Observations of the change in extraction rates during the cooldown stage illustrate the significance of the loss of vacuum downhole, which occurred with steam formation during the heating stage. An approximate order of magnitude rise in the extraction rates was observed during the cooldown stage of the test. This effect is due largely to the recovery of higher vacuum levels within the well as downhole temperatures dropped. The ability to attain a sufficient vacuum downhole resulted in more than doubling the flow rate. In addition, the higher vacuum levels extended the zone of influence, yielding an approximate eight-fold increase in offgas concentration of perchloroethylene.

2.2.3 Horizontal Well Zone of Influence

The zone of influence of the well vacuum, which is a function of the apparent permeability of the formation, improved significantly in the control zone (MHV 27-29) and in the area of greatest thermal exposure (MHV 24). A condition where an increase in the vacuum influence after heating stopped and the well temperatures began to cool was observed in the "B" and "C" piezometer measurements (screened within and above the clay lens, respectively) of the control zone monitoring wells and of the MHV 24 monitoring well. Figure 2-9, shows the changes in vacuum levels over time for the "C" monitoring wells. Beyond those induced by cyclic barometric changes, little or no effect on the recorded vacuum levels in the piezometers was observed during the initial cold vacuum extraction and heating stage. As a result of the limited zone of influence caused by high saturation levels within the clays, at the start of the test and of the low vacuum in the well from steam formation during heating, it is difficult to ascribe the change to an effect of heating. This conclusion is supported in that the strongest increases in draw-down were observed in the control zone.

Despite the enhanced zone of influence, the absolute drawdowns were small. Drawdowns in the control zone of 4 to 5 inches of water were measured at approximately 14 feet from the well (at vacuum levels of near 70 inches of water in the well). At distances of approximately 30 feet from the well, drawdowns were on the order of two inches.

2.3 Radio Frequency System

2.3.1 Radio Frequency Radiation Coupling to Clayey Sediments

The radio frequency energy was coupled efficiently to the targeted clay layer. The RF applicator delivered over 95%

of its available energy to the surrounding clay. The applicator was connected to the RF generator by a low-loss, 305-ft RF transmission line with a total insertion loss of 0.389 dB (91% efficiency). The applicator was tuned to the clay environment to present a volt-standing wave ratio (VSWR) of 1.75 to the transmission line. This VSWR was further matched to the RF generator through the tuner to present a VSWR of 1.05 to the generator. The entire RF system (generator output to applicator output) was estimated to operate with an 80% delivered energy efficiency to the clayey layer surrounding the applicator. Excellent impedance matching existed throughout the heating test, illustrating the effectiveness of pretest studies conducted to determine the dielectric properties of the targeted sediments and modeling studies conducted to support applicator design.

2.3.2 Temperature Ramp-Up Rates

The measured temperature at MHV-24T ("B") increased at an average rate of 0.1°F/hr. This monitoring point was located in the clay layer @ a distance of approximately 6.25 feet from the center of the applicator slightly above the plane of the horizontal well. The maximum temperature achieved at this location was 146°F (63°C), approximately 80°F above ambient conditions. A temperature rise above ambient was detected a maximum distance of 15 feet from the applicator. Figure 2-10 shows temperatures at the monitoring points where the most significant effects were measured.

2.3.3 Heated Subsurface Volume

The maximum temperatures and the volume of the subsurface heated by the RF field was considerably smaller than predicted with pretest modeling. This result is due in part to the reduced duty cycle of the applicator required by the temperature limits of the well screen and to simplifying assumptions used in the pretest model (Kasevich and Benham 1992) (for further discussion, see Chapter 5). Figure 2-11 is a three-dimensional (3-D) image of the heated zone at the conclusion of the heating stage of the test. An image of the heated zone predicted by the model is given in Figure 2-12. The temperature distribution images were generated from scattered data sets using a commercially available 3-D modeling software package (Interactive Volume Modeling™ [IVM], version 5.0, Dynamic Graphics, Alameda, CA). The scattered data set for the field test was constructed primarily from thermocouple data while the model was generated by rotating a 2-D temperature contour plot around the applicator axis. To remove any bias associated with both the gridding program algorithm and the difference in available data points between the actual field and model data sets, the model fit using only points located nearest the temperature monitoring wells used in

the field. The pretest modeling predicted that a volume of approximately 4000 cubic feet would be heated to temperatures at or above 60°C, assuming a continuous output of 20 kW over a 21-day period (10.08 MWH total energy output). The calculation for the actual test data gives a volume of nearly 1500 cubic feet heated to temperatures in excess of 60°C. The analogous calculation of volumes bounded by higher temperatures near the applicator were not made because the well wall temperature was the only monitoring point within this region. It should be noted that the well wall temperature, which was used in the data sets, underestimates the maximum temperature achieved in the clays adjacent to the well caused by enhanced convective heat transfer losses within the well casing. A more rigorous 3-D/multi-phase, heat and transport model (TOUGH2) is being investigated to improve the accuracy of the predicted performance of both the horizontal well and the RF applicator.

2.3.4 Radio Frequency Surface Fields

The field detected on the surface posed no hazard to personnel. The onsite measurements did not exceed 50 V²/m² at any time. Typical electric field values measured above the heating zone ranged from 0.1 to 5 V²/m², with 0.1 to 0.5 being the most typically recorded values within 1 meter of the soil surface.

The threshold limit values⁴ (TLV) for the 13.56 MHz heating frequency are

$$\begin{aligned} \text{power density} & \quad (\text{mW/cm}^2) = 4.89 \\ \text{electric field strength squared} & \quad (\text{V}^2/\text{m}^2) = 770. \end{aligned}$$

The measured values were low enough that they would not have been measurable on some electromagnetic field meters designed to measure only near hazardous.

2.3.5 Thermal Stresses on Radio Frequency Transmission Line

The thermal expansion and contraction allowances of Industry Standard RF transmission line components were not adequate to compensate for the temperature extremes encountered during the RF heating cycle.

⁴This limit is for 6 minutes of continuous exposure to this specific frequency of non-ionizing radiation. It is calculated from ANSI standard C95.1 and is recognized by OSHA and the American Conference of Government Industrial Hygienists.

The thermal expansion of the transmission line center conductor caused the line to "short" or heavily "load" several times during the early heating cycles. The events were diagnosed with a time domain reflectometer (TDR) and were resolved by physically shortening the copper center conductor of the transmission line.

The thermal contraction of the transmission line also produced "opens" during the cooldown cycles of the system. The "opens" were diagnosed by the TDR in combination with power pulses from the RF generator. In these cases, the center conductor tube cooled more slowly than the center conductor junction anchors that joined the rigid transmission line sections. The difference in radial contraction rates created "perfect" open circuits for several minutes after power was removed from the system. This problem limited the use of low-power diagnostic tests immediately after a heating period was concluded. However, the open circuits proved to be "self healing", and temperatures at these points equilibrated. This problem would also not have allowed the use of typical solid-state RF power generators that would have sensed the "open circuit" and protectively shut down.

2.4 Vacuum Extraction System Thermal Catalytic Destruction Efficiency

The CVOC destruction efficiency in the offgas stream was below expectations. The catalytic oxidation (Catox) system destroyed TCE at an efficiency of greater than 99% and PCE at an efficiency ranging between 80% and 90%. However, total discharges were well within those allowed by the South Carolina Department of Health and Environmental Control (SCDHEC) Air Permit exemption. The destruction performance of PCE degraded over time. The system was designed to destroy 95+% TCE and 90+% PCE at the operating conditions supplied by the vendor. The low destruction efficiency for PCE is not a result of poor catalyst performance, but is believed to stem from bypassing the catalyst block caused by leaks in the ceramic insulation. Figure 2-13 displays the destruction efficiency of PCE over time.

2.5 Temperature Monitoring

2.5.1 Spectrophotometric Fiber Optic Temperature Sensors

Several problems were encountered with the fiber optic probes used as in situ temperature monitors. These sensors, which were developed and patented at SRTC, give highly accurate temperature readings by measuring the

temperature-dependent light absorption of neodymium-doped glass. All of the probes placed in the ground were not inspected before installation. As a result, approximately half of the probes were not useful and several additional probes failed over the course of the demonstration. In addition, the transmission efficiency and quality in the fiber optic lines used at the surface were both light and temperature sensitive. This effect degraded the signal at the spectrophotometer and introduced a large background noise. The effect was minimized by placing the lines within PVC pipe. The remaining probes functioned well during the test. However, the multiplexer and spectrophotometer system were not robust enough to handle the frequent power outages encountered in the field that resulted in shifts in the baseline absorption spectra. Fortunately, no temperature monitoring boreholes were located in a strong enough RF field to adversely affect the measurements with the T-type thermocouples. However, as a result of the loss of the fiber optic probe data, the number of monitoring locations for 3-D gridding of the heated zone was effectively cut in half. The data from the fiber optic probes are currently being analyzed by the SRTC Analytical Development Section that will provide a report on the assessment of the sensors at a later date.

2.5.2 T-Type Thermocouples

The T-type thermocouples operated successfully in parallel with fiber optic temperature probes and provided resolution on the order of $\pm 1^\circ\text{F}$ even in the presence of a significant RF field (at MHV-24T "B" sensor). Measurements with the isotropic electric field probe indicated that the leads did conduct low but measurable levels of RF energy to the soil surface. Even the thermocouple positioned within 6 feet of the applicator was usable throughout the entire heating program. This appears to be due to the perpendicular orientation of the thermocouple wire relative to the axis of the applicator, the use of a non-magnetic T-type thermocouple and the input common mode rejection, and filtering the temperature indication instrument. It is also believed that the use of an isolated AC power source, physically distant from the RF heating system generator, may also have minimized RF interference problems that may have been associated with a common ground system.

2.5.3 Fluorescence Decay Fiber Optic Temperature Sensors

The fluorescence decay sensors were used to monitor the temperature of the borehole wall and the surfaces of the applicator components. The probe tips were threaded into protective TeflonTM tubes. The measurements made with this system were limited in accuracy to ± 3 degrees on

some channels because of the attenuation introduced by the length of the sensing fiber's interface cable and splice losses. In general, the borehole wall sensor channel operated within ± 2 degrees of a mean value trend. The wall sensor provided a relative indication of the borehole wall temperature since it was encased in a Teflon™/air jacket that was configured to push against the wall. The exact contact pressure and air flow characteristics about the sensor could not be known precisely and, therefore, limited the interpretation of the temperature data.

2.6 Sediment Characterization

A complete description of the lithology and stratigraphy at the site and the sampling and analytical techniques used for core analysis can be found in a separate report on the characterization activities for the test (Eddy et al. 1993).

2.6.1 Volatile Organic Contaminant Content

The demonstration did not reduce contaminant levels in the affected sediments. Based on the small zone of influence of the well vacuum coupled with the characteristic low permeability of the clays, this finding is not surprising. The large extent of the vadose zone plume at the site makes it difficult to analyze sediment data with the intent of obtaining a mass balance for demonstrations smaller in scale. This is especially true in heating demonstrations where the zone of influence for vacuum extraction is typically significantly greater than the zone of influence of the heating source. The results show that there is, however, a distinct movement of contaminant towards the well. An analysis of the contaminant extraction rates observed over the course of the demonstration suggests that the solvents were mobilized after heating when the well vacuum and zone of influence increased significantly. Figures 2-14 - 2-17 are images of the PCE and TCE content of the sediments (at concentrations >1 mg/kg) for both the pre-test and post-test analysis. Databases from the pre-test and post-test VOC chemical analysis values were prepared for graphical representation using the same software program as described in Section 2.3.3. These images clearly identify the highest residual contaminant concentrations distributed in the clay-rich sediment layers. Volumetric analysis from these images suggest that the concentrations within the monitored zone (heated and control) increased as solvent vapors from regions of greater residual content were drawn in towards the horizontal well.

2.6.2 Moisture Content

The moisture content of the cores sampled from the clay-rich layers in the heated zone decreased substantially. (See Figures 2-18 and 2-19; the MHV designation refers to pre-test coring data and MHB refers to post-test data). Saturation levels were calculated based on gravimetric analysis using estimated sediment properties (density, grain size, porosity) from previous studies conducted at the site. While a general drying trend is apparent, the post-test saturations levels remain relatively high at 60 – 70% (these values are at or below the estimated residual saturation levels for the clays). The corings occurred approximately five months apart and no statistical information on seasonal variations in moisture content of the clays is available. It is unlikely, however, that clays at this depth would experience such variations over the time span of this demonstration.

2.6.3 Effect on Biopopulation

There was little observed effect of heating on the population of subsurface microorganisms. Typically, viable counts of cultured bacterial strains were below detectable limits and no enhanced thermal effects from elevated incubation temperatures were observed. It is difficult, in general, to extract and culture microbial populations from clayey sediments. To adequately assess the impact, direct fluorescent antibodies (DFAs) were used as probes for organisms previously identified at the site. Further analyses of samples are being conducted and additional testing will be performed to assess the adequacy of the techniques for employment in future in situ thermal demonstrations.

Figure 2-1. Daily and Cumulative Rainfall at Demonstration Site January 1 - May 31, 1993

Figure 2-2. Schematic of Horizontal Well Surveyed Elevation View

Figure 2-3. Schematic of Vapor Lock Formed Downhole at Temperatures above 100°C

Figure 2-4. Comparison of Measured Wall Temperature, Total Flow from Well, and Vacuum Levels at Well Head during the Heating Stage

Figure 2-5. Comparison of Measured Horizontal Well Piezometer Vacuums to Wall Temperature during Heating Stage and Start of Cooldown

Figure 2-6. Illustration of Equipment Crowding Well Opening at Well Head Entry

Figure 2-7. Horizontal Well Head during Normal extraction and RF Power Operations

Figure 2-8. Measured PCE, TCE, and TCA Gas Concentrations at Well Head during Heating Stage

Figure 2.9. Piezometer Pressures for 28 Depth (28 ft) Wells during Heating and Cooldown Stage

Figure 2-10. Measured Subsurface Temperatures at Selected Monitoring Wells over the Course of the Demonstration

Figure 2-11. 3-D Image of Temperature Distribution in Heated Zone at End of Heating Stage on April 27, 1993 (Boxes depict horizontal Well Survey.)

Figure 2-12. 3-D Image of Predicted Temperature Distribution of Heated Zone from Model at End of Heating Zone

Figure 2-13. PCE Destruction Efficiency over Course of the Demonstration

Figure 2-14. 3-D Image of PCE and TCE Sediment Concentration 1ppm (mg/kg) Iso-Surface from Pre-test and Post-test Cores (Dotted vertical lines depict borehole locations.)

Figure 2-15. 3-D Image of PCE and TCE Sediment Concentration 1ppm (mg/kg) Iso-Surface from Pre-test and Post-test Core Samples (Dotted vertical lines depict borehole locations.)

Figure 2-16. 3-D Image of PCE and TCE Sediment Concentration 1 ppm (mg/kg) Iso-Surface from Pre-test and Post-test Core Sample (Dotted vertical lines depict borehole locations.)

Figure 2-17. 3-D Image of PCE and TCE Sediment Concentration 1 ppm (mg/kg) Iso-Surface from Pre-test and Post-test Core Samples (Dotted vertical lines depict borehole locations.)

Figure 2-18. Moisture Content from Pre-test (MHV) and Post-test (MHB) Cores within Heated Zone (Approximately 7 feet from Applicator)

Figure 2-19. Moisture Content from Pre-test (MHV) and Post-test (MHB) Cores in Heated Zone (Approximately 5 feet from Applicator)

3.0 Recommendations

The field results suggest that a second demonstration is necessary to fully assess the radio frequency applicator technology. An improved remedial design would incorporate the lessons learned from this demonstration and would also provide a basis to technically and economically evaluate removing residual chlorinated solvents from clayey sediments using RF thermal techniques. Specific system design considerations should include the items listed in the following sections.

3.1 Extraction Wells

Results demonstrate that any new system design should use extraction wells that are independent from the well used for RF application. This change would resolve most of the problems encountered during the demonstration. Using a horizontal borehole for heating is still a viable and very advantageous application, especially since clay layers tend to be tabular in extent. With such a design, the antenna can be moved through the well, progressively heating a larger volume of the clay within a single borehole. This demonstration showed that modifications can be made to the RF hardware to minimize thermal expansion effects in a horizontal application. Extraction wells could be horizontal or vertical and should be located both within and on the perimeter of the zone anticipated to be heated by the RF applicator. Problems with heat loss and condensation from the gas stream through the long transition to the surface were encountered in this demonstration. In addition, removing excess water is necessary in a continuous horizontal well and will require a pump that can operate by skimming water from the bottom of the casing. For these reasons, vertical extraction wells may be less problematic from both a technical and economic standpoint. The perimeter radius for extraction wells should be selected such that contaminant transport caused by vacuum influence will bound any possible contaminant transport that results from thermal effects, ensuring adequate containment. If the targeted region for heating is a low permeable formation (e.g., clays), then the extraction wells should be screened both within the targeted formation and in surrounding strata with higher permeability if possible (above and below the clay lens for this application).

3.2 Drilling Technology/Well Completion Materials

For this demonstration, the horizontal well drilling technology was selected independent from RF compatibility

considerations. Choosing the completion materials that have the mechanical, thermal, and RF-compatible properties suitable for the installation technique is critical to successfully applying the technology. In this demonstration, a lower temperature-rated material was used to facilitate casing installation, thereby significantly reducing power output.

Using the RF applicator technology requires casing materials that are not typically employed in conventional environmental remediation wells, especially horizontal well installations. The added stress and flexibility required for the casing materials used in horizontal well completion may call for high temperature plastics or composites, which may add costs for tooling and machining.

An additional affect from using a horizontal well is the uncertainty of surveying its location. This uncertainty is a few feet and would not typically be critical in commercial applications. However, for this demonstration, uncertainties in the well location affected positioning the temperature monitoring boreholes. The risk of hitting the horizontal well by placing a vertical borehole within 5 feet was considered too high, so the closest temperature monitoring point in the clay was approximately 6 feet from the applicator. This effect, combined with the reduced zone of heating, limited analyzing the high temperature regions surrounding the applicator.

3.3 Baseline Vacuum Extraction

To adequately assess any vacuum extraction enhancement technology, the vacuum extraction parameters and characteristics for the ambient (baseline) condition must be understood. Inadequate time was allotted in the demonstration to establish this baseline for the RF heating effects on extraction. The contaminant release characteristics observed during the demonstration were very gradual and may have been unique to that of clay, independent of heat application. Had an adequate baseline extraction rate been established, the RF heating effects on the vacuum extraction process from clay could have been analyzed more conclusively.

3.4 Demonstration Length

Because of the unpredictable release characteristics during the vacuum extraction process and the lessons learned during the two-month in situ RF heating demonstration, a demonstration of longer duration is appropriate to effectively test the limits of the RF-enhanced vacuum extraction process from a clay. It should be clearly understood that the length of any demonstration will depend significantly on the overall design. With a design chosen to limit the num-

ber of interdependent variables (e.g., separate vertical extraction wells, high-temperature casing materials, and perhaps, a vertical well for the applicator), the length chosen for this demonstration would have been adequate.

3.5 Pretest Laboratory Studies/ Modeling

The pretest laboratory studies to determine the dielectric properties of the targeted clayey sediments were successful. Because of pretest study experience, matching the impedance of the applicator, to the impedance of the surrounding lossy sediment was excellent throughout the demonstration. However, a more rigorous model to predict the effective heated volume is necessary. The model used for this demonstration was simplistic and must be expanded to include the following critical phenomenon (for a more thorough description of the model used see: R.T. Harold, T.S. Snyder, R.S. Kasevich, "In Situ Radio Frequency Soil Remediation Heating Demonstration: Final Report on Treatability Studies", Westinghouse Science and Technology Center Report No. 93-9TD0-RFHET-R1, 1993, completed as partial fulfillment of Contract No. AA80586W for the Department of Energy):

1. Transport effects to account for energy losses resulting from the movement of air and water (as liquid and vapor) through the heated zone
2. Latent heat effects to account for this relatively large energy sink required to produce water vapor
3. Phase change effects to account for the effects of reduced water content on both thermal and dielectric properties.

Each of these effects is a critical aspect of the energy balance required to reasonably predict subsurface temperature contours. The latent heat effect alone can account for nearly 50% of the total energy output from the applicator to the formation. A number of computer codes are available that can be coupled to codes for the RF field calculations to adequately assess the effective heated zone. At present, one such code, TOUGH2 (or Transport Of Unsaturated Groundwater and Heat, developed at Lawrence Berkeley Laboratory) is being used to investigate ambient extraction from clays.

4.0 System Description

4.1 Equipment Description

4.1.1 Radio Frequency Heating System Equipment

The KAI RF heating system is an 8-ft $\times$ 8-ft $\times$ 20-ft shelter, that is mobilized by a 28-foot flatbed trailer and a 1-ton pickup truck (Figure 4-1). This system is configured for complete, unattended, remote control operation as well as for onsite support diagnostics. Figure 4-2 is a schematic of the complete system used for the RF demonstration. The AC power was provided by a diesel generator (described in Section 4.1.6). The details of the system are described in the following subsections.

4.1.1.1 Phone Line

The remote control and monitoring "phone line" is provided by a 3-watt transportable cellular phone with a data interface that is connected to a high-speed modem port of the control computer.

4.1.1.2 Radio Frequency Generator

The RFPP model 25,000D, 25 kW, 13.56 MHz RF generator is a modified, industrial tube-type design. The generator operates with a typical 240 volt, 3-phase AC power to RF power conversion efficiency of 65%. The unit employs two stages of ceramic power tubes that have operating lifetimes of between 3,000 and 5,000 hours. The balance of the circuitry is a stable, high-reliability design with an estimated mean time between failure (MTBF) of over 25,000 hours, which has been established over the past 10 years that this generator has been on the market. The generator has an internal analog control circuit configured to protect the generator from rapid load (applicator) changes. The generator is monitored and controlled by a series of switch state sensors, relays, and monitoring instruments that are interfaced to the system controller.

4.1.1.3 Matching Network (Tuner)

The 25 kW, 13.56 MHz tuner, a proprietary design of KAI Technologies, is capable of smoothly matching the RF generator to a wide range of load conditions. The tuner is typically capable of matching to applicator loads presenting volt-standing-wave ratios (VSWR) of greater than 3 for a nominal line impedance of 50 ohms.

4.1.1.4 Transmission Line

The 290-foot transmission line, external to the shelter, was constructed with 150 feet of flexible, high temperature, 7/8-inch transmission line (Andrews HT5-50) and 140 feet of rigid 7/8-inch EIA (Electrical Industry Association) transmission line (Radio Frequency Systems Model 1-78-50 in 20-ft sections), which was connected to the rigid feed section that was integral to the applicator. Both transmission lines contained Teflon™ spacer components that limited their useful temperature range at or below 200°C. The total transmission line attenuation was 0.389 dB (91% efficiency). The couplings used between the rigid transmission line's sections and the applicator were 3-bolt brass termination flanges with o-ring seals. The flanges were then enclosed in ellipsoidal-shaped, clam-shell covers machined from Teflon™ to eliminate any edges that may catch in imperfections expected at the section joints in the horizontal well. Figure 4-3 and 4-4 are photographs of the termination flange, clam-shell cover joints.

4.1.1.5 Radio Frequency Heating Applicator

The applicator is a proprietary design of KAI Technologies. The basic structure of the applicator is that of a modified end-feed dipole antenna. The flexible 2.25-inch-diameter antenna is constructed of copper, brass, Teflon™, and ceramic components. The flexibility of this antenna was limited to a bend radius of 50 feet and operating temperatures at or below 200°C because of Teflon™ component limitations. The antenna elements can be adjusted to match to the site soil conditions with a VSWR of less than 2. Figures 4-5 and 4-6, respectively, show the applicator prior to insertion into the borehole and a top-level mechanical view of the applicator used in the demonstration.

4.1.1.6 Controller

The system controller was an 80386 processor with IEEE-488, RS-232C, and modem interfaces. Control commands and system states were processed by an HP 3488A switch controller. System status was reported and polled over a high-speed modem using an MNP10 (Microcon Networking Protocol) high-reliability, error-correcting protocol for communications over the system's cellular phone link. System status and alarm states were broadcast to the system operators using a paging service supporting 80 character, alphanumeric pager receivers.

4.1.1.7 Diagnostics

The system diagnostics consisted of instruments directly interfaced to the controller as well as portable, stand alone support equipment.

System diagnostics - computer interfaced

- Vector voltmeter - HP 8508A
- Signal generator - Marconi 2022A
- Digital multimeter/scanner - HP 3457A
- Digital multimeter - HP 34401A
- Switch controller - HP 3488A
- Fiber optic thermometer - Luxtron 760
- Network analyzer - HP3577A/HP35677A

System diagnostics - stand alone

- Time domain reflectometer - Tektronix 1502C
- Megger - Biddle 218650CL
- Type J thermocouple converter indicator - Omega Model TAC-80J with Fluke Model 21 Meter
- Type K thermocouple indicator - Fluke 80TK

4.1.1.8 Environmental Monitors

The following monitors were used to verify that system operation was within OSHA safety guidelines for RF exposure and FCC guidelines for interference:

- Broadband isotropic probe - Holiday Model HI-3005
- Calibrated receiver - Electrometrics R-70B
- Portable AM/FM/MW/shortwave receiver
- Portable VHF/UHF TV set

4.1.1.9 Data Analysis

The control computer was supported for off-line data analysis by a second, identical computer configured with a LaserJet HiP printer for data output.

4.1.2 Vacuum Extraction And Offgas Treatment System

Vacuum extraction and offgas treatment was performed using a skid mounted, Brown Engineering (Seattle, WA), combined vacuum extraction and thermal-catalytic destruction system (Catox System). A schematic of the system employed is provided in Figure 4-7. This system was designed to destroy chlorinated hydrocarbon contaminants at an efficiency of $\geq 95\%$ from a stream of humid air containing a maximum contaminant concentration of 2500 ppmv (1250 ppmv each of PCE and TCE).

The destruction system employed a proprietary, Allied Signal monolith catalyst. The catalyst consisted of a wash coat of platinum group metals deposited on a 400-cell/in² honeycomb alumina substrate. The reaction chamber was equipped with silicon carbide resistance heaters, which heated the incoming stream to the catalytic reaction temperature of 850-900°F. Power to the heaters and furnace temperature was controlled by a Payne Engineering, Model 18E-4-80H silicon controlled rectifier in conjunction with an Omron E5AX temperature controller.

Vacuum extraction was driven by a Roots (Division of Dresser Industries), Frame 36, rotary lobe blower. This blower has maximum input of 10 inches Hg vacuum at 200 scfm.

4.1.3 Horizontal Well Description

The horizontal well used for the RF heating test was installed with an experimental compaction/dry drilling technique developed by Charles Machine Works (Ditch Witch™) of Perry, Oklahoma. Additional detailed information on the drilling rig and tool, the steering technique, and the liner installation can be found in WSRC-TR-93-008. The compaction drilling technique produces no surface returns and uses a minimal amount of fluid to cool and lubricate the drill bit and steering equipment. However, a disadvantage is that the method requires using materials significantly stronger than conventional nonmetallic casings (tensile strength greater than 5000 psi). In addition, the completion technique does not permit installation of a gravel-packed zone around the screen and the drill bit produces a low permeable skin immediately adjacent to the borehole.

The well was completed with casing and well screen consisting of 30-foot sections of 3-inch nominal (3.35 inch ID, 0.110 inch wall thickness) Centron™ fiberglass epoxy line pipe connected by pin and box screw joints. Three rows of 0.010-inch slots were machined into the pipe to construct the well screen (available surface area is approximately 1.84 in²/foot). The pipe has an axial wall tensile strength of 12,000 psi. No measurements were made to determine the final strength of the screened sections. The joints were belled for added strength. The elevation view of the well is given in Figure 4-8. Each point in the diagram is a surveyed location taken every 10 feet downhole. The well consists of two 140-foot surface transition zones constructed of solid casing connected by a 300-foot zone screened within the clay-rich lens at 315 – 325 msl. The minimum radius of curvature in the transition zones is approximately 250 feet.

4.1.4 Field Equipment For Monitoring Test Conditions

4.1.4.1 Monitoring Borehole Layout

Ten pairs of vertical monitoring boreholes were drilled in the field around the horizontal well bounded between the 160-foot and 260-foot positions of the horizontal well as shown in Figure 4-9. One borehole in each pair was used for pressure monitoring and the other borehole for temperature monitoring. Seven of the borehole pairs were positioned around the expected heated zone in an asymmetrical pattern relative to the location of the horizontal well. The remaining three borehole pairs were positioned well outside the bounds of the expected heated zone, and were used as control points. Figure 4-9 also displays the post-test borehole locations (labeled as MHB wells).

4.1.4.2 Subsurface Pressure Monitoring

Three piezometers (1 inch OD) were installed in each of the pressure monitoring boreholes and screened in the following zones:

28-33 ft depth

38-43 ft depth

48-53 ft depth

The surface end of each piezometer was closed with a polyvinyl chloride pipe cap and equipped with a quick-connect fitting. The identification numbers MHV 20 through MHV 29 were assigned to the 10 piezometer boreholes prepared for this demonstration. The individual piezometers within the borehole were identified with an alpha designation based on piezometer depth. The letter "A" was assigned to the deepest piezometers, "B" was assigned to the middle and "C" was assigned to the shallowest piezometers. Figure 4-10 schematically displays the piezometer arrangement.

Piezometer pressures were measured primarily with Magnehelic diaphragm differential gages, with the exception of MHV 21. At MHV 21, piezoelectric pressure transducers were installed on the three piezometers. These transducers were installed primarily to assess their performance. However, they also provided the capability of continuous pressure monitoring of that borehole. In addition, a fourth pressure transducer was provided to measure ambient (barometric) pressure at MHV 21. This measurement was considered the baseline barometric pressure reading at the demonstration site. Barometric pressure readings taken at the SRS Weather Station were used as backup.

4.1.4.3 Subsurface Temperature Monitoring

The temperature monitoring boreholes were equipped with both fiber optic temperature probes and thermocouples as shown schematically in Figure 4-11. The fiber optics were considered the primary measuring devices because their signals is not affected by RF emissions. T-type thermocouples were installed as a backup to fiber optics in all boreholes at depths corresponding with the piezometers (28, 38 and 48 feet). Fiber optic probes were installed with greater frequency to provide better temperature coverage in each borehole, and they were loaded mostly into the locations of greatest expected temperature effect. The temperature monitoring boreholes were identified as MHV 20T through MHV 29T to coincide with the analogous pressure monitoring boreholes. Table 4.1 lists the depth and location of all the fiber optic probes. Individual thermocouples were identified with an alpha designation congruous with the piezometer system. Individual fiber optic probes were simply identified by a numeric suffix corresponding to their actual depth location in feet.

4.1.4.4 Horizontal Well Monitoring

In addition to the borehole piezometers in the field, piezometers were also installed along the length of the horizontal well. These piezometers were used to monitor pressure drop along the well. The construction of these piezometers was differing lengths of 1/4-inch polyethylene tubing attached to a vacuum gage on the surface. The open ends of the piezometer tubes were located at the interfaces between the slotted and unslotted liner at both ends of the well (i.e., 140 and 440 feet from well head), immediately downstream from the applicator (i.e., 225 feet from well head), upstream from the applicator (i.e., 270-300 feet from well head), and at each end of the well (i.e., 0 and 580 feet from well head). The locations of these piezometers are shown schematically by the letters "PI" in Figure 4-12. They were identified by their distance into the well relative to the well head (well head = 0 feet).

Table 4.1 Fiber Optic Probes

Temperature Monitoring Well Identification	Number of Fiber Optic Probe Positions	Fiber Optic Probe Positions Depth in Feet
MHV-20T	6	28,33,38,43,48,53
MHV-21T	6	28,33,38,43,48,53
MHV-22T	6	28,33,38,43,48,53
MHV-23T	6	28,33,38,43,48,53
MHV-24T	6	28,33,38,43,48,53
MHV-25T	3	28,38,48
MHV-26T	3	28,38,48
MHV-27T	3	28,38,48
MHV-28T	3	28,38,48
MHV-29T	3	28,38,48

4.1.5 Sampling/Analytical Equipment

Routine gas/vapor samples were taken from the wellhead, Catox inlet, Catox stack, and the borehole piezometers to monitor both contaminant concentrations being extracted and changes to contaminant vapor concentrations within the formation itself. The samples were collected in 1-liter Tedlar™ sampling bags. Representative samples were ensured by inflating and purging (by squeezing) the bag several times before capturing the sample. Small, laboratory-sized diaphragm or oil-less rotary vane pumps were employed to pump samples from sample points under vacuum. All VOC analyses were performed on a Hewlett-Packard 5890 Series II gas chromatograph via direct injection. The unit was equipped with a 60-meter, mega-bore VOCOL (Supelco™) glass column and both an electron capture and flame ionization detector. The instrument was calibrated externally for gas sampling with calibrated gas standards on a routine basis.

4.1.6 AC Power Supply

Two portable 100-kW diesel generators supplied the required three-phase power. One generator supplied 480 VAC service for the Catox system and the other supplied 240 VAC Wye service to the RF generation and application equipment.

Electrical power for the field monitoring and sampling equipment (fiber optic equipment, sampling pumps) was primarily supplied by portable, 3800-watt gasoline-powered generators. A diesel-powered portable light plant was also procured by loan to supply lighting in the monitoring field and to serve as an auxiliary power supply.

4.1.7 Water/Condensate Removal Equipment

To pump water that accumulated in the well during the demonstration, a Timco™ air-displacement pump was modified to operate in a horizontal position. The small diameter (1.35-inch OD) polyvinyl chloride pump was installed along side the RF transmission line. A schematic of the pump and its operation is provided in Figure 4-13. The effectiveness of this pump was enhanced by using a vacuum to speed up filling of the pump chamber, a timer, and a three-way solenoid valve to make the pumping operation automatic. The pumping system is shown schematically in Figure 4-14. The maximum pumping rate achieved with this pump was approximately 2 gph.

4.1.8 Catox Monitoring Interfaces for Automatic Radio Frequency Shutdown

Key catox alarms were connected to the RF control system to shut down the RF generator if any of the following occurred with the catox system:

- Loss of power to the catox system
- Low catalyst temperature (insufficient voc destruction)
- Lo-hi liquid level alarm on vapor-liquid separator

4.1.9 Final Steady-State System Configuration

The final system configuration is displayed schematically in Figure 4-15. Listed below are the instruments and locations of attachment in the well:

- Open end of 440-foot piezometer (440) — It later was consolidated with the 270-foot piezometer into a single piezometer at 300 feet. This reduced the complexity of the insertion/removal process significantly.
- Open end of 270-foot piezometer (270)
- Center applicator fiber optic temperature probe (240)
- Well wall fiber optic temperature probe (240)
- Open end of 225-foot piezometer (225)
- Transmission line fiber optic temperature probe (225)
- Transmission line backup "J" thermocouple (225)
- Pump suction tube (205)
- Pump (145)
- Open end of 140-foot piezometer (140)

Figure 4-16 is a photograph of the system as installed at the Savannah River Site Integrated Demonstration.

4.2 Operation

4.2.1 Applicator Insertion and Removal

Inserting/removing the applicator to/from the horizontal well required the following actions:

- Section by section assembly/disassembly of the transmission line
- Attachment/removal of temperature probes, piezometers, and water pump to the transmission line, applicator, and/or pulling cable
- Well opening/sealing
- Impedance mapping scans of the horizontal well during insertion
- Instrument/gauge connection/disconnections
- Transmission line drying with N₂ flushing

In general, the insertion/removal process required five or six people. Two people were required to make/break transmission line connections and to attach/remove the monitoring hardware and water pump. One or two people were required to prevent tangling/kinking the relatively long lengths of fragile fiber optics cable and piezometer tubes. Finally, two people were required to manually pull the applicator into position (via cable) or to pull the applicator from the well. Mechanical pulling devices were avoided to minimize accidentally damaging components with excessive force.

The time required for one removal/insertion cycle was refined from a 20-hour to an 8-hour process as the team became experienced with the techniques and logistics.

4.2.2 Radio Frequency Operation

The basic elements of the RF operation are:

- Preheat Testing — A series of measurements taken to determine baseline conditions and to verify that the system is ready to safely operate at high power.
- Engaging RF Power ON — Turning the system on by operator commands to the control computer and data logger. RF power heating cycles were initiated for a specific number of heating hours (typically 4, 8, or 12 hours) that were then followed by RF Power OFF diagnostic tests.
- Monitoring RF Heating Cycles — Continuing RF Power ON measurements by the system controller. The heating cycles also contain periods of RF Power OFF when the applicator reaches its set point temperature and is allowed to cool to a point where the RF is again turned on automatically. Routine surface monitoring

measurements are also made during RF Heating ON periods of the heating cycle.

- RF Power OFF — A series of measurements taken that are identical to those of preheat testing.

More detailed descriptions of these elements are provided in the following sections.

4.2.2.1 Preheat Testing and RF Power OFF Measurements

- TDR measurement of transmission line/applicator assembly — Time domain reflectometer (TDR) measurements were used to verify the integrity of the coaxial transmission line system that delivers power to the applicator. The TDR uses an electrical pulse to probe the transmission line's characteristics along its entire length. The reflections return to the TDR as the probing pulse passes line junction points. Bends and transitions are processed to display the electrical distance from the TDR to each of these reflection points.

The reflection information is typically plotted on a strip chart recorder as a record of line impedance versus transmission line length. The displays are plotted on a strip chart recorder to provide a permanent record of the condition of the transmission line before high levels of heating power are applied. The TDR can be used to verify proper transmission line assembly, identify thermally distorted areas of the transmission line, and note trends in the heating environment of the applicator.

Figure 4-17 is an example of a TDR record that was typically made before each heating cycle, during heating cycle RF OFF pauses, and at the conclusion of the heating cycle.

The RF heating system was operated through a system control and monitoring program during all RF heating cycles. The computer monitoring and logging functions were supplemented by the observations of an operator who recorded system, heating applicator, and site environmental parameters that could not be recorded during the heating power ON portions of the operating cycle.

- Megger measurements — A high voltage DC megohmmeter (megger) was used during preheat testing to verify the insulation integrity of the internal transmission preheat line spacers and junctions at a level of 5,000 volts. A typical "good" reading exceeded 300 gigohms.

The megger was also used with the applicator (attached to the transmission line and positioned in the horizontal well) during preheat, RF OFF, and post-heating cycle periods. In this manner the megger was used to estimate the conductivity of the feedpoint surface junction of the applicator and the surfaces

which the applicator element arms contacted. The megger voltage was typically stepped from 500 to 5,000 volts. The reading ranges from under 1 megohm for a moist, preheated environment to over 700 megohms in a dry region, immediately after full-power heating. The megger was also used to verify the presence and passage of water along the floor of the horizontal well during "quenching events".

Megger readings were typically taken in conjunction with TDR measurements.

- Network analyzer measurements — The network analyzer was used to make impedance measurements as a function of frequency at two points within the RF heating system during power OFF conditions. Measurement point 1 was that of the applicator itself, located in the horizontal well prior to heating. Measurement point 2 was at the input to the tuner. Measurement 1 was typically displayed in terms of return loss to display the matching trends seen during the heating cycle (Figure 4-18). Measurement 2 was typically used to guide adjustments of the tuner and to record before and after shifts in the settings (Figure 4-19). Measurement sets were typically taken before and after adjustments were made to the system.

Measurement point 1 was also used to scan the horizontal well heating region as the applicator was pushed into position. Scans consisted of a number of return loss measurements that were typically post-processed to VSWR or impedance displays. Figure 4-20 is an example of a scan.

- Transmission line thermocouple measurement — A type J thermocouple was located on the RF transmission line at the sleeve entrance to the heating applicator. This measurement point was checked immediately after power OFF conditions to determine the maximum temperature experienced by the outer shell of the RF transmission line.

4.2.2.2 Routine Radio Frequency Power ON Measurements

The following measurements were recorded as measurement channels of the Time Acquisition (TAQR) program or logged in the site notebook.

- RF vector voltmeter channels — The vector voltmeter was used with a directional coupler to measure the voltage of the RF power input to the applicator. The reflected voltage was measured in terms of its magnitude and phase relative to the input power voltage. This information, along with a preheating calibration measurement, allowed the vector voltmeter measurement files to be post-processed to produce a plot of applicator

feedpoint impedance versus time. The coupler for this measurement was located at the output of the tuner.

- RF generator RF output power channel — This measurement recorded the power output from the RF generator into the tuner. The power pickup was via a dual port directional coupler. This measurement produced similar data to that produced by the vector voltmeter's forward voltage measurement. During heating cycle 5, this channel was converted to sense reflected power. This channel was then used in part of an auxiliary sensing scheme to recover from horizontal well quenching events.
- RF generator AC input power channel — This measurement recorded the AC input power used by the RF power generator. The measurement was made by a three-phase true RMS (root-mean squared) transducer that was connected to make an absolute input power measurement. This measurement was used with the RF generator RF output power channel to determine the absolute efficiency of the generator.
- Horizontal well temperature sensors — A four-channel fiber optic thermometer was employed to monitor horizontal well temperature conditions during the heating cycle. One to three sensors were employed during the program.
- Air temperature sensor channels — Temperature sensors were used to monitor the input ambient temperature to the cooling system, the generator exhaust temperature, and the shelter instrumentation environment.
- AC voltage sensor channels — Three AC voltage sensor channels monitored the phase-to-phase voltages of the three-phase power input from the diesel generator.
- Transmission line nitrogen pressure — This measurement recorded the changes in pressure as the transmission line heated. This channel was monitored to alarm and turn off the RF power if the pressure dropped below 5 psi. The alarm condition indicates a failure in a transmission line seal.

4.2.2.3 Routine Surface Monitoring Measurements

- Isotropic RF probe — An isotropic broadband probe was used to detect RF fields that could approach OSHA hazard levels on the surface.
- Calibrated RF receiver — A narrowband, tuned calibrated receiver was used to map the surface electromagnetic field strength above the heating area.

4.2.3 Extraction Operation

4.2.3.1 Preliminary Testing

Prior to committing the unit to service, attempts were made to operate the Brown Engineering Catox system per

the vendor's operating manual and perform a final check of the pre-set system control, alarm, and shutdown setpoints for the system. During this testing, several errors were found in the operating manual, as well some minor hardware problems. The details of the system check out findings were documented in SRS procurement QA records. Hardware problems were corrected and operating procedures were written in time for system start up on March 4, 1993. In addition to operational checks, PCE was introduced to the unit to check halocarbon destruction efficiency. Destruction efficiency during these tests ranged from 85 to 92%.

4.2.3.2 Routine Operation

Routine extraction operation was comprised of recording Catox system parameters and securing a set of gas/vapor samples, one each from the wellhead between the extraction pump and catalyst (thus referred to as the Catox Inlet), and from the Catox stack. These sample points are identified in Figure 4-17 as a blocked "S". Catox system readings and samples were taken typically four times daily during heat application with a minimum frequency of twice daily. Readings were taken at approximately the same times each day. The complete record of Catox System readings are provided in Volume II of this report.

4.2.3.3 Planned Interruptions

Planned interruptions of vacuum extraction operations were scheduled to perform preventive maintenance on the portable diesel generator and extraction pump. Downtime for these planned interruptions averaged approximately 2 hours per week.

4.2.3.4 Water/Condensate Pumping

Water/condensate pumping operated continuously during vacuum extraction operations. Water levels in the collection vessel and knockout pot were checked at the same time Catox samples were secured. Water from primary collection vessels was transferred 2-3 times daily to secondary vessels. All water collected was picked up and transported to the SRS air stripper on a biweekly basis. Daily accumulation of water/condensate was recorded in the demonstration log book.

4.2.4 Field Monitoring

4.2.4.1 Piezometer Monitoring

Pressure measurements from the horizontal well piezometers were recorded at a frequency in conjunction with Catox system readings and extraction sampling (minimum

of four times daily). Pressure measurements from the 30 field monitoring piezometers were taken a minimum of twice daily. All measurements were recorded in inches of water column (w.c.), except for readings taken with the MHV 21 transducers. Transducer readings were taken in millibar (mbar). The record of all piezometer measurements taken during the course of the demonstration are provided in Volume II of this report.

4.2.4.2 Temperature Monitoring

Temperature monitoring activities were conducted with both fiber optic probes and thermocouples. Indication hardware was not available to continuously monitor all installed fiber optic or thermocouple temperature probes. Therefore, field temperature measurements focused on the expected heating area. Periodic checks of those points outside of the focus group during heating indicated no change in temperature from ambient, confirming the selected monitoring points were appropriate.

Ten fiber optic probes from inside and bounding the expected heated zone were connected to a data acquisition system and provided continuous monitoring of those points. Points continuously monitored by fiber optic probes are summarized in Table 4.2.

Ten of the field monitoring thermocouples inside and bounding the expected heated zone were connected to a multi-channel digital readout. Measurements from these ten points were recorded a minimum of twice daily. Table 4.3 lists the ten selected points. The complete record of data collected from thermocouples during the demonstration is provided in Volume II of this report.

Table 4.2 Fiber Optic Probes Continuously Monitored

Monitoring Well Identification	Depth(s) of Monitoring Point(s) (feet)
MHV-20T	38
MHV-21T	33, 43, 53
MHV-22T	33
MHV-24T	33, 38, 43, 48
MHV-26T ^c	28
MHV-29T ^c	38

^cMHV-29T (38) was used as ambient temperature at the start of heating stage then replaced by MHV-26T (28) approximately halfway through the heating stage.

Table 4.3 Thermocouples Continuously Monitored

Monitoring Well Identification	Depth(s) of Monitoring Point(s) (feet)
MHV-20T	38
MHV-21T	28, 38, 48
MHV-22T	38
MHV-23T	38
MHV-24T	28, 38, 48
MHV-26T	38

4.2.4.3 Piezometer Sampling

Gas/vapor sampling from the field monitoring piezometers was employed to monitor changes in contaminant concentrations in the formation during the course of the demonstration. Piezometer samples were secured at a rate of approximately eight samples per day. A schedule was developed to ensure data would be obtained from all of the piezometers (30), but also to ensure that the selected areas under the greatest influence of the RF heat were sampled at a greater frequency. Sample schedule and frequency was modified accordingly as trends and events evolved during the demonstration.

Figure 4-1. Mobile KAI RF Application Unit

Figure 4-2. Schematic Diagram of RF Heating System used for Demonstration

Figure 4-3. Transmission Cable Joint with Teflon™ Clam-Shell Cover

Figure 4-4. Modified Half-Cann Shell "Skin" Used in Operation to Reduce Flow Restrictions

Figure 4-5. RF Applicator for SRS Demonstration

ORIGINAL

Figure 4-6. Mechanical View of the Applicator Used in SRS Demonstration

Figure 4-7. Schematic of Catox System Employed at RF Heating Demonstration

Figure 4-8. Schematic of Horizontal Well Surveyed Elevation View

Figure 4-9. Monitoring Well Layout with Respect to the Horizontal Well

Figure 4-10. Schematic of Piezometer Arrangement in each Borehole

Figure 4-11. Schematic of Temperature Probe Arrangement in each Borehole

Figure 4-12. Schematic of Horizontal Well Piezometer Positions

Figure 4-13. Schematic of Modified Air Lift Pump

Figure 4-14. Schematic of Air Lift Pumping System

1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
---	---	---	---	---	---	---	---	---	---	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	-----

Figure 4-16. Photograph of In Situ RF-Enhanced Vacuum Extraction System

Figure 4-17. Typical TDR Record

Cursor 318.000 ftΔ
Distance/Div..... 50 ft/div
Vertical Scale.... 500 mV/div
VP 0.99
Noise Filter..... 8 avs
Power ac

Tektronix 1502C TDR
Date 3/19/93 6:11 PM
Cable Fed Appl. C150
Notes _____
Input Trace _____
Stored Trace _____
Difference Trace _____

Cursor 318.000 ftΔ
Distance/Div..... 50 ft/div
Vertical Scale.... 100 mV/div
VP 0.99
Noise Filter..... 8 avs
Power ac

Tektronix 1502C TDR
Date 3/19/93 6:12
Cable Fed Appl.
Notes _____
Input Trace _____
Stored Trace _____
Difference Trace _____

Cursor 318.000 ftΔ
Distance/Div..... 2 ft/div
Vertical Scale.... 200 mV/div
VP 0.99
Noise Filter..... 8 avs
Power ac

Tektronix 1502C TDR
Date 3/19/93 6:14
Cable _____
Notes _____
Input Trace _____
Stored Trace _____
Difference Trace _____

Cursor 318.6
Distance/Div..... 2 ft/
Vertical Scale.... 200
VP 0.99
Noise Filter..... 8 avs
Power ac

Tektronix 1502C TDR
Date 3/19/93 6:15
Cable _____
Notes _____
Input Trace _____
Stored Trace _____
Difference Trace _____

Figure 17. Typical TDR Record (contd)

Cursor 317.200 ftΔ
 Distance/Div 0.5 ft/div
 Vertical Scale 100 mV/div
 VP 0.99
 Noise Filter 64 avg
 Power ac

Tektronix 1502C TDR
 Date 4/2/93 08:31
 Cable Application
 Notes 20 Mc @ 5 Kw

Input Trace _____
 Stored Trace _____
 Difference Trace _____

Cursor 296.256 ftΔ
 Distance/Div 5 ft/div
 Vertical Scale 200 mV/div
 VP 0.99
 Noise Filter 64 avg
 Power ac

Tektronix 1502C TDR
 Date 4/2/93 14:16
 Cable _____
 Notes Transmission Line
Failure

Input Trace 1
 Stored Trace _____
 Difference Trace _____

WSRS5212.01L Heat 4 WB heat, Return Loss 8-Apr-93 7: 30: 48

Instr=HP3577A, H units=Hz, V units=dB, Npw= 401, VSCL= 10 T1,
 Freq MHz= 16, H span MHz= 30, Res KHz= 1, Avg= 1, Wscale= 100.

Figure 4-18. Typical Return Loss Measurements of the Applicator

WSRS9212.01L Heat 4 NB tuner IN heat - end 4, Return Loss 8-Apr-93 7: 27: 41

Instr=HP3577A, H units=Hz, V units=dB, Npw= 401, VSCL= 2 T1,
 Freq MHz= 12.5, H span MHz= 5, Res KHz= 1, Avg= 1, Wscale= 100.

Figure 4-19. Typical Return Loss Measurement of the Tuner Input

Preheat scan L=144 @ RF, Return Loss 24-Mar-93 10:54:44 WSR05.TXT

Figure 4-20. Typical Applicator Insertion Scan (Return Loss vs Distance Downhole)

5.0 Results And Discussion

5.1 Mobilization

5.1.1 Overall Assessment

The critical path item in the mobilization effort was procuring and installing the vacuum extraction/thermal catalytic oxidation system. Primarily because of catalyst supply delays, this system was not ready for operation until early March 1993.

5.1.2 Radio Frequency Application System

Setting up and testing the RF application hardware consisted of connecting AC power, assembling the applicator and transmission line, readying the RF generation equipment, and conducting control system and diagnostic checks. The applicator was ready for initial insertion for preliminary diagnostic checks in three days.

5.1.3 Catox System

Installing the skid-mounted Catox system was relatively simple and included skid positioning, leveling, piping to the well, placing the catalyst, and connecting the AC power. After the system arrived at SRS, a flaw was discovered in the catalyst mounting frame and required a field modification before installing the catalyst. This modification was suspected as the root cause of a bypass in the catalyst block, which potentially reduced the overall destruction efficiency of the system. In addition to the design error, several errors in the operating manual were identified. Inspecting, installing, and testing the equipment required approximately three weeks.

5.1.4 Applicator Insertion and Removal

The applicator insertion/removal process was cumbersome and very labor intensive. Initial plans to assemble the rigid transmission line entirely above ground had to be altered because of the likelihood of damaging the coupling joints during insertion. As a result, the transmission line had to be assembled (disassembled) at each step of inserting (removing) the applicator. Inserting the instrumented applicator complicated the process. Monitoring lines had to be secured to the transmission line at 2-foot intervals along the first 60 feet of transmission line and every 18 feet thereafter. This technique ensured adequate protection of the delicate fiber optic probes, cables, and connections and reliable delivery and retrieval of the piezometer lines and water pump. The presence and flexible nature of the

down hole piezometers complicated the process. To reduce the down time when the applicator was removed, the two upstream piezometers were replaced about mid way through the demonstration with a single, stainless steel tube (1/4-inch OD) located 300 feet down hole.

Two factors that complicated the insertion process were a direct result of either the demonstration nature of the test (i.e., a first-run operation coupled with obtaining sufficient data for technology assessment) or the use of a single horizontal well for both heating and vacuum extraction (i.e., placing piezometer lines and the water pump). Instrumentation necessary for applicator operation (primarily fiber optic lines for temperature control) could be preassembled in a single delivery feed line to facilitate insertion.

5.2 System Operation

5.2.1 Radio Frequency Heating System/ Applicator Operation

5.2.1.1 Radio Frequency Generator and Matching Network (Tuner)

The RF generator and tuner operated without incident throughout the program. The 240 VAC, 3-phase generator provided stable input power and allowed the RF generator to provide its fully rated, 25,000 watts of RF output at 13.56 MHz. The generator's primary, analog control system protected the generator during load variations, which were caused by the quenching events from water influx to the well upstream of the applicator. The KAI control and monitoring system provided a secondary, digital system that controlled the generator's overall operation in terms of energy and temperature control. This programmable, digital system was used to adapt the generator to deal with the water quenching events that would have required significant amounts of round-the-clock onsite operator intervention if it had not been field adaptable.

The matching network was operated well within its electrical and thermal design parameters. Within the entire 27-day heating program, the tune was adjusted fewer than 10 times. The majority of these adjustments were minor trimming adjustments that represented less than 5/100th of a turn on the control capacitors. In terms of tuning, an operational period in excess of 20 days would have been possible. If a fully remote controlled tuning and measurement system were engaged, the RF system would not have required onsite support for the entire program.

5.2.1.2 Transmission Line and Radio Frequency Applicator

The transmission line was composed of flexible and rigid sections. The original deployment plan called for the transmission line to be completely assembled and pressurized before inserting the applicator and transmission line into the well. Field site logistics and limitations on fixture sizes available to handle the rigid line did not allow it to be fully assembled. Therefore, the line had to be assembled in 20-foot sections. Sensor lines (pressure, temperature) were attached with heavy duty tape. This assembly-intensive approach required that the number of horizontal well insertions be kept to a minimum.

The transmission line was operated in a higher temperature environment than its manufacturer had anticipated. The transmission line sections were joined with junction anchors that were designed to "slip" with the expansion and contraction of the transmission line. However, the standard expansion range of this joint was not sufficient for the temperature differentials encountered. Electrical shorting and continuity problems were encountered on the heating and cooling cycles of the line. These problems were solved for the specifics of this transmission line system. Analysis of the problem suggests that a number of engineering solutions may be used to permanently address this problem in the future.

The initial insertion included network analyzer diagnostic checks at low power to ensure that the applicator's length was optimal for matching the output impedance to the effective impedance of the borehole and soil. Following this initial insertion, the applicator was removed and the final coupling brazed in place for the proper dipole length. The applicator operated within its design range. However, because of difficulties in inserting and removing the applicator and rigid transmission line system from the horizontal well and program time constraints, the tuning was not optimized. A starting voltage standing wave ratio (VSWR) of 2 was accepted as the initial match for the applicator. This less than optimum match was chosen with tuning conditions that would allow the VSWR to improve toward a value of 1.75 or better as the moisture in the soil surrounding the antenna decreased from drying. Figure 5-1 is a scan of the matching characteristics of the horizontal well at the beginning of final heating cycle (4/8). It can be seen that the region between 11 and 14 MHz for the 230- and 240-foot positions indicate changes from that shown in the pre-heat scan example in Figure 4-20. These changes can be better seen by comparing these two borehole scans with single frequency "slices" of the respective data sets. Figure 5-2 shows the return loss as the 16.7-ft applicator is pulled into the well from the 150-foot to 240-

foot center line position. The "hump" in the return loss between 180 feet and 200 feet was most likely caused by the close coupling of the antenna to the wall within this bend region of the horizontal well. Figure 5-3 is the same type of "slice". Within the 230- to 240-foot interval occupied by one-half of the applicator, it can be seen that the return loss match has improved. This improvement is within the predicted range for "drying" the heated region. In fact, the extension of this heating zone effect to the 220-foot region is also expected. At the 240-foot position, the return loss has improved to approximately 12.5 dB for a nominal VSWR of 1.75. The return loss minima shown between 180 and 190 feet may again be due to bending the applicator, but the effect may be enhanced by a thin layer of water distributed along the base of the horizontal well in this region. This area is the lowest point of the horizontal well and the region that accumulated water after the vacuum was applied to the horizontal well.

5.2.1.3 Temperature Monitoring and Control System

Monitoring the temperature of the horizontal well region surrounding the applicator was necessary to protect the well liner from damage. The damage temperature was estimated to be 120°C (250°F). To protect against liner damage, a fiber optic temperature sensor was positioned against the borehole line wall. This sensor was used as part of a temperature control circuit to limit the RF generator's heating cycle time. Typical setpoints of 115, 120, 125, and 130°C were used. Because of this control feedback, the RF generator operated with a duty cycle of 90 to 75%, which meant that the generator RF power would be off from 6 to 15 minutes every operating hour. This duty cycle limited the amount of energy that could be delivered to the formation.

5.2.1.4 Power Use/Output

The total AC power input to the RF generator and forward coupled RF power was monitored continuously by the KAI control system for each heating cycle. Data files of power values versus heating cycle time were generated by the control system and serve as the basis for power utilization and delivered power calculations. A hard copy of each of these data files appear in Volume II of this report. Each data file calculated the average power measurement over the corresponding cycle time. This averaging takes into account the duty cycle limitations. AC power was converted to RF with an efficiency of 65% based on the measured values of AC input and forward coupled power values. To determine actual RF power delivered to the formation, the forward coupled power measurements must be corrected to account for losses between the RF generator,

tuner, transmission line and applicator and reflected power. For this RF delivery system (based on KAI experience), the correction factor is assigned a value of 0.85. Therefore, the overall efficiency of the power delivery is approximately 55%. Of the 21,200 kW-hr of AC input energy, 11,675 kW-hr were successfully coupled to the formation.

5.2.1.5 Radio Frequency Effects on Site Communications

Transmission of the RF energy at 25 kW and a frequency of 13.56 MHz posed no detectable interference with other SRS users of RF or with site communications.

5.2.2 Extraction System Operation

5.2.2.1 Horizontal Well Flow, Vacuum, and Temperature Relationships

Relatively low flow from the well was experienced throughout the demonstration with recorded values rarely exceeding 30 scfm (typical flows over the course of the initial cold pump test and heating stage ranged from <5 to 20 scfm). Low flow rates are believed to result from the characteristic low permeability of the clays (typical intrinsic permeabilities for the clays range from 10^{-10} to 10^{-12} cm²). High saturation levels in the clays reduced the effective permeability further and resulted in water influx into the well (typical water influx rates ranged from 5 to 15 gallons per day).

The flow was directly related to the vacuum applied in the well and inversely related to the well wall temperature. Figures 5-4 – 5-6 displays plots of the well wall temperature (measured at the center of the RF applicator), the measured flow from the well, and the vacuum applied in the well for the entire demonstration period.

Figure 5-4 shows the temperature-flow-vacuum relationship during the early stages of the demonstration. The time frame covered in Figure 5-4 includes the first 4, relatively short, heating periods where water infiltration and transmission line problems were discovered and resolved. A continued decrease in flow as the wall temperature increases is observed in the first extended heating period (from March 28 to March 31). The rapid rise in flow on April 5 is response to a two-fold increase in the vacuum level and a brief powerdown period for the applicator (to conduct subsurface resistance measurements). The flow drops back to a steady level, slightly less than 15 scfm thereafter. To limit the effects of water quenching events on the applicator and tuner and to reduce adverse effects of thermal expansion on the transmission line, power output

was controlled to keep the well wall temperature below 100°C over this time frame.

Figure 5-5 shows the same parameters during the fifth and most extended (uninterrupted) heating period of the demonstration. This plot clearly shows the inverse relationship between flow and wall temperature. As the well wall temperature initially exceeded 100°C (late April 10), the flow dropped rapidly to approximately one-third of its original value (from 15 to less than 5 scfm). At this point, any water in the vicinity of the applicator was converted to steam, causing a vapor lock. The flow responded slightly to gradual increases in the vacuum level (April 11 to April 17), although of smaller magnitude than indicated in Figure 5-4. Supporting evidence for asserting steam formation in the well comes from analyzing horizontal well piezometer data and the air lift pump operation (see Section 5.2.2.2).

Effects consistent with steam formation and the subsequent loss of vacuum down hole at the applicator were observed in the results of the electrical resistance tomography (ERT) measurements made by Lawrence Livermore National Laboratory (LLNL) (a more detailed discussion of the monitoring technology and results can be found in A. L. Ramirez and W. D. Daily, "Monitoring Radio-Frequency Heating of Contaminated Soils Using Electrical Resistance Tomography", UCRL-ID-115373, 1993, LLNL). The ERT technique maps planar changes in subsurface resistances, which can be correlated to changes in moisture content and temperature. Two-dimensional images of a subsurface plane perpendicular to the well and applicator were collected prior to and following the onset of steam formation down hole. Changes in measured conductivity illustrate a dramatic shift in the preferred direction of heat transport in the area around the applicator. Prior to steam formation (data collected on and before April 8), the greatest increases in conductivity were observed in the region below the applicator, indicating the likelihood of higher temperatures in this zone. Following the formation of steam down hole (data collected on April 16 and April 18), the conductivity in the region above the applicator rose dramatically. This result is consistent with the loss of vacuum influence from the well and the subsequent rise of steam upward through the formation that transferred heat to the region above the applicator. Prior to steam formation downhole, an adequate vacuum level within the well may have provided sufficient flow through the formation above the applicator to remove the added heat. While measured vacuum levels at the piezometer screened above the clay indicate a stronger influence from the well in this region (see Section 5.2.3.2), the magnitude of the influence during the heat stage was small. It is suspected, therefore, that variations in the rainfall levels at the

demonstration site (no significant rainfall occurred after April 9) also contributed to the observed changes in conductivity. Water infiltration can provide a greater cooling effect than air due to a significantly larger heat capacity. Unfortunately, excessive drying around the ERT electrodes during the demonstration prevented analysis during the cooldown stage when higher vacuum influences from the well should have cooled the region above the applicator more rapidly.

When it became evident that extraction rates were suffering at the higher control temperatures (measured at the well wall adjacent to the center of the applicator), the control temperature was reduced to below 100°C. At a control temperature below 100°C, the flow from the well increased back to, or slightly exceeded previous levels (April 17 to April 19). However, to maintain this lower control temperature, the duty cycle of the applicator was significantly lowered to less than half the original energy output. As a result, the rate of temperature increase measured at the MHV-24T "B" thermocouple located in the clay approximately six feet from the center of the applicator dropped by 70%. This drop in rate is indicated in Figure 5-7. While the flow rates approximately doubled at the lower control temperature, the average offgas concentrations dropped by a factor of roughly 20%. Therefore, the net contaminant extraction rates did increase. This result demonstrates the importance of maintaining adequate flow from the formation while heating, and further illustrates the impact which the single well design had on the demonstration. Since the magnitude of enhanced extraction rates would be relatively small regardless of control temperature, efforts to maximize extraction rates were relinquished in favor of maximizing RF energy input into the formation. Control temperatures were raised in increments in an effort to more closely monitor contaminant concentration changes versus wall temperature. The final control temperature of 130°C was the highest temperature the team was willing to risk considering the 120°C maximum temperature rating of the well screen. The period April 19 to April 27 in Figure 5-5 shows again how flow responded inversely with temperature while vacuum was held relatively constant.

The relatively rapid response of flow to applicator "off" cycles (downward spikes in the temperature plot) indicates that the vapor lock formed down hole generates and subsides rapidly. This rapid generation of steam may originate from two sources; steam generated within the well from vaporization of excess free standing water, and steam generated within the formation near the well screen. If the latter source is the major contributor, the results suggest that there may not be enough energy stored in the formation to overcome the latent heat of water vaporization during

applicator "off" cycles (i.e., latent heat could not be overcome without the continuous energy input from the applicator). No temperature monitoring within the sediment in the region adjacent to the applicator was available (within a radial distance less than five feet), therefore, it is difficult to determine what volume of sediment was at or above 100°C. However, analysis of temperature data, presented in Section 5.2.3.1, is consistent with the assumption that only a small volume of sediment close to the well screen was at temperatures near or above 100°C.

Following the heating stage, the flow responded rapidly, rising to levels in excess of 30 scfm during the initial stages of the cooldown period. Figure 5-6 shows the relation between flow and vacuum during the cool down period. Downhole temperature monitoring was halted during this stage of the demonstration.

5.2.2.2 Well Piezometer and Temperature Relationships

Figure 5-8 illustrates the response of the well piezometers to changes in the measured wall temperature at the applicator. During the early stages of the demonstration (March 25 to April 10) there was minimal pressure drop through the well with vacuum measurements at all piezometer locations closely tracking the well head vacuum. However, as the well wall temperature exceeded 100°C (approximately mid-day on April 10), the piezometers upstream and immediately downstream of the applicator (580, 270/300, and 225 feet) dropped to near atmospheric pressure, indicating the onset of the steam block in the well. Increasing the vacuum applied to the well had virtually no effect on improving vacuum levels upstream of the applicator while the control temperature was in excess of 100°C (mid April 10 to mid April 16). The piezometer located at the start of the well screen (140-foot depth) showed little response to increases in applied vacuum, maintaining a relatively constant vacuum reading near 30 inches wc. The vacuum conditions at this location and other points downstream of the applicator were more strongly influenced by the thermodynamic characteristics of the water phase change as the gas stream cooled than by the momentum influences of the applied vacuum. A compressor capable of generating higher flow rates could be used to ensure that the water vapor is removed and an adequate vacuum is maintained. However, such a modification for this demonstration would be limited by the large heat transfer surface provided by the relatively long transition to the surface from the heated region (approximately 240 feet). The use of vertical extraction wells, which would provide shorter paths to the region, would have alleviated this limitation. Figure 5-9 explodes the April 8 to May 1 portion of Figure 5-8 to make the trends clearer

during this key period in the demonstration. The upstream piezometers responded slightly to lowering the control temperature to 100°C (April 16 to April 18). However, the vapor block was still significant enough to maintain a large pressure drop through the well.

The response of the piezometer nearest the applicator may be indicative of potential thermal damage within the well. This piezometer, positioned at 225 feet down hole, was approximately 15 feet downstream of the applicator's center point. While the control temperature remained below 100°C, the vacuum level tracked with the 580- and 270/300-foot piezometers located upstream of the applicator. The vacuum level suddenly increased on April 10, exceeding the inlet 0 foot value as the well wall temperature increased to approximately 110°C. It is believed at this point the 225-foot piezometer tube melted shut, which was confirmed by attempts to clear the tube with high pressure N₂. All subsequent indications of vacuum at the 225-foot piezometer correspond to a significant dip in the well wall temperature, indicative of the expansion and contraction of a gas in a sealed tube. The measured temperatures of the transmission line near the coupling to the applicator (located 232 feet downhole) reached an observed maximum of 177°C during the later stages of heating. This measured transmission line temperature was as high as 50°C higher than the measured wall temperature used to control power to the applicator. Therefore, thermal damage could have occurred to instrument and monitoring lines or the well casing if they were in contact with the applicator and transmission line.

Coincident with the onset of steam formation down hole, water flow from the air displacement pump ceased. However, a corresponding increase in condensate collected in the vacuum knockout pot was observed. The increase in condensate indicated that the pump suction was no longer in water, but in water vapor. It is believed that the tygon suction tube for the pump (located at approximately 205 feet down hole) may have been damaged by high temperatures.

A sufficient volume of steam was entering at some location in the pump line or at the pump itself (located at 14 feet down hole) to allow adequate recovery of the condensate, which could be pulled to the surface as it filled the relatively small diameter recovery line (1/4-inch OD high-density polyethylene). Condensate pumping continued for the remainder of the demonstration. Water pumping could not be restored even when well wall temperatures decreased below 100°C, thereby confirming the likelihood of thermal damage to the pump intake line.

Significant changes were observed following the heating stage as the cooldown period was monitored (after April 27 on Figure 5-8). The 140-foot piezometer indication

increased and approached the well head vacuum levels while the upstream piezometer indications remained at or near atmospheric conditions. This observation indicates that the bulk of the flow enters the well from the screened zone nearest the vacuum source (i.e., the control zone) and/or that possible well screen damage (from exceeding the maximum rated temperature) was significant enough to block upstream flow. The positive vacuum response to the upstream piezometers (i.e., 580 foot and 270/300 foot) immediately after heating was terminated (and after the first attempt at applicator retrieval, [Figure 5-9] suggests that a flow path through the well exists. (It should be noted that the 225-foot piezometer was abandoned at this point and its corresponding gage connected to the air lift pump discharge line. Therefore, the 225-foot piezometer indication from this point for the remainder of the demonstration was monitoring the open end of the pump suction line, a point somewhere between the 140-foot and 205-foot well position.) After approximately 24 hours of cooling, the upstream piezometer readings dropped back to near atmospheric. This drop corresponded to the initial sharp rise in PCE offgas concentrations observed in the early stages of the cooldown period (see Figure 5-10). The significant changes at this point would suggest that as the well cooled, the clayey formation became the primary source of flow in the downstream sections of the screen with minimum flow coming from the sections in the region upstream of the applicator (580-foot and 270/300-foot piezometers).

5.2.2.3 VOC Concentrations

Evidence of a direct RF-induced thermal effect on the formation occurred from March 25, 1993, to April 13, 1993. During this period, there appeared to be a correlation between dips in PCE concentration measured at the well head and periods of no power output. In addition, there is a general upward trend in concentrations following the initiation of RF energy input to the formation (see Figure 5-11). This would lead to the belief that the source of the contamination detected at the wellhead would be from the soil in the vicinity of the well screen, rather than deeper in the formation. This area would experience the maximum temperatures produced by the RF applicator and would be the area more subject to rapid cooling because of convective flow through the well. However, it is difficult to discern whether the PCE concentration dips were caused by the direct effect of the RF applicator. During each power "off" cycle of this initial heating stage, vacuum extraction was halted, and the well was opened to atmospheric conditions for a period ranging from one-half to three days. The coincident rise in offgas concentration with renewed power output from the applicator may be due in part to transient mass transfer effects characteristic of the clays. The contaminant release characteristics from clay may differ from the conventional initial concentration

"spike" observed as the initial pore volume is flushed out in soil vacuum extraction applications from more permeable formations. During the final heating period (April 8 to April 27), the PCE concentration does appear to cycle in direct response to changes in well wall (control) temperature (i.e., RF power output cycles). However, the changes detected appear to be near or within the statistical error of the sample set or may result from stripping occurring as steam is formed (discussed later). It was unfortunate that extraction was unable to continue independently from applicator handling. Since the well had to be opened to the surface during these times, extraction could not continue, preventing possible observation of a steady PCE concentration decrease over several sample periods. A one-to-one correlation between RF input and concentration is needed to decisively conclude a positive RF effect.

The total volume of water extracted from the well during the demonstration (approximately 250 gallons) played a small role in the overall mass removal of contaminants. The removal rates for both water and condensate varied from a few to as high as 15 gallons per day (typical rates ranged from 5 to 10 gallons per day). Samples of the water and condensate removed from the well were periodically analyzed for TCE and PCE content using an ion trap mass spectrometer (ITMS). The PCE concentrations in the water were typically between 80 and 100 ppb (ug/l), while concentrations in the condensate were between 35 and 50 ppb. The TCE concentrations were below 10 ppb in both water and condensate samples. These water concentrations are approximately an order of magnitude below levels calculated from Henry's Law constants assuming equilibrium with the measured gas-phase concentrations at the well head during heating. It can be assumed, therefore, that the bulk of the CVOCs removed during the heating stage of the demonstration were extracted from the formation as vapor. However, small variations in the wellhead gas concentrations (on the order of 10 to 20%) in response to the measured wall temperature could result from the enhanced thermal stripping of water either within the formation, infiltrating into or free standing in the well. No water was extracted during the cooldown stage of the demonstration.

Figure 5-12 displays the contaminant concentrations measured at the wellhead during the cooldown portion of the demonstration. The dramatic rise in PCE and TCA levels correlates with both the increased flow and extended zone of influence from the well vacuum experienced during the cool down period. These effects will be discussed further in Section 5.2.3.2. The TCE concentration also increased, but not as dramatically.

The initial concentrations of TCA (1,1,1-trichloroethane) were close to the typical levels observed in previous soil gas measurements conducted at the site; approximately 10

to 20% of the TCE levels. Use of this solvent began in 1979, and it is estimated that it made up less than 2% of the chlorinated solvents sent through the process sewer line (Marine and Bledsoe, October 1984, "Supplemental Technical Data Summary; M-Area Groundwater Investigation" DPSTD-84 112). The TCA concentrations continued to rise during the heating stage and surpassed TCE levels just before shutting down power to the applicator. The concentrations were estimated as no TCA gas standard was available at the time of the demonstration. The estimate was made assuming TCA would have a response similar to TCE for the electron capture detector (typically concentrations less than 500 ppmv) and have a response similar to PCE for the flame ionization detector (concentrations greater than 500 ppmv). Subsequent analysis of a TCA gas standard has shown this assumption to be accurate within 5 to 10%. The concentration of TCA during the cooldown stage of the test continued to rise dramatically approaching levels of nearly two-thirds those of PCE. The reason for this large source of TCA is uncertain. Soil concentrations in core samples for this demonstration and other tests conducted at the site are currently being studied to determine the location of the source. The presence of TCA was not critical to continued operation of the demonstration. It is not on the SCDHEC list of toxic substances, and is actually destroyed more efficiently with the thermal catalytic offgas system.

5.2.2.4 Catox System Operation

The overall destruction efficiency for CVOCs by the Catox system was below expectations. Destruction efficiencies for PCE ranged from 75 to 90% at temperatures from 450 to 500°C (typical values of 80% were observed at the higher concentrations encountered at the end of the demonstration). Degradation in destruction efficiency is believed to arise from bypassing the catalyst block resulting from progressively growing leaks in the ceramic insulation. It should be noted that the catalyst block mounting frame was field modified to properly fit the catalyst block. The modification was made to correct a design error in the required catalyst volume made by the system manufacturer. The destruction efficiency of TCA was higher than PCE, with typical values in the range of 90 – 95%. The TCE concentration levels measured at the Catox inlet and stack were generally too low to make a realistic assessment of destruction performance.

Figures 5-13 and 5-14 are plots that respectively show cumulative values of contaminants extracted and system discharges for the demonstration. Table 5.1 summarizes the extraction and discharge data of all constituents for the heating portion as well as the entire demonstration.

Table 5.1 Total mass of chlorinated solvents extracted and total mass emissions to the atmosphere

Compound	End of Heating Stage		End of Cool Down Stage	
	Extracted (kg)	Emitted (kg)	Extracted (kg)	Emitted (kg)
Perchloroethylene	11.8	1.9	116.5	24.9
Trichloroethylene	2.0	.01	6.9	0.9
1,1,1-Trichloroethane	.14	.01	48.1	4.1
Hydrochloric Acid ⁽¹⁾	-	9.5	-	120.9
Carbon Dioxide ⁽¹⁾	-	6.0	-	81.3

(1) Calculated based on complete oxidation of chlorinated organics

Table 5.2 Distances (in feet) from temperature monitoring locations to nearest point on RF applicator (calculations based on field well surveys and logs).

Temperature Monitoring Borehole (Distance to Applicator)	"A" (48 ft)	"B" (38 ft)	"C" (28 ft)
MHV-20T (to applicator feed end)	13.9	11.6	16.6
MHV-21T	11.3	8.3	14.6
MHV-22T (to applicator tip)	12.8	10.1	15.5
MHV-24T	9.4	6.1	13.7

5.2.3 Field Monitoring

5.2.3.1 Subsurface Temperature

Figure 5-15 displays a plot of subsurface temperature measurements at selected points in the clay ("B" labeled locations at a depth of 38 feet). The points selected include the four nearest the applicator that indicated a response (MHVs -20T, -21T, -22T, and -24T) and one located in the control zone (MHV-28T) to provide a baseline reference. Table 5.2 lists the distance from each heated zone monitoring location to the applicator (located at a depth of approximately 40 feet). The subsurface temperature sensor at the MHV-24T B position (referred to as simply 24B for this discussion) responded almost immediately to RF power application. This point was used as the primary indicator of heating progress throughout the demonstration.

The greatest rate of temperature increase observed at the 24B sensor was 0.2°F/hr, which occurred during the first prolonged heating period (March 28 to March 31). Following this period, the heating rate dropped significantly, responding rapidly to suspension of RF energy application. The temperature rise continued without RF applica-

tion at a rate of approximately 30% of the initial value. The immediate response to suspension of RF application suggests heating at the 24B point was primarily caused by the RF field. The residual temperature increase observed during the period of no RF input gives an initial measure of the rate of thermal conduction within the subsurface. When applicator power output was resumed (April 3 to April 16), the rate returned to an elevated value of approximately 0.14°F. Over the period in which the applicator control temperature was lowered (April 16 to April 19), the rate nearly leveled off, again responding rapidly to reduced power output from the applicator. As the applicator power output was stepped up over the final week of the heating stage, the rate of temperature increase responded directly, but with diminishing magnitude. The inability to achieve the initial rate of temperature increase, even at higher applicator energy output, suggests that the contribution of heat transfer due to conduction gradually increases relative to the RF field contribution (at a radial distance greater than 6 feet). This conclusion is supported by the observation that the rates near the end of the heating stage were equal to those observed without applicator power output following the first prolonged heating period: approximately 0.05 – 0.06°F/hr (March 31 to April 3). Conduction rates at a fixed location should change as temperature gradients vary with time. However, a distinct drop in the absorption of RF energy at a fixed radial distance from the applicator is apparent. This result is consistent with the observation of increased electrical conductivity measured with electrical resistance tomography (Ramirez and Dailey 1993). The attenuation rate of radio frequency waves is proportional to the electrical conductivity of the absorbing media (sediments). As the conductivity within the heated zone rose, the attenuation increased. Therefore, more energy was absorbed in the inner, hot core surrounding the applicator. If this inner region was near or above 100°C, the conductivity should drop as water is removed as vapor. Attenuation would decrease even further as water vapor will not absorb RF

energy. However, once a significant vacuum was lost in the well when steam was formed, there was no driving force to remove the water vapor generated in the formation. It is therefore possible that only a small volume was heated to temperatures above 100°C, and/or that RF energy was spent heating the same water as it vaporized and condensed within the formation.

An immediate drop in temperature was measured at 24B in response to stopping RF power output. The rate of decrease at 24B during the cooldown portion of the demonstration nearly matches the heating rate, and may offer further evidence that heat transfer at 24B was primarily conductive in the latter period of the heating stage. However, the effect of vacuum influence (i.e., air flow) must again be considered when comparing the heating stage to the cooling stage. The heated zone was effectively isolated from the vacuum in the well by the vapor lock, creating a virtual stagnant environment. During cooling, more air was flowing through the heated zone formation, evidenced by the greater zone of influence described later in Section 5.2.3.2. Therefore, the initial rapid drop in temperature, at rates equal to or greater than during the heating stage, can be an effect of the added heat loss to air being pulled through the formation.

Figures 5-16 and 5-17 respectively display plots of subsurface temperature measurements in the "A" (48-foot depth) and "C" (28-foot depth) horizontal planes of the monitoring boreholes. The measurements in the "A" plane indicate a greater temperature response than the "C" measurements because they are approximately 25 to 30% closer the RF applicator (see Table 5.2). Although the flow from the formation was limited during the heating portion of the demonstration, the bulk of what little flow was observed appeared to originate from the above the clay, thereby providing added cooling to the region above the applicator. This conclusion is based on the greater vacuum response at the "C" plane piezometers relative to the "A" plane piezometers throughout the demonstration (see Section 5.2.3.2).

While the temperature monitored at 24B responded rapidly to halting of RF power output, the temperature measurements for all other monitoring points continue to rise for a period after RF application was terminated on April 27, 1993. This continued rise in temperature suggests that conduction is the primary heat transfer mechanism at these distances from the applicator.

Figures 5-18 – 5-24 are three-dimensional images of temperature distributions surrounding the applicator which show the progression of heating/cooling of the subsurface strata between April 3, 1993 and May 10, 1993. Figure 5-

25 is an image of the modeled heated zone (based on KAI modeling data). The images were generated from irregularly spaced scattered data sets using a commercially available three-dimensional (3-D) modeling software package (Interactive Volume Modeling [IVMTM], version 5.0, Dynamic Graphics, Alameda, CA). The software transforms the data sets into a regularly spaced 3-D grid using a technique of minimum tension gridding that employs a bi-cubic spline algorithm. For further information on the manipulation of parameters required to run the program, refer to the following references:

R. L. Nichols, B. B. Looney, J. E. Huddleston, "3-D Digital Imaging; Revealing the Location, Depth, and Concentration of Subsurface Pollutants," *Environmental Science and Technology*, 26, 1992, 642-649;

C. A. Eddy and B. B. Looney, "Three-Dimensional Digital Imaging of Environmental Data: Selection of Gridding Parameters", *Int. J. Geophysical Information Systems*, 7(2), 1993, 165-172

The data sets for the field test images were constructed of thermocouple data from monitoring borehole (core temperatures taken on the final day of heating were also used). The data sets used for images of the heating stage also included the down hole fluorescence decay fiber optic measurements at the screen wall. The images made after the termination of RF application do not include applicator temperature data as input to the gridding program. Therefore, the post-heating images were produced without data from the 40-foot depth, causing them to appear to have a center point located higher, at the 38-foot level (the "B" plane), above the position of the horizontal well. The data set for the model was generated by rotating a two-dimensional temperature contour plot around the applicator axis.

Table 5.3 provides a listing of calculated heated subsurface volumes in cubic feet, segmented by temperature ranges within the volume and total energy coupled to the formation on the dates corresponding with Figures 5-18 – 5-24 and the predicted values corresponding with Figure 5-25. It should be noted that the volumes calculated from fitting the field data with temperatures of less than 50°C should be adjusted upward approximately 10 to 20%. This adjustment must be made to account for the position of the grid model boundaries, which clip off part of the zone north (toward MHV-23T and) and west (beyond MHV-24T) of the applicator. This clipping is performed in an effort to limit extrapolation beyond actual data point locations to reasonable boundaries. The data from the model were fit with the same gridding parameters and clipping surfaces to ensure that any biases introduced by the fitting program are minimized.

The KAI modeling of temperature distributions was performed without consideration of the temperature limit of the fiberglass screen, mass transport of air and water (as liquid or vapor), nor the latent heat effect for the vaporization of water. The omission of these critical factors was the overriding cause of overestimating the predicted heated subsurface volume, and explains the differences between Figures 5-22, the actual heated volume at the termination of RF application, and Figure 5-25, the predicted heated volume. The primary focus of model used by KAI, however, is to map changes in the effective borehole impedance (casing and surrounding sediment) to ensure proper matching with the output impedance of the applicator as temperatures and dielectric properties change throughout the demonstration. Since the maximum temperature measured in the monitoring boreholes was 63°C, the gridding program fit may not adequately describe the hotter region surrounding the applicator (i.e., radial distances within six feet). Therefore, the most accurate measure of the field performance relative to the model can be made by comparing volumes heated to temperatures greater than 60°C. While the actual heated zone (>60°C) volume was only approximately 50% of that predicted by the KAI model, the total affected volume (i.e., volume raised above ambient temperature conditions) was much larger than predicted. The model temperature distribution, however, was predicted following a continuous power application of 20 kW for 21 days. The energy delivered in the field, while very close to that used in the model, occurred over a 34-day period. Therefore, the larger affected volume is the result of a longer time provided for conduction of heat out from the hotter regions around the applicator.

5.2.3.2 Soil Vacuum Levels

There was little observed influence from the well vacuum measured at the piezometers over the course of the initial ambient extraction and heating stage of the demonstration. These piezometers vary in radial distance from the well, ranging from 9 to 36 feet (see Figure 4-6). At these distances, the low zone of influence is not surprising given both the low permeability of the clays and the reduced vacuum achieved in the well during the heating stage with the formation of a steam block down hole. During this period, the measured vacuum levels rose and fell in response to swings in the barometric pressure. The amplitude of the swings was dampened relative to barometric and the periodicity displayed a typical time lag of one to two days. Figures 5-26 – 5-28 display the vacuum levels measured at each depth monitored with the piezometers (depth levels A - C respectively) over the course of the final heating periods and the initial 10 days of cooldown (note that the barometric pressure is plotted as a difference above 1000 mbar in these figures). While the drawdowns

during heating were small, a distinctly greater effect, on the order of a few mbar, was observed in the "C" piezometers screened above the clay layer. A dramatic change in the vacuum effect is observed after heating has stopped. At this point, the drawdowns increase significantly in response to higher vacuum levels in the well as the temperature dropped and the steam block dissipated. The greatest drawdowns are, again, observed in the sediment above the clay ("C" piezometers), with the most significant effects observed in the control zone wells (MHV-27C - 29C) and the well nearest the applicator (MHV-24C). In addition, the variance observed between readings from a single well at different depths increases to values greater than 10 mbar.

The results of a "pump" test conducted three days into the cooldown stage (April 30) illustrate the effects described above. Figure 5-29 is a plot of the drawdown observed in MHV-24 following resumption of vacuum extraction. This figure displays how the vacuum effect experienced in the "C" piezometer screened above the clay layer was significantly greater than that observed both within and below the targeted clay. Figure 5-30 is a plot of the drawdown observed in several "C" piezometers located at varying distances from the wellhead (vacuum source). This figure displays how the vacuum effect diminished as one moves progressively further from the well head. The drawdown observed nearer the start of the screen zone (MHV-28C) is significantly greater than that observed beyond the applicator location (MHV-23C). The drawdowns observed at the two piezometers located at the applicator (MHV-24C and MHV-21C) are intermediate to those observed upstream and downstream of the heated zone. The drawdown at MHV-24C is greater than that at MHV-21C, although both are located roughly perpendicular to the applicators center, because it is approximately twice as close to the horizontal well (a distance of 9 feet for MHV-24C vs 17 feet for MHV-21C; MHV-28C and MHV-23C are approximately 13 feet and 18 feet from the well, respectively). These results suggest that the bulk of the flow entering the well originates from above the clay and is strongest in the control zone at the start of the screened zone.

5.2.3.3 Soil Gas Concentrations

Soil gas concentrations taken at the piezometers were used to monitor for evidence of enhanced volatility, to observe the effects of changes in permeability, and as indicators of the primary source locations for concentrations observed in the well offgas. In general, CVOC concentrations at all the monitoring wells either rose gradually over the course of heating or showed little change. Similar to the vacuum effects discussed above, the greatest concentration

changes were observed after heating stopped. Figure 5-31 is a graph of the PCE concentration measured at the "C" piezometers located within and surrounding the heated zone over the course of the entire demonstration. The most dramatic rise in concentration is observed at MHV-25C, located approximately 36 feet west of the well. This dramatic rise was also observed in the control zone piezometers located west and south of the heated zone. The rise in concentration, coincident with the enhanced zone of influence from the well following heating suggests that a "hot" pocket of residual solvents located west and south of the heated zone, perhaps even beyond the location of the piezometers, is a significant contributor to the total rate of contaminants extracted. This conclusion is also supported by observing the 24- to 36-hour delay between resumption of vacuum extraction following heating and the rise in CVOC concentration observed in the well offgas (see Figure 5.6). Such a delay would result from the greater mean travel time required for vapors from this high concentration source to reach the horizontal well. The conclusion that the bulk of the flow into the well originates from the control zone is also supported by the soil gas data. In particular, the unexpected appearance of high concentrations of TCA permitted the advantageous use of this compound as a tracer in the soil gas measurements. While the relative concentration of TCA was found to increase in nearly all the piezometers, again, the most dramatic rise was observed in the control zone. Figure 5-32 is a plot of the TCA/TCE ratio measured in the soil gas from the control zone piezometers together with the TCA/TCE ratio observed in the well offgas. A strong, direct correlation exists between the relative and absolute TCA concentrations observed in the control zone and the coincident rise observed in the well offgas. Therefore, both the draw down data and the soil gas data are consistent with the piezometer measurements taken within the horizontal well, all of which show that the bulk of the flow entering the well originates from the control zone near the start of the well screen.

5.3 Demobilization

5.3.1 Failure to Retrieve Applicator

During the latter stages of the demonstration it was decided to maximize RF energy coupling to the formation. To accomplish this, the control temperature was increased to 130°C, exceeding the maximum temperature rating of the well liner by 10°C. While operating at 130°C, a hot spot on the transmission line reached a temperature as high as 170°C. Therefore, it is highly probable that either the well liner deformed and/or sagged around the applicator; or the applicator/transmission line melted into the liner. In any case, when an attempt to retrieve the applicator

was made it was found securely stuck at its original position even with an application of 600 pounds of tension force. Application of greater force was attempted, causing the transmission line to fail and break free at the flex-rigid coaxial cable joint. Excavation to retrieve the applicator is not planned.

5.4 Demonstration Economics

5.4.1 Background For Economic Basis

Commercial remediation costs are influenced by the physical and chemical characteristics of the targeted contaminant and sediment, the depth of the targeted sediment, and the size of the site to be remediated. The in situ RF heating demonstration at SRS was the first attempt at vacuum extraction of VOCs from a horizontal well screened entirely in a clay layer. Based on the observations at SRS, it appears that remediation by vacuum extraction from low permeable, high moisture content clay sediments will be a relatively long, time-consuming process. The subsurface vacuum levels obtained in the clay during the demonstration are approximately an order of magnitude smaller than vacuum levels obtained with similar processes operated in more permeable sediment. Assuming a direct relationship between subsurface vacuum levels and flow in the formation, remediation time may increase by as much as a factor of ten, indicating variable costs will also increase by a similar factor. In addition, the high moisture content of the clay (~80%-90% by weight) suggests heating the sediments will require considerable energy due to the relatively high heat capacity of water (with respect to the soil). The energy requirements for heating become even more significant if subsurface target temperatures exceed 100°C and latent heat effects become applicable. For the heating to be advantageous, its anticipated consequential effects (i.e., increased volatilization rates, increased soil permeability and flow because of drying and cracking of the clays, and steam stripping effects) must reduce remediation time or increase contaminant removal efficiency to a degree that justifies the cost of the added energy input.

The integrated system design, time constraints, and problems encountered in this demonstration, when viewed collectively, did not permit acquiring enough information to reasonably define a treated volume or project a total remediation time on which a commercial cost projection could be based. A typical cost analysis should have as its basis a treated volume (i.e., \$/yd or \$/ton) based either on a final acceptable contaminant level or, perhaps more applicable in this instance, a volume heated to or above a predetermined temperature goal. It was understood at the outset of

this demonstration, that a final contaminant level would be an inappropriate criteria for assessing the success of the test. Such a criteria would be inappropriate because the scale of the contaminant plume is far larger than the zone of influence of either the vacuum or RF radiation. Therefore, criteria for success of this demonstration were focused on increases in rate of removal and heating efficiency (i.e., efficiency of the RF energy coupling to the clay). Unfortunately, the single well design adversely affected vacuum levels attained down hole and, consequently, extraction rates when a steam block formed. In addition, the choice of well casing material and water influx events placed limitations on the applicator duty cycle, which reduced the amount of energy that could be coupled to the clays over the time frame of the test. Therefore, a projected cost based on the volume of sediments heated would be misleading. As a result, the analyses presented in this report list costs for the actual demonstration and projected costs on a kWh basis (delivered to the sediments).

5.4.2 Demonstration Costs

The total cost of the in situ RF heating demonstration was on the order of \$850,000. This cost includes engineering costs and subcontractor fees that normally would not be considered in commercial cost projections. Table 5.3 shows the breakdown of demonstration costs per function area and the bases for calculation. Table 5.4 shows how capital installed costs were determined. Capital installed costs and depreciation charges for the RF delivery equipment are not included in Table 5.3 because this equipment was "rented" at a negotiated fixed price for the entire demonstration. The capital cost of \$500,000 provided by KAI includes first time engineering costs and analytical equipment costs that would not be required in a commercial unit.

5.4.3 Commercial Cost Projections

Since the RF heating demonstration did not provide enough information or insights to define or project a treatment volume, this analysis will focus on understanding the daily variable costs associated with a remediation operation. In addition to the variable costs, there will be fixed costs that are site-dependent and site-independent. Examples of site dependent fixed costs are the costs for treatability studies and well preparation. Independent fixed charges include mobilization, demobilization, and amortization of capital equipment.

Table 5.5 projects operating costs for a commercial remediation activity from clay sediments using a similar process, with energy requirements and a time period analogous to the RF heating demonstration. Major assumptions for this case are:

- AC electric power will be supplied by rented diesel generators at an average charge of \$0.10/kW-hr (includes both rental and fuel costs)
- Daily sampling at the Offgas Treatment unit inlet and outlet will be required by state/local regulators as a minimum.
- Samples will be secured and analyzed by a subcontracted service on a price-per-sample basis.
- Capital costs of a 25 kW commercial RF delivery unit will be approximately \$200,000 (based on KAI projection).
- Site selected and well design is analogous to the SRS site, including use of:
 - a single horizontal well with same insertion angle, liner material, transition radius, and depth
 - vertical monitoring wells of same depth
 - an identical vacuum extraction/catalytic oxidation system
- The horizontal well will be terminated in the subsurface targeted area (i.e., well will not be open on both ends).
- RF coupling efficiencies will be approximately the same as with the SRS demonstration.

Other assumptions are listed on Table 5.4a. Table 5.4b summarizes the projected capital costs associated with the commercial system.

In this case, the daily variable costs for the remediation operation are approximately \$325/day. The costs assigned for the RF delivery (\$95/day), offgas treatment (\$102/day) and monitoring (\$27/day) areas are reasonably accurate based on the SRS experience. The analytical cost, however, will be dependent on permit sampling requirements and may have considerable variability from location to location. If sampling requirements were reduced to a weekly or monthly basis, the daily variable costs could be reduced into the \$230/day to \$250/day range.

Well preparation and treatability determination costs also will vary from site to site. The costs assigned to this case were an attempt to fit a commercial projection to the SRS conditions and approximate minimum charges. Approximately two-thirds of these site-dependent fixed costs are attributable to well preparation. Since horizontal well drilling charges are 8-10 times higher than of vertical well charges, careful consideration of horizontal well benefits versus cost should be employed prior to final selection extraction/monitoring well layouts. A minimum cost on the order of \$45,000 for site-dependent fixed charges can be expected. These costs will vary directly with the number, orientation (horizontal, slant or vertical), and length of required wells (site size). Attempts to establish variance boundaries for site dependent costs would be completely

Table 5.4 Actual Cost Associated with RF Demonstration

Total Test Duration (man days) -	88
Duration of RF Operation (man days)	40
Loaded SRS Labor Charge (\$/hr)	60
Loaded SRS Supervision Charge (\$/hr)	100 Basis: 8 hr/day
Length of Horizontal Well (ft)	580
Horizontal Well Drilling Charge (\$/ft)	110
Number of Monitoring Boreholes Req'd	20
Vertical Well Drilling Charge (\$/ft)	10
Depth of Vertical Borehole (ft)	55
Total AC Input Power to RF Generator (kW-hr)	21200
Load for RF Aux and Monitoring Equip (kW)	6
Total Measured Forward Coupled RF Power (kW-hr)	13800
RF Coupling Efficiency	0.85
Total "RF on" hours	651
Total Hours RF FWD Coupled Power >20 kW	543
Total AC Power Required by CATOX System (kW-hr)	74000 Basis: Avg. supply - 480 volts, avg. current req'd-73 amps over the course of the job

Costs	Factor	RF Delivery	Offgas Treatment	Well Prep/ Monitoring	Analytical	Field Support	Totals
Capital Installed Cost (CIC)			\$121,440		\$50,900		\$172,340
Direct Production Costs							
Site Operating Labor (OL)		\$2,880	\$21,120	\$21,120	\$84,480		\$129,600
Direct Supervision Labor(s)		\$8,800	\$26,400		\$35,200		\$70,400
Electricity (diesel)	0.1	\$2,696	\$7,400	\$924			\$11,020
Maintenance and Repairs (M) Est.)		\$2,000	\$2,000				\$4,000
Operating Suppliers (% of M)	0.05	\$100	\$100		\$7,789		\$7,989
Total Direct Production Costs		\$16,476	\$57,020	\$22,044	\$127,469		\$223,009
Total Direct Production Costs per Day of Operation		\$412	\$648	\$251	\$1,449		\$2,759
Fixed Charges							
Westinghouse Divisional Support						\$150,000	\$150,000
Subcontract Labor (lump sum-IWR)		\$139,646				\$91,390	\$231,036
Depreciation (% CIC)	0.1		\$2,969		\$1,244		\$4,213
Horizontal Wells				\$69,510			\$69,510
Monitoring Wells				\$86,481			\$86,481
Treatability		\$89,745					\$89,745
Total Fixed Costs		\$229,391	\$2,969	\$155,991	\$1,244	\$241,390	\$630,985
Total Product Cost (TPC)		\$245,867	\$59,989	\$178,035	\$128,713	\$241,390	\$853,994

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Area	Item	Quantity	Capacity	Vendor	Contact	Date	Price Each (\$)	Total Cost (\$)	Area Cost (\$)
RF Delivery	System, including RF generator amplifier controls cable applicator	1	25 kW	KAI Technologies, Inc.	D. L. Faust	9/21/93	\$500,000	\$500,000	
Total									\$500,000
Offgas Treatment System	Thermal Catalytic	1	200 SCFM	Brown Engineering Company	R. Schulke	11/92	\$120,000	\$120,000	
	Halocarbon Destruction System Installation	24 man-hours	SRS Construction				\$60	\$1,440	
Total									\$121,440
Horizontal Well	Centron Slotted Liner and Press Installation, Drill and line	580	1 ft	Centron			\$12	\$6,960	
			580 per ft	Charles Machine Works			\$102	\$59,160	
	Well head/pad/posts	2 each		Charles Machine Works			100	200	
	Oversite	400 man-hours		CDM Federal			\$60	\$2,400	
	Air lift pump	1 each		TIMCO			\$205	\$205	
	Vacuum pump (rotary vane)	1 each		Cole-Palmer	93-'94 Catalog		\$300	\$300	
	Tubing/valves/solenoid/timer		1 lot	Various			\$285	\$285	
Total									\$69,510
Monitoring Well	Liner, temp monitoring	10	45 ft	McMaster-Carr	Catalog #98		\$57	\$570	
	Piezometer	30	45 ft	McMaster-Carr	Catalog #98		\$29	\$857	
	Termocouples Type T, teflon Ins.	30	100 ft	Omega	Catalog #28		\$43	\$1,290	
	Fiber Optic Probes & Cable	45	100 ft	SRTC Analytical Dev			\$167	\$7,515	
	Spectrophotometer	1			Eng. Est.		\$10,000	\$10,000	
	Data Acquisition System	1			Eng. Est.		\$3,000	\$3,000	
	Installation, drill, coring	1100 per ft					\$50	\$55,000	
		10	55ft				\$825	\$8,250	
Total									\$86,481
	Gas Chromatograph and Integrator	1			Eng. Est.		\$50,000	\$50,000	

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Area	Item	Quantity	Capacity	Vendor	Contact	Date	Price Each (\$)	Total Cost (\$)	Area Cost (\$)
	Sampling Pump (rotary vane)	3		Cole-Palmer	93-'94 Catalog		\$300	\$900	
Total									\$828,331

Table 5.5 Commercial Cost Projection Case: Basis - Time Period and Electric Power Costs Consistent with SRS Demonstration

Nominal Treatability Determination Charge (\$)	10000
Total Job Duration (man days)	88
Time RF System AC Power (man days)	35
Loaded Labor Charge (\$/hr)	100 Bases: One Full Time (8 Hr/Day) Attendant during Routine Operation
Length of Horizontal Well (ft)	175
Horizontal Well Preparation Charge (\$/ft)	110
Number of Monitoring Boreholes Req'd	4
Vertical Well Preparation Charge (\$/ft)	50
Depth of Vertical Borehole (ft)	55
Total AC Input Power to RF Generator (kW-hr)	21200
Load for RF Aux and Monitoring Equip (kW)	6
Total Measured Forward Coupled RF Power (kW-hr)	13800
RF Coupling Efficiency	0.85
Actual RF Power Coupled to Formation (kW-hr)	11730
Total AC Power Required by Catox System (kW-hr)	74000 Basis: Avg Supply - 480 Volts, Avg Current Req'd - 73 AMPS over the Course of the Job
Number of Samples Required per Day	2
Cost per Analysis (\$)	50
Time Required to Mobilize/Demobilize (man-hours)	32

Costs	Factor	RF Deliver	Offgas Treatment	Well Prep/ Monitoring	Analytical	Totals
Capital Installed Cost (CIC)		\$200,000	\$120,000			\$320,000
Variable Production Costs						
Site Operating Labor (OL)		\$183	\$1,283	\$1,467		\$2,933
Electricity (diesel)	0.1	\$2,624	\$7,400	\$924		\$10,948
Maintenance and Repairs (M) (% of CIC)	0.01	\$489	\$293			\$782
Operating Supplies (% of M)	0.05	\$24	\$15			\$39
Laboratory Charges					\$8,800	\$8,800
Total Variable Cost (over defined time period)		\$3,321	\$8,991	\$2,391	\$8,800	\$23,503
Variable Cost per Day		\$95	\$102	\$27	\$100	\$324
Variable Cost per kW-hr RF Power Delivered to Formation		\$0.28	\$0.77	\$0.20	\$0.75	\$2.00
Site Dependent Fixed Charges						
Horizontal Wells				\$21,350		\$21,350
Monitoring Wells				\$11,843		\$11,843
Treatability		\$10,000				\$10,000
Total Site Dependent Fixed Cost		\$10,000	\$0	\$33,193	\$0	\$43,193
Independent Fixed Charges						
Mobilization (basis: one RF deliver, one offgas treatment unit)		\$3,200	\$1,600			\$4,800
Depreciation (% CIC, annual basis)	0.1	\$4,889	\$2,933			\$7,822
Demobilization (basis: one RF deliver, one offgas treatment unit)		\$3,200	\$1,600			\$4,800
Total Independent Fixed Cost		\$11,289	\$6,133	\$0	\$0	\$17,422
Total Product Cost (TPC) (over defined time period)		\$24,610	\$15,125	\$35,584	\$8,800	\$84,118
TPC per kW-hr RF Power Delivered to Formation (88 Days)		\$2.10	\$1.29	\$3.03	\$0.75	\$7.17

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Area	Item	Quantity	Capacity	Vendor	Contact	Date	Price Each (\$)	Total Cost (\$)	Area Cost (\$)
RF Delivery	System, including RF generator amplifier controls cable applicator	1	25 kW	KAI Technologies, Inc.	D. L. Faust	9/21/93	\$200,000	\$200,000	
Total									\$200,000
Offgas Treatment System	Thermal-Catalytic	1	200 SCFM	Brown Engineering Company	R. Schulke	11/92	\$120,000	\$120,000	
	Halocarbon Destruction System								
Total									\$120,000
Horizontal Well	Centron Slotted Liner and Press Installation, Drill and line	175	1 ft	Centron			\$12	\$6,960	
			175 per ft	Charles Machine Works			\$110	\$19,250	
Total									\$21,350
Monitoring Well	Liner, temp monitoring	20	50 ft	McMaster-Carr	Catalog #98		\$57	\$114	
	Piezometer	6	50 ft	McMaster-Carr	Catalog #98		\$29	\$171	
	Termocouples Type T, teflon Ins.	6	100ft	Omega	Catalog #28		\$43	\$258	
	Installation, drill, and line	220 per ft					\$50	\$11,000	
	Sampling Pump (rotary vane)	3		Cole-Palmer	93-'94 Catalog		\$300	\$300	
Total									\$353,193

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speculative at this point and will not be included in this analysis.

Mobilization, demobilization, and capital depreciation charges will be incurred independent from site. These charges will typically be on the order of \$18,000 for a capital equipment investment of \$320,000 over a 90-day operation. Total depreciation costs are time dependent and will increase linearly at a fixed rate (\$97/day) for each additional day of operation.

In all, the total cost for a single horizontal well, 90 day operation will be on the order of \$110,000. This cost may vary by as much as $\pm 50\%$ depending on particular sampling and analytical requirements.

Preheat 5 scan L=150, Return Loss 8-Apr-93 15:02:14 WSR553.TXT

Figure 5-1. Network Analyzer Scan of Return Loss prior to Final Heating Period on April 8

Preheat scan L=144 @ RF, Return Loss 24-Mar-93 10:54:44 WSRS05.TXT at 13.56MHz

WSRS0501.01L NWA 1-31 Preheat scan L=144 @ RF, Return Loss 24-Mar-93 10:54:44
WSRS0501.01L ... WSRS0520.01L

Figure 5-2.

Return Loss Scan at 13.56 MHz Versus Downhole Distance Data from Pre-heating Stage on March 24

Figure 5-5. Well Flow, Applied Vacuum and Well Wall Temperature 4/8/93 - 4/27/93

Figure 5-6. Well Flow, Applied Vacuum and Well Wall Temperature 4/27/93 - 5/31/93 (Cooldown Period)

Figure 5-7. Comparison of Well Wall Temperature to Subsurface Temperature Measured @ MHV-24T "B" (38 foot depth in clay zone)

Figure 5-8. Horizontal Well Piezometer Data Related to Well Wall Temperature During RF Heating Demonstration

Figure 5-9. Exploded View of Figure 5-8 During the Final Heating Stage of the RF Heating Demonstration

Figure 5-10. Horizontal Well Piezometer, Flow, and PCE Concentration Data During Early Stages of Cool down

Figure 5-11. Contaminant Concentration During Heating Portion of Demonstration

Figure 5-12. Contaminant Concentration During Cool Down Portion of Demonstration

Figure 5-13. Cumulative Contaminants Extracted

Figure S-14. Cumulative Discharges to Environment

Figure 5-15. Subsurface Temperatures in Clay at 38 ft Depth

Figure 5-16. Plots of Temperatures Measured at <18-ft Depth

Figure 5-17. Plot of Temperatures taken at 28-ft Depth

Figure 5-18. Three Dimensional Image of Temperature Distribution on 4/3/93

Figure 5-19. Three-Dimensional Image of Temperature Distribution on 4/9/93

Figure 5-20. Three-Dimensional Image of Temperature Distribution on 4/16/93

Figure 5-21. Three-Dimensional Images of Temperature Distributions on 4/21/93

Figure 5-22. Three-Dimensional Image of Temperature Distributions on 4/27/93

Figure 5-23. Three-Dimensional Image of Temperature Distributions on 5/3/93

Figure 5-24. Three-Dimensional Image of Temperature Distributions on 5/10/93

Figure 5-25. Three-Dimensional Image of RF Heating Model Temperature Distribution

Figure 5-26. Vacuum Levels at a Depth of 48 Feet

Figure S-27. Vacuum Levels at a Depth of 38 Feet

Figure 5-28. Vacuum Levels at a Depth of 28 Feet

Figure 5-29. Plot of Drawdown in Well MHV-24 after Vacuum Extraction Resumed

Figure 5-30. Plot of the Drawdown in Several "C" Piezometers at Varying Distances from the Wellhead

PCE Vapor Concentration at 6 Heated Zone Wells

Figure 5-31. Graph of PCE Concentration at "C" Piezometers Located within and Surrounding the Heated Zone of the Demonstration

Figure 5-32. Plot of TCA/TCE Ratio Measured in the Soil Gas from the Control Zone Piezometers

6.0 References

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