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ELECTRICAL RESISTANCE HEATING OF SOILS AT C-REACTOR AT THE SAVANNAH RIVER SITE

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ABSTRACT

Chlorinated solvent contamination of soils and groundwater is an endemic problem at the Savannah River Site (SRS), and originated as by-products from the nuclear materials manufacturing process. Five nuclear reactors at the SRS produced special nuclear materials for the nation's defense program throughout the cold war era. An important step in the process was thorough degreasing of the fuel and target assemblies prior to irradiation. Discharges from this degreasing process resulted in significant groundwater contamination that would continue well into the future unless a soil remediation action was performed. The largest reactor contamination plume originated from C-Reactor and an interim action was selected in 2004 to remove the residual trichloroethylene (TCE) source material by electrical resistance heating (ERH) technology. This would be followed by monitoring to determine the rate of decrease in concentration in the contaminant plume. Because of the existence of numerous chlorinated solvent sources around SRS, it was elected to generate in-house expertise in the design and operation of ERH, together with the construction of a portable ERH/SVE system that could be deployed at multiple locations around the site. This paper describes the waste unit characteristics, the ERH system design and operation, together with extensive data accumulated from the first deployment adjacent to the C-Reactor building. The installation heated the vadose zone down to 62 feet bgs over a 60 day period during the summer of 2006 and raised soil temperatures to over 200 °F. A total of 730 lbs of trichloroethylene (TCE) were removed over this period, and subsequent sampling indicated a removal efficiency of 99.4%.

Key words: Electrical Resistance Heating, Savannah River Site, Reactor, trichloroethylene

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INTRODUCTION

The Savannah River Site (SRS) is a 310 square mile Federal facility located near to Aiken, South Carolina. The site is owned by the U.S. Department of Energy (DOE) and is operated by the Washington Savannah River Company with Bechtel Savannah River Company being responsible for the Environmental Restoration program. SRS was built in the early 1950's to produce special nuclear materials for the nation's defense program. SRS operated throughout the Cold War era until the late 1980's when the site transitioned to environmental clean up activities. The central components of the production process at SRS, were the 5 nuclear reactors which irradiated special target materials to generate the plutonium and tritium. The nuclear fuel and target materials were fabricated into assemblies in the manufacturing area (M-Area) of SRS and were then transported to the reactor areas for processing. An important part of the fuel loading step was a thorough initial degreasing of the reactor fuel and target assemblies, prior to loading into the reactor vessel. In the early years, this degreasing step was performed within the reactor building itself. The degreasing operation consisted of a large vapor degreasing tank located in the assembly area of the reactor and contained 2,300 gallons of trichloroethylene (TCE). After the early 1970's this step was transferred back to M-Area. However, while degreasing was still being performed at the reactor areas, the inevitable spillage resulted in a source of solvent contamination to the groundwater that persisted until recently.

A remedial investigation of C Area (WSRC, 2003) was conducted between 1996 and 2000, with a subsequent investigation conducted in 2002. These investigations revealed the presence of two TCE contaminated groundwater plumes, that are shown in Figure 1. The northern plume emanates from a construction waste pit (C Area Burning Rubble Pit), which has been under a separate remediation action since 1999 (WSRC, 2003a), and initially utilized conventional soil vapor extraction (SVE), but has since reverted to passive SVE (i.e. Baroballs^R). The southern plume, which emanates from a source near to the reactor building, discharges into Castor Creek at concentrations above the maximum contaminant levels (MCLs) for groundwater. Due to the extended period of operation of the SVE units, it was determined that an accelerated technique for source removal would be the most desirable method to address the southern plume, and in 2003 an agreement was reached with the site environmental oversight regulatory agencies, the U.S. Environmental Protection Agency and South Carolina Department of Health and Environmental Control, to execute an interim source removal action using Electrical Resistance Heating (ERH) (WSRC, 2003b).

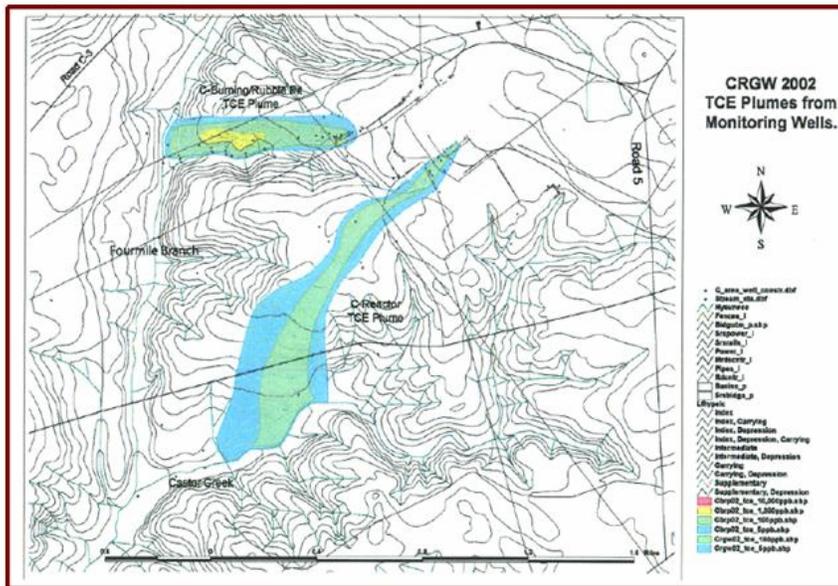


Figure 1. Groundwater TCE plumes emanating from C Area

A remedial investigation conducted in 2002, identified the TCE source as being adjacent to the assembly building of the reactor, in a near vertical column descending from an area near to storm drain. The vertical distribution is shown in Figure 2. The ERH action would take place in a partially disturbed soil region that had been excavated and then backfilled during the reactor construction phase. The stratigraphy consisted of two clayey-sand layers (Engineering Unified Soil Classification system) that were believed to be relatively electrically conductive, interspersed in a sandy-clay matrix that would be less electrically conductive but conducive to SVE. The upper electrically conductive clayey-sand layers is located between -8 to -28 feet below ground surface (bgs), and was designated as the A zone; the lower zone is located between -52 to -64 feet bgs, and was designated as the C zone. The local area water table is located at around -70 feet bgs. The majority of the TCE inventory was believed to be contained in the upper clay-sand layer from approximately -15 to -39 feet bgs. Further investigation for the presence of buried utilities in the area, revealed the area to be crisscrossed with several steel utility water pipes and steel reinforced concrete storm drainage pipes. All these utilities were connected to the internal piping systems within the building. This feature of the location could present both a significant safety hazard for personnel within the building, and also a source of power drain while the ERH system was operating.

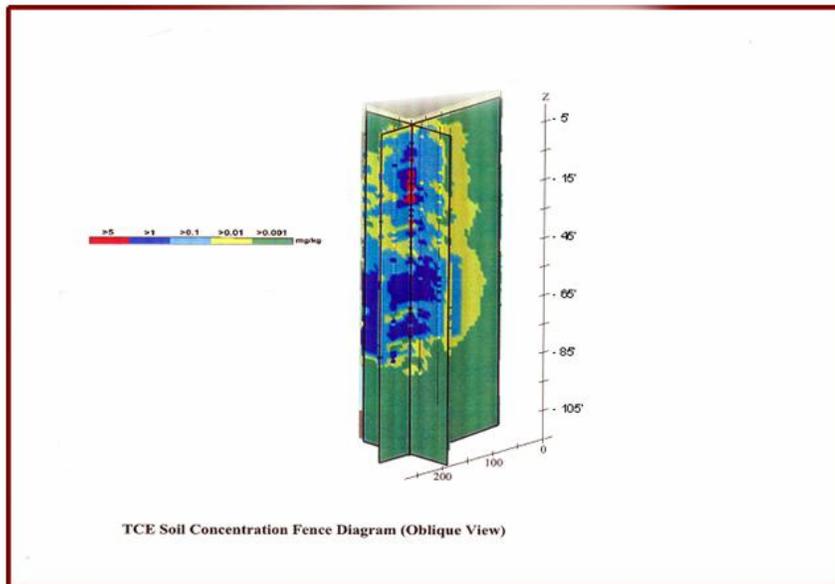


Figure 2. TCE soil contamination fence diagram

The negotiated remedial goals for the interim action were basically two fold. The first objective was to sustain an average soil temperature in excess of 189 °F within the heated zones for a minimum of 30 continuous days. As 189 °F is the boiling temperature of pure TCE, this would ensure that all of the solvent was transformed into the vapor phase. The second goal would be to reduce TCE concentrations in the source zone to the point where any further leaching would not cause groundwater concentrations to exceed the regulatory MCL limit of 5.0 µg/L. This reduction would be determined by taking soil cores after heating had been terminated.

MATERIALS AND METHODS

ERH technology was originally developed by Pacific Northwest National Laboratory (Heath et al., 1992) in the early 1990's with DOE funding, and has since been proven to be a highly successful technology with licenses being held by a number of commercial vendors. Chlorinated solvents are a soil contamination problem at many SRS waste units, and although conventional SVE had previously been deployed, it has been found to require extended operating time frames to achieve an effective level of source reduction. ERH has the potential to greatly accelerate the rate of solvent removal in low permeability soils, therefore it was concluded that ERH could potentially be deployed at other locations at SRS following the deployment at C Reactor. With the prospect of

accelerating the SRS clean up program, it was decided to develop an in-house capability in ERH technology, which included obtaining a site specific license, designing and constructing portable ERH equipment together with developing internal operating expertise.

Electrical power was obtained from the reactor 13.8kV electrical distribution system. The voltage was simultaneously stepped down and split from 3 phase 60 Hz AC, to 6 phase, 60 Hz AC via a 1,250 kVA capacity mobile power supply manufactured by Spang Power Electronics. Six phase electrical power provides for more even heating than 2 or 3 phase power (Carrigan and Nitao, 2000). In operation, the power supply could maintain a preset voltage between 0 and 1,100 volts at each electrode by multi step transformer tap changes. The constant voltage at each electrode was set by a remote computer and controlled within the range of the tap setting by automatic control of the applied current by silicon controlled rectifiers. The desired voltage was set at the start of each day, based on the trend in change of soil resistance.

The ERH design consisted of six electrodes placed in a 30 foot diameter circle, effectively surrounding the soil column to apply the electrical heating. A central neutral electrode was installed to absorb the electrical imbalance generated by differences in soil resistance. The design of the neutral electrode was the same as the power electrodes, even though the power transmitted through the neutral would be less. As the power supply effectively operated in an ungrounded arrangement, the central neutral electrode enabled the power supply to provide more stable overall voltage control from a well defined electrical reference. The SVE vapor extraction wells were co-located internally within the electrode boreholes.

Soil is effectively an electrical insulator, and in applying electrical power to the subsurface, significant “stray” voltages can appear outside of the six power electrode array. These “stray” voltages can energize any metal in contact with the ground, resulting in step-touch potentials and potentially significant safety issues. Therefore a number of safety features were implemented to mitigate potential electrical safety issues:

- A wood fence was erected around the electrodes with a single gate that was administratively locked out with the power supply. The power to the electrodes had to be turned off before personnel could enter the electrode field.
- A grounding ring consisting of a bare No. 4 bare copper wire was buried at a depth of approximately one foot and circled the installation. All metal parts in the above ground equipment were grounded to this ring, thus effectively eliminating any potential differences between components.
- A wire mesh equipotential mat was placed over the energized zone and was also connected to the grounding ring. This effectively eliminated any possible step-touch potentials.
- During ERH start up and operation, stray voltage checks were performed weekly at strategic locations around the ERH site, including test points within the building and also whenever the applied voltage was increased. The highest stray voltage recorded between a metal structure and the ground, was 12 volts which was well below the OSHA limit of 50 volts.

During operation, the offgas vapor was withdrawn from the SVE wells through a gas treatment system supplied by REP Inc, before being released to the atmosphere, where the TCE is degraded by ultra violet sunlight (Corbo, 1985). The above ground gas treatment train collected the hot vapor from each electrode/SVE well via a manifold system and then into a primary water droplet/particulate separator. The gas temperature was reduced to 140 °F by a heat exchanger and the condensate removed in the secondary condensate separator. Cool water to the heat exchanger was maintained by a packaged Delta 100 ton capacity cooling tower. The offgas vapor then passed through a Dresser Roots type blower which had the capability of drawing up to 300 acfm at a vacuum of up to 12 inches of mercury. TCE concentrations between the vapor and condensate phases partitioned according to Henry’s Law or roughly 100 to 1. However TCE concentrations in the condensate were too high for immediate discharge, therefore the condensate was stored in two 7,500 gallon tanks, and was finally dispositioned to the large M-1 air stripper, that is located elsewhere on site. To maintain good electrical contact between the electrodes and the subsurface soil, an electrolyte consisting of 0.1M Mg_2SO_4 was drip fed to each electrode.

In the ERH process, the Joule heating effect is generated by utilizing electrical resistance of the soil as a heating element. The electrodes themselves merely transmit the electrical power to the soil, and do not get any hotter than the surrounding soil. The electrodes are therefore the most critical component of the ERH system and must be designed carefully to ensure continuing electrical contact with the soil and focus the electrical power to the most contaminated region as the soil heats up. The electrode design schematic is shown in Figure 3.

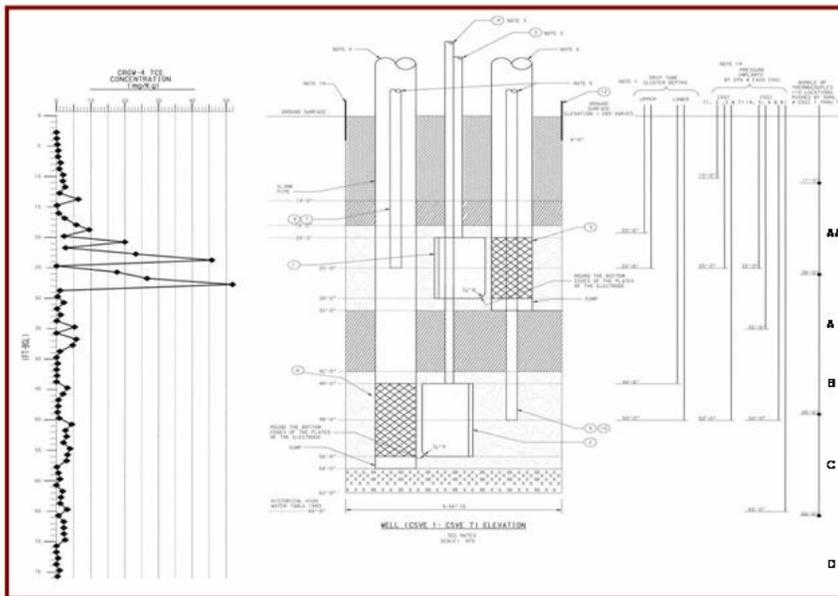


Figure 3. Individual electrode design schematic (both power and neutral)

Each electrode borehole was drilled to a depth of 62 feet using a 10 inch diameter Rotosonic rig. The upper heating zone was located from -16 to -32 feet bgs and the lower heating zone from -42 to -58 feet bgs. The upper elevation was set so that the electrically energized zone was below the underground pipes, and the lower elevation was set to be just above the water table. The intervening space between the two heating zones in the electrodes was filled with bentonite pellets to achieve electrical separation. The electrode connection was accomplished by running 4/0 Teflon^R insulated electrical cables from the surface down to a 12 feet long by 3 x 3 inch, 304 grade stainless steel angles, placed in the center of each heating zone. Electrical contact between these angles and the soil was maintained by filling the intervening gap with coarse graphite powder. The upper and lower heating zones were electrically connected at the surface so that in normal operation, the two zones were connected in parallel. However power could be applied separately to either zone if necessary. The co-located vapor extraction wells were fabricated from spirally wound 2 inch epoxy fiberglass pipe that was capable of withstanding temperatures of up to 300 °F. The vapor extraction screens were 10 feet long and were slotted directly into the epoxy pipe which was located at the same elevations as the electrodes. The graphite also acted as the well packing media. Even though six-phase power provides fairly even soil heating, the power density is still highest in the soil immediately surrounding the electrode. To maintain good electrical conductivity in the soil in this area, each electrode zone was equipped with two ¼ inch internal diameter Kynar^R drip tubes to allow electrolyte to saturate the graphite and the adjacent soil. Electrolyte flow rate was adjustable, but was set at a nominal 0.1 gallons per minute to each electrode including the neutral.

The earlier geotechnical investigation (WSRC, 2003c) showed that the backfilled soil around the reactor, where the ERH array was located, to be highly compacted and it was suspected that the co-located electrode SVE wells would not be able to capture all of the vapor that would be generated. Therefore three additional 6 inch diameter SVE only wells were drilled on a 35 feet diameter circle, centered on the neutral electrode, using the Rotosonic drill rig. These wells were screened from -27 feet to -67 feet bgs, and the TX-50 sand filter extended from -18 feet to -70 feet bgs. Post construction flow testing revealed that these SVE only wells yielded negligible air flow, even after extensive well development. The cause of the low flow was believed to be due to the action of the Rotosonic drill concentrating the soil fines on the surface of the well bore. Gas sampling of the SVE wells after installation, also revealed that the highest TCE gas concentrations were located in the south west quadrant of the array, possibly indicating the location of the highest soil contaminant concentrations. As good operation of these outer SVE wells was believed to be essential for efficient TCE removal, three additional wells were drilled using a hollow stem auger. Two of these wells were located in the south west quadrant and one was located to the north of the array. The flow performance of these hollow stem auger drilled wells proved to be satisfactory. The above ground equipment arrangement is shown schematically in Figure 4 below.

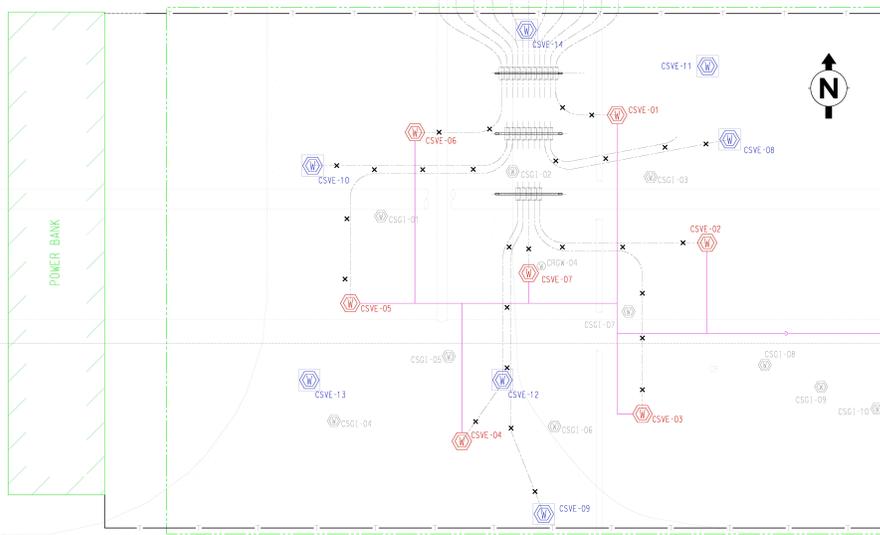


Figure 4. Layout of electrode array, SVE wells, piping and sensors

Figure 5 shows the ERH installation with the assembly building of the reactor building in the background. Two process monitoring systems were placed in the subsurface to facilitate control of heating. Thermocouples were placed at 10 locations around the array, with individual thermocouples at 4 elevations (-11, -26, -49 and -66 feet bgs). In addition a series of pressure measurement implants were placed at 8 locations around the array with the ability to sense the vacuum in the subsurface at 5 depths: -10 feet bgs (AA zone), -25 feet bgs (A zone), -35 feet bgs (B zone), -50 feet bgs (C zone) and -65 feet bgs (D zone). These were used to verify that, while the vapor extraction system was operating, the heating zones were consistently under negative pressure, thus minimizing TCE migration out of the heating volume.

Although not strictly required by the remedial goals, the quantity of TCE extracted was an important indication of the effectiveness of the treatment process. Due to the rapid heating provided by the ERH process, an innovative approach was introduced to measure TCE and PCE concentrations in the off gas, and hence measure the quantity of contaminants removed. The conventional monitoring approach employed with SVE systems at SRS, takes weekly Tedlar bag samples, followed by analysis in a laboratory gas chromatograph/mass spectrometer. Because of the rapid heating rate with ERH, the expected erratic rate of TCE evolution and the possibility of an air discharge permit excursion, it was believed that the low sampling frequency combined with normal laboratory turn around time, would be too slow to obtain an accurate measurement of mass removal rate and also give advanced warning of an impending permit excursion.



Figure 5. The ERH installation looking east. The electrode array is at top right, the electrical power supply is in the right foreground, the hut housing the control equipment is in the center foreground and the condensate tanks in the left foreground.

The continuous off gas monitoring system consisted of a gas diffusion sampling probe to separate the TCE vapor from the water vapor, a photoacoustic gas analyzer manufactured by California Analytical, a Rosemont Annubar mass flow meter which were all linked by a dedicated computer. The photoacoustic analyzer measured off gas concentrations of TCE and PCE every minute. The algorithm in the computer integrated the concentrations with the mass flow rates to give both instantaneous and cumulative read outs of the mass of solvent removal. The photoacoustic analyzer was calibrated weekly against the weekly bag sample/gas chromatograph technique.

RESULTS

Heating commenced on June 15, 2006, and continued uninterrupted until September 7, 2007. The planned operating strategy was to maintain 30 kW of power at each electrode until the soil dried out and the electrical resistance became too high.

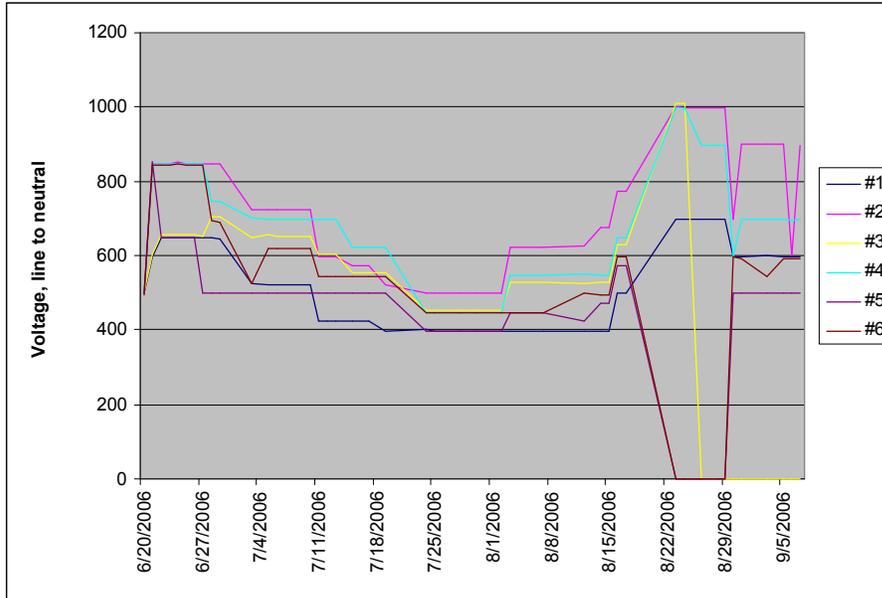


Figure 6. Individual electrode phase voltages (line to neutral)

Figure 6 shows the voltage at each electrode (measured line to neutral) and Figure 7 shows the electrical power delivered to each of the six electrodes over the duration of the project. Figure 8 shows the change in phase resistance measured at each electrode over the duration of the project. In Figure 8, phase resistance is defined as the line voltage at each electrode with respect to the neutral, divided by the current applied to that electrode. Initially the array exhibited a wide variation in soil resistance, which was accommodated by daily power adjustments to obtain a consistent power distribution at each electrode. As the array area heated up, the soil resistance initially decreased. This is due to the electrical conductive path being via the interstitial soil moisture, and the electrical conductivity of aqueous solutions decreases as temperature increases. The electrical resistance remained stable until the middle of August, when soil moisture had been reduced by evaporation to a level where electrical continuity within the soil began to break down and resistance increased sharply. Electrical contact was then lost at one electrode after another. Some limited success was achieved in recovering electrode operation by increasing the electrolyte drip rate, but on September 7, the power supply was switched off.

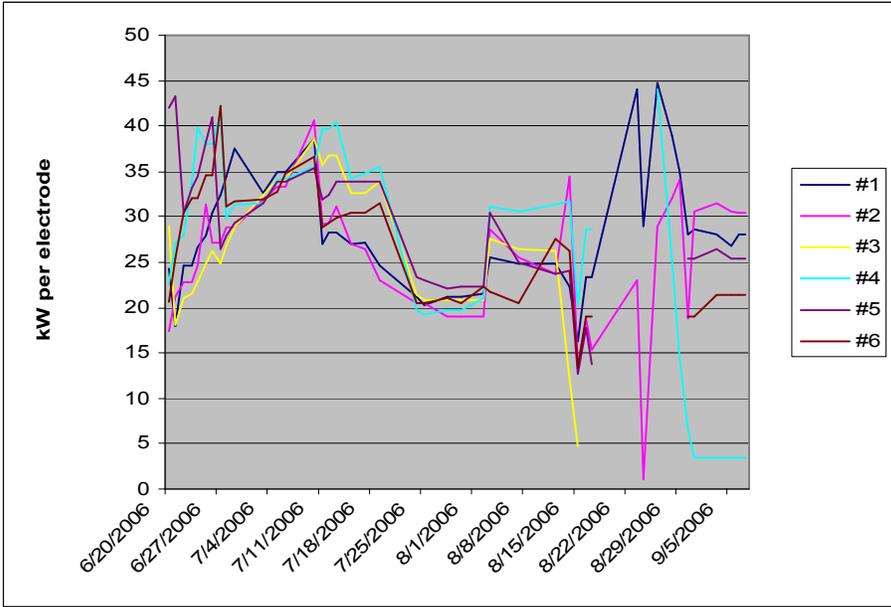


Figure 7. Individual electrode power levels

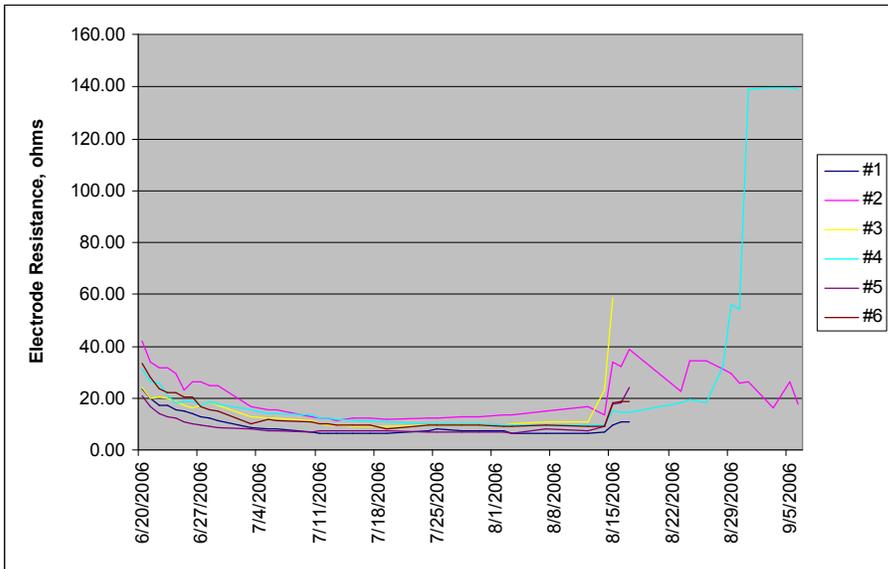


Figure 8. Individual electrode phase resistance

Figure 9 shows the resulting average temperature recorded by the thermocouples located in the upper and lower heating zones. The lower C heating zone reached the target temperature of 189 °F after two weeks of heating, this was followed by the upper A zone reaching the target temperature one week later. When the average temperature reached the theoretical maximum of 212 °F, power was reduced to around 20 kW per electrode to conserve soil moisture. Heating continued past the 30 day target, as gas concentration measurements made at each electrode and SVE well indicated that the majority of the TCE source was located in the upper A zone in the south west quadrant of the array, but that region proved reluctant to ramp up to the 189 °F target temperature. From archived photographs of the reactor construction, it appeared that the array location straddled the transition between the area native soil and the sand fill that had been used to backfill around the building after the 40 feet deep foundation had been completed. This produced a disparity in soil resistance between the north-east and south-west segments of the array, which resulted in channeling of the power towards the northern segment of the array. The underground piping did not have a significant effect on the ERH operation until the applied voltage exceeded 700 volts, when the N-S steel pipe that passed close to electrodes CSVE-01 and CSVE -03, began to act as a parallel conductor, which resulted in an excessive current draw.

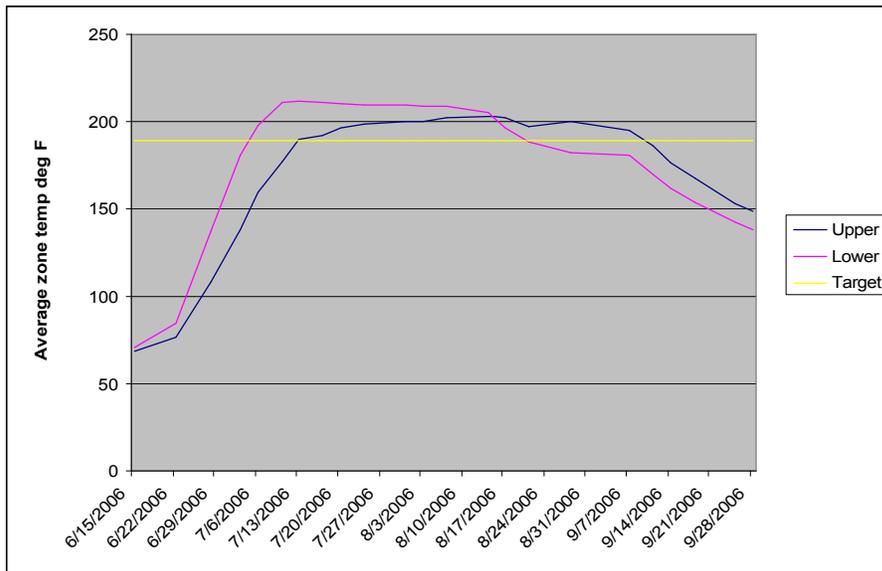


Figure 9. Average heating zone temperature timeline

Figure 10 shows the cumulative mass of TCE and PCE removed over the duration of the project. The extraction rate peaked as each heating zone approached the boiling temperature of TCE, with the majority being removed as the upper A zone, heated up. A total of 730 pounds of solvents were removed. As anticipated, the rate of solvent

removal was too rapid during these peaks, for the conventional bag sampling technique to permit representative sampling. Although the measured gas concentrations between the continuous system and the Tedlar bag - GC/MS technique did not differ by more than 10%, the continuous system recorded a mass of TCE removed to be 3 times greater.

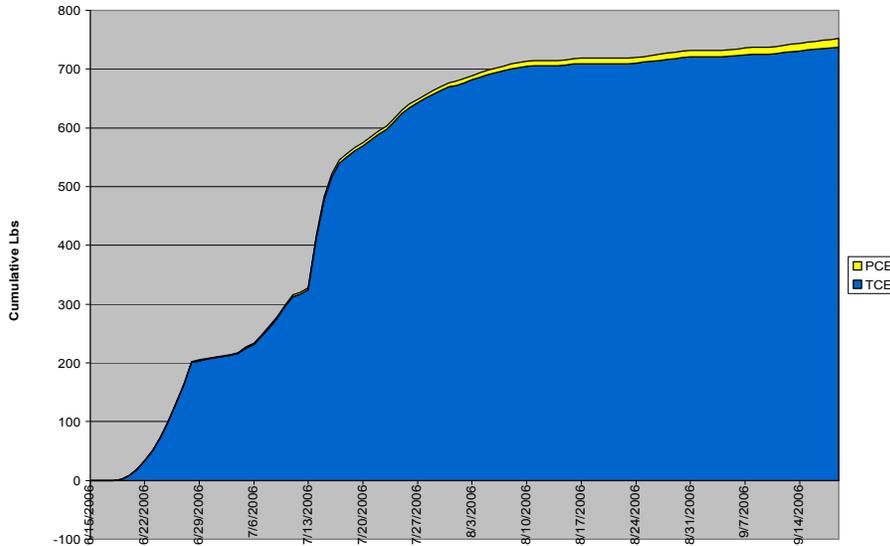


Figure 10. Cumulative mass of solvent extracted

DISCUSSION

A total of 229 MW hours of electrical energy was consumed over the duration of the project, which included the energy required to heat the soil, power the blower and the other above ground equipment.

A total of 55,619 gallons of electrolyte was injected over the heating period. The initial soil resistance was found to be quite high due to the soil around the electrode boreholes drying out during construction. Therefore the injection rate was higher over the first two weeks the first two weeks of heating. A total of 47,300 gallons of condensate was collected, mostly over the latter stages of heating when the whole heating zone was close to 212 °F.

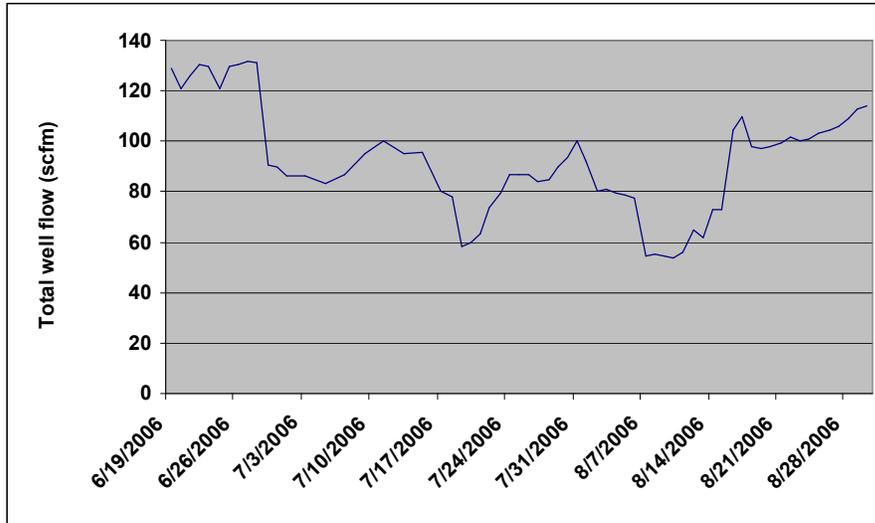


Figure 11. Air flow from the SVE wells throughout heating period

The combined air flow from the SVE wells is shown in Figure 11 and averaged 90 scfm throughout the heating period at an average manifold vacuum of 10 ins Hg. Air flow was kept to a minimum to the SVE wells in the SW quadrant of the array in the middle part of the heating period to facilitate heating. As this area reached the target temperature, air flow was then increased. The range of vacuum levels in the 5 subsurface zones are given in Table 1 and confirm that relatively high vacuums occurred at the beginning of heating which fell quite sharply as the soil dried out. Nevertheless, the heated region remained under negative pressure, particularly beneath the lower heating zone (D zone) thus minimizing TCE vapor migration to the groundwater.

Zone	Depth (feet bgs)	Zone Type	Vacuum range (ins W.C.)
AA	-10	Above Heating	-1.5 to -0.1
A	-25	Upper Heating/SVE	-20 to -1.0
B	-35	Intermediate	-22 to -6.0
C	-50	Lower Heating/SVE	-32 to -1.0
D	-65	Beneath Heating	-17 to -3.5

Table 1. Subsurface vacuum levels in the five zones

The initial soil core TCE concentration profile is shown in Figure 3 and the final soil concentrations in the two confirmatory soil cores are shown in Table 2. Substantial concentration reductions throughout the heating zone can be seen. Integrating the before and after profiles indicate a reduction of over 99% was achieved.

Depth bgs (feet)	Concentration in 2002 (mg/Kg)	Conc. at CRGW-13 in 2006 (mg/Kg)	Conc. at CRGW-14 in 2006 (mg/Kg)
16	6,360	656	25
18	670	427	40
20	5,780	111	29
22	2,220	3	19
24	2,640	0	6
26	45,760	4	2
28	17,630	2	1
30	51,840	4	0
32	310	0	0
34	140	1	0
36	70	0	0
38	NA	0	0
40	5,740	0	0
42	1,030	0	0
44	360	0	0
46	160	0	1
48	NA	1	1
50	3,160	3	1
52	570	3	1
54	340	0	10
56	4,440	10	26
58	NA	20	35
60	2,970	11	22
62	3,940	7	32
64	2,980	NA	60
66	610	2	18
68	0	0	44
70	1,330	20	50
72	3,140	106	399
Average	6,310	50	28
TCE/PCE Removal Efficiency %		99.2	99.5

Table 2. Soil core results

CONCLUSIONS

ERH proved to be a very effective technology for accelerating the removal of chlorinated solvents that had proven to be tightly bound to the SRS clayey soils. The previous solvent removal action at C-Burning Rubble Pit, required 5 years of operation with a conventional SVE system followed by an ongoing passive SVE using Baroballs^R before the rate of removal reached an acceptable asymptotic condition. ERH achieved a similar solvent removal condition in just 12 weeks of operation. The increased cost of power and capital equipment with ERH was more than compensated by the reduction in operating costs.

The ERH design allowed sufficient power to be applied to reach the target temperature within 2 to 3 weeks and hold the temperature at or close to 212 °F for 30 days, thus meeting the regulatory remedial goals.

The TCE removal efficiency, in excess of 99%, was very high throughout the heating zone, as indicated by the two soil cores. The vacuum implant readings confirmed that negative pressure was sustained throughout the heating zone, despite the highly compacted soils and the possibility of air channeling via the sandy strata, the buried sewer systems and drains.

Despite the presence of electrically conductive underground pipes and drains running through the heating area and the close proximity of the reactor building basement, no significant stray voltages were detected in any metallic components in the vicinity of the project or within the building itself.

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