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SITE Technology Capsule

KAI Radio Frequency Heating Technology

Introduction

In 1980 the U.S. Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, committed to protecting human health and the environment from uncontrolled hazardous waste sites. CERCLA was amended by the Superfund Amendments and Reauthorization Act (SARA) in 1986. These amendments emphasize the long-term effectiveness and permanence of remedies at Superfund sites. SARA mandates implementing permanent solutions and using alternative treatment technologies or resource recovery technologies, to the maximum extent possible, to clean up hazardous waste sites.

State and Federal agencies, as well as private parties, are now exploring a growing number of innovative technologies for treating hazardous wastes. The sites on the National Priorities List total more than 1,200 and comprise a broad spectrum of physical, chemical, and environmental conditions requiring varying types of remediation. The U.S. Environmental Protection Agency (EPA) has focused on policy, technical, and informational issues related to exploring and applying new remediation technologies applicable to Superfund sites. One such initiative is EPA's Superfund Innovative Technology Evaluation (SITE) Program, which was established to accelerate development, demonstration, and use of innovative technologies for site cleanups. EPA SITE Technology Capsules summarize the latest information available on selected innovative treatment and site remediation technologies and related issues. These capsules are designed to help EPA remedial project managers, EPA on-scene coordinators, contractors, and other site cleanup managers understand the type of data and site characteristics needed to effectively evaluate a technology's applicability for cleaning up Superfund sites. Additional details regarding technology demonstrations are presented in the Innovative Technology Evaluation Reports.

This capsule provides information on the in situ radio frequency heating (RFH) technology developed by KAI Technologies, Inc. This technology was developed to remove semivolatile organic compounds (SVOCs) and volatile organic compounds (VOCs) from the soil without excavation. The KAI RFH process was evaluated under the SITE Program from January through July 1994 at Kelly Air Force Base (AFB) in San Antonio, Texas. This demonstration was performed in conjunction with a technology evaluation performed by the U.S. Air Force (USAF). Information in this capsule emphasizes specific site characteristics and results of the SITE field demonstration at Kelly AFB. This capsule presents the following information:

- Abstract
- Technology description
- Technology applicability
- Technology limitations
- Process residuals
- Site requirements
- Performance data
- Technology status
- Sources of further information
- References

Abstract

RFH technologies use electromagnetic energy in the radio frequency (RF) band to heat soil in situ, thereby potentially enhancing the performance of standard soil vapor extraction (SVE) technologies. Contaminants are removed from in situ soils and transferred to collection or treatment facilities. Contaminant removal during the demonstration was evaluated by measuring contaminant concentrations in the soil before and after treatment.

The KAI RFH process was evaluated under the SITE Program at a site containing various organic contaminants in

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a heterogeneous soil matrix. The original treatment zone was 10 feet wide, 15 feet long, and 20 feet deep. Because RF heat was actually applied only to the upper half of the original treatment zone, this upper region is being designated the "revised treatment zone." A comparison of pre- and post-treatment soil samples within these two zones yielded the following results:

- Within the original treatment zone, the mean removal for total recoverable petroleum hydrocarbons (TRPH) was 30 percent, which was statistically significant at the 80 percent confidence interval. Concentrations in the pre-treatment samples varied from less than 169 to 105,000 parts per million (ppm); post-treatment samples varied from less than 33 to 53,200 ppm.
- Within the revised treatment zone, the mean removal for TRPH was 49 percent, which was statistically significant at the 95 percent confidence interval. Concentrations in the pre-treatment samples varied from less than 169 to 6,910 ppm; post-treatment concentrations varied from less than 33 to 4,510 ppm.
- Pre- and post-treatment concentrations of individual SVOCs were also measured. Benzo(b)fluoranthene, benzo(a)pyrene, and bis(2-ethylhexyl)phthalate exhibited statistically significant removals within the original treatment zone. Benzo(b)fluoranthene, benzo(a)pyrene, chrysene, pyrene, and fluoranthene exhibited statistically significant removals within the revised treatment zone.
- Pre- and post-treatment concentrations of individual VOCs were also measured, but these data did not indicate any statistically significant removals. This was partially a result of the low pretreatment concentrations of many VOCs.
- The migration of contaminants into and out the revised treatment zone was also evaluated. Downward migration out of the revised treatment zone may have occurred due to the design and operation of the SVE system.
- The cost to treat approximately 10,000 tons of contaminated soil using a proposed full-scale in situ RFH system (including costs associated with SVE) was estimated by scaling up costs for the original treatment zone. Cleanup costs are estimated to be $315 per ton if the system is utilized 90 percent of the time.

Contaminant removals were not as high as projected. Because of timing and funding limitations placed on the project by the USAF, only a portion of the revised treatment zone reached the target temperature of 100 to 130°C. It appears that the treatment zone did not achieve adequate temperature to achieve the goal of 90 percent removal of TRPH. The design and operation of the SVE system and problems with the available electrical power may have also adversely affected contaminant removals.

The KAI RFH technology was evaluated based on the nine criteria used for decision making in the Superfund feasibility study (FS) process. Results of the evaluation are summarized in Table 1.

Technology Description

RFH technologies use RF energy to heat soil in situ, thereby potentially enhancing the performance of standard SVE technologies. The RF energy causes radiative heating of the soil, which is a faster and more efficient mechanism for heating solids than is convective heating. Some conductive heating also occurs in the soil.

Figure 1 is a schematic diagram of the KAI RFH system used for the SITE Technology Demonstration at Kelly AFB. The Quality Assurance Project Plan (QAPP) developed under the SITE Program described KAI's original treatment zone, which was 10 feet wide, 15 feet long, and 20 feet deep. To adapt to budgetary and time constraints associated with the USAF funding, KAI modified their system to treat the revised treatment zone, which was 10 feet wide and 15 feet long but only extended from 4 feet below ground surface (bgs) to 14 feet bgs.

A 25-kW, 27.12-MHz RF generator served as the energy source for the system. Coaxial transmission lines supplied energy alternately to two antennae installed near the center of the revised treatment zone, progressively heating the soil in a radial direction from each antenna. Water and contaminants volatilized as the soil was heated.

RF energy was initially applied to antenna A2 for 28.9 days, was then applied to antenna A1 for 8.2 days, and back to antenna A2 for 12.9 days. At any given time, the soil near the antenna to which RF energy was being applied absorbed more energy than the soil located further away from that antenna.

Extraction wells were installed prior to treatment. The system used during the SITE Demonstration employed six extraction wells on the edges of the revised treatment zone and two extraction wells near the center of the revised treatment zone. These extraction wells are shown and labelled in Figure 1. Only two of the extraction wells (E2 and E7) had screened intervals that approximately matched the depth of the revised treatment zone. These two wells were screened from 0 to 10 feet bgs; the other six extraction wells were screened from 10 to 20 feet bgs.

An SVE system provided a vacuum to one or more extraction wells. The vacuum level and the extraction wells to which the vacuum was applied were varied periodically. Vacuum was not applied to wells E6, E7, or E8 at any time, and they were capped for most of the demonstration. The SVE system initially operated at a suction pressure of 30 inches of water column for 22 days. The vacuum was gradually reduced throughout the rest of the demonstration to a low of 7 inches of water column while heat was being applied. The flow rate through the vapor treatment system was approximately 120 standard cubic feet per minute (scfm). The SVE system was operated for 8 days before heating was initiated, throughout the heating portion of the demonstration (50 days), and for 14 days as the soil cooled down after treatment.

The vapors collected during the demonstration were treated using standard techniques. Condensate that formed in the vapor collection and treatment systems was collected, and then transferred to a Kelly AFB wastewater treatment facility. Uncondensed vapors were burned in a propane flare. This vapor treatment system was site- and contaminant-specific and was not evaluated as part of the RFH system. Samples of the vapors being extracted from the soil were, however, collected and analyzed periodically to characterize the vapor stream.

At the end of the treatment period, the soil was allowed to cool. Soil contamination was measured both before and after treatment. Concentrations of TRPH and specific SVOCs and VOCs were measured in matched pairs of pre- and post-treatment soil samples. Within the original treatment zone, 40 matched pairs of soil samples were collected; 22 of these matched pairs were within the revised treatment zone. Outside the original treatment zone, 24 matched pairs of soil samples were collected. As specified in the QAPP, all matched pairs of samples were analyzed for TRPH, and half of the matched pairs were analyzed for specific SVOCs and VOCs.

The implementation of the KAI RFH system varies depending on site size and characteristics. Vapor collection or

Table 1. *Evaluation Criteria for the KAI RFH Technology*

Evaluation Criteria	*Performance*
Overall Protection of Human Health and the Environment	• *The contaminant removals achieved may not provide adequate protection.* • *Requires measures to protect workers during installation and treatment.* • *During the limited time period of the SITE demonstration, soil samples exhibited average TRPH removals of 30 percent in the original treatment zone and 49 percent in the revised treatment zone.*
Compliance with Federal ARAR[1]	• *Vapor collection and treatment are needed to ensure compliance with air quality standards.* • *Construction and operation of onsite vapor treatment unit may require compliance with location-specific ARARs.* • *RF generator must be operated in accordance with Occupational Safety and Health Administration (OSHA) and Federal Communication Commission (FCC) requirements.*
Long-term Effectiveness	• *The contaminant removals achieved during the limited demonstration period may not and Performance adequately remove the contamination source.* • *Involves some residuals treatment (vapor stream).*
Reduction of Toxicity, Mobility, or Volume through Treatment	• *Potentially reduces waste volume by volatilizing contaminants, which are then collected (in a more concentrated form) by an SVE system.* • *Potentially reduces long-term contaminant mobility by volatilizing contaminants, which are then removed from the soil and collected by an SVE system.*
Short-term Effectiveness	• *Presents minimal short-term risks to workers and community from air release during treatment.* • *No excavation is required, although drilling will disturb the soil to some extent.*
Implementability	• *RF generator must be operated in accordance with OSHA and FCC requirements.* • *Other pilot-scale tests have been completed; no full-scale applications to date.*
Cost[2]	• *$315 per ton.*
State Acceptance	• *No excavation is required, which should improve state acceptance.*
Community Acceptance	• *No excavation is required, which should improve community acceptance.* • *May require some community education to assure residents that the operation of the RFH system is compliant with OSHA safety requirements.*

[1] *ARARs = Applicable or Relevant and Appropriate Requirements*
[2] *Actual cost of a remediation technology is highly site-specific and dependent on the original target cleanup level, contaminant concentrations, soil characteristics, and volume of soil. Cost data presented in this table are based on the treatment of approximately 10,000 tons of soil, and include costs associated with SVE.*

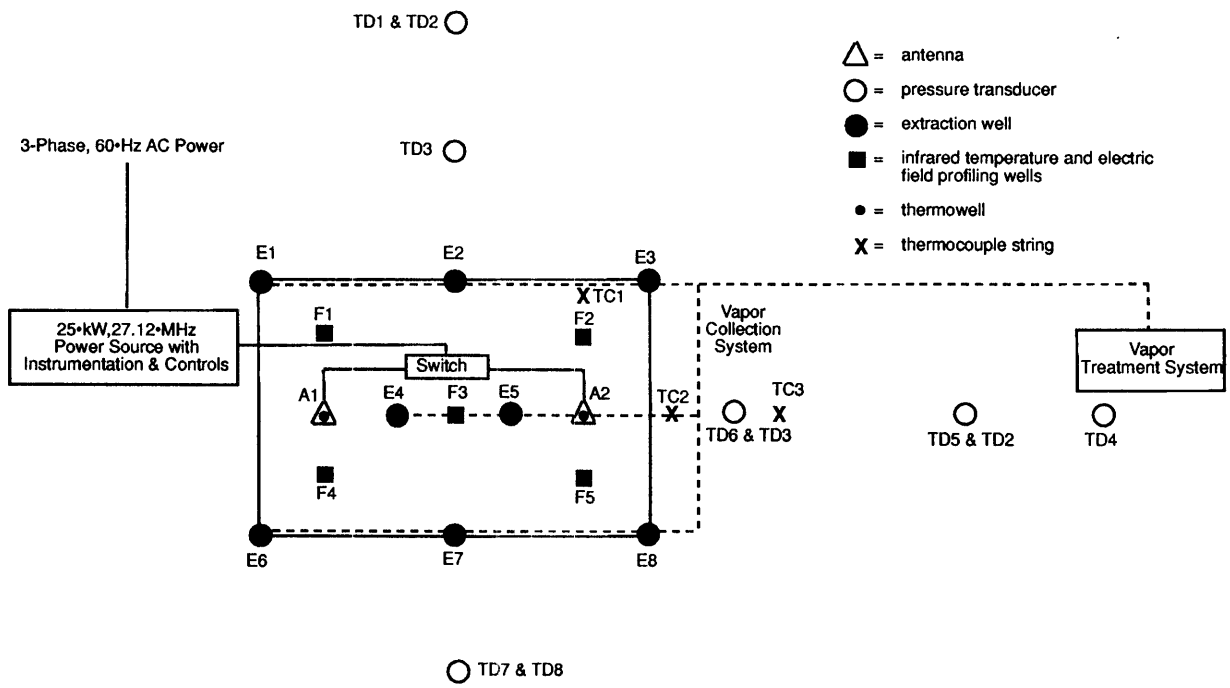

Figure 1. *Schematic diagram of KAI RFH system.*

treatment techniques, numbers and configurations of extraction wells and antennae, and other design details are site-specific.

Technology Applicability

The heat provided by the RFH process increases the vapor pressure of contaminants in the soil, thereby potentially improving the effectiveness of SVE. RFH may make it possible to remove SVOCs that would not normally be removed by standard SVE technologies. RFH may also speed the recovery of VOCs, which can be removed by standard SVE technologies. Contaminants that can potentially be removed using RFH include a wide variety of organics such as halogenated and nonhalogenated solvents and straight-chain and polycyclic aromatic hydrocarbons found in gasoline, jet fuel, and diesel fuel.

Technology Limitations

The KAI RFH technology cannot be used as a stand-alone technology. Vaporized contaminants and steam must be collected for reuse or treatment. In some cases, residual contaminants may remain in the soil after treatment.

This technology currently may be limited to unsaturated soils. Groundwater pumping may be used to lower the water table and increase the depth to which the soil can be treated. Soils composed primarily of sand and other coarse materials may be best suited to this technology. Nonvolatile organics, metals, and inorganics will not normally be removed by RFH or SVE technologies.

Process Residuals

The KAI RFH process generates one process waste stream that contains vaporized contaminants and steam mixed with extraction air. This waste stream can be treated by any of a number of standard vapor treatment technologies including vapor-phase carbon, condensation, or incineration. During the demonstration, steam and some contaminants in the vapor stream were condensed and collected. These condensed residuals were handled along with other site wastes at Kelly AFB. A propane flare was used to treat uncondensed contaminants in the vapor waste stream. When groundwater is pumped to lower the water table, the groundwater must also be handled as a liquid residual.

Some soil contaminants may remain after treatment. At a given site, the removals achieved and site-specific cleanup requirements will determine whether the soil will require additional treatment.

Site Requirements

Onsite assembly of the full-scale system will take several weeks, including drilling time. It is expected that medium to large sites will be divided into several sections that will be treated consecutively. The soil must be allowed to cool before final soil samples can be collected to confirm cleanup of each section. After treatment is completed, system demobilization may take up to one week. Access roads are needed for equipment transport. Approximately 4,600 square feet of flat ground are needed to accommodate the trailer-mounted RF transmitters, controllers, and other support equipment. A bermed area is needed for decontamination of the drill rig. Areas are also needed for storage of condensed vapors, if applicable, and the selected vapor treatment system.

Remediation using the RF heating process will require that certain utilities be available at the site. Water must be available for steam cleaning and other equipment and personnel decontamination activities. Electrical power must also be available. If carbon adsorption is used to treat vapors, compressed air may be required for system control, and steam or hot air will be needed if the carbon is regenerated onsite. Natural gas or propane will be required if a flare is used to control vapors.

The operation of a RFH system is specifically addressed by the FCC under regulations governing industrial, scientific, and medical equipment. Health and safety issues are regulated under OSHA. All requirements were reportedly met by the developer during the SITE Demonstration. The system is relatively quiet, and only during installation will dust and vapors be a potential problem. Therefore, the RFH technology can be applied near residential areas.

Performance Data

The demonstration system was designed to heat the soil in the revised treatment zone to a temperature of 100 to 130°C. Soil temperatures within and outside the revised treatment zone were monitored at various depths throughout the demonstration using thermocouples, infrared temperature sensors and fiber-optic temperature probes. All temperature measuring devices were mounted in lined boreholes, which made direct readings of the soil temperature impossible. The developer claims that actual soil temperatures were higher than the measurements indicate; however, this difference cannot be quantified. The maximum measured temperature on the perimeter of the revised treatment zone was 61°C. The maximum measured temperature near the center of the revised treatment zone was 234°C, but this peak was not representative of the majority of the temperature measurements at this location. During most of the heating period, temperatures between 100 and 150°C were measured near the antenna to which energy was being applied. Although not observed during the demonstration, the developer claims that temperatures will become more uniform after all moisture is removed from around the antennae.

Soil samples were collected before and after the soil was treated using KAI's RFH technology. The soil samples were collected as matched pairs; each post-treatment sample was collected as near as possible to its corresponding pretreatment sample. Only complete matched pairs were used in the evaluation of the data. For each contaminant, the mean percent removal was calculated, and a t-test was conducted to determine whether the mean removal was statistically significant at the 80 percent confidence interval or higher.

EPA Method 418.1 [1] was used to determine TRPH concentrations in the soil samples following extraction with freon according to EPA Method 9071 [2]. TRPH data are listed in Tables 2 and 3. For each complete matched pair of TRPH data, sample location and depth (of the pretreatment sample), pretreatment concentration, post-treatment concentration, and percent removal are shown. The mean removals in the original and revised treatment zones are 30 percent and 49 percent, respectively. These removals were accepted at the 80 and 95 percent significance levels, respectively.

SVOCs and VOCs were designated as noncritical measurements for this demonstration because samples collected prior to the demonstration indicated that the soil at the site generally contained low concentrations of SVOCs and VOCs. Because SVOCs and VOCs were noncritical measurements,

Table 2. *TRPH Concentrations Within the Revised Treatment Zone* [1]

Sample Location and Depth	Pretreatment Concentration (ppm)	Post-treatment Concentration (ppm)	Percent Removal [2]
E1, 10-12'	3,350	1,160	65.4%
E6, 8-10'	1,860	930	50.0%
F1, 4-6'	6,910	828	88.0%
F1, 10-12'	1,240	1,580	(27%)
E4, 7-9'	1,310	1,090	16.8%
E4, 9-11'	729	593	18.7%
F4, 12-14'	1,790	643	64.1%
E2, 10-12'	168.5 [3]	582	(>245%)
F3, 4-6'	4,920	702	85.7%
F3, 10-12'	336	4,510	(1,240%)
E7, 12-14'	1,400	825	41.1%
E5, 4-6'	2,710	673	75.2%
E5, 6-8'	1,530	587	61.6%
E5, 10-12'	668	330	50.6%
E5, 12-14'	739	1,450	(96.2%)
F5, 12-14'	1,220	1,530	(25.4%)
A2, 4-6'	1,530	154	89.9%
A2, 10-12'	1,290	33.3 [3]	>97.4%
A2, 12-14'	622	106	83.0%
E8, 6-8'	655	861	(31.5%)

[1] These data were used to determine the mean percent removal of TRPH within the revised treatment zone. These data were also used, in conjunction with the data presented in Table 3, to determine the mean percent removal of TRPH within the original treatment zone. The mean percent removals were calculated using the geometric mean, since the data are log-normally distributed.
[2] Parentheses around a value in this column indicate a percent increase, rather than a percent removal.
[3] TRPH was not detected in this sample above the practical quantitation limit; therefore, the practical quantitation limit is provided.

Table 3. *TRPH Concentrations Within the Original Treatment Zone But Outside the Revised Treatment Zone* [1]

Sample Location and Depth	Pretreatment Concentration (ppm)	Post-treatment Concentration (ppm)	Percent Removal [2]
E1, 0-2'	352	4,830	(1,270%)
E1, 16-18'	22,000	19,200	12.7%
A1, 0-2'	458	184	59.8%
A1, 16-18'	79,700	20,800	73.9%
A1, 18-20'	39,300	28,300	28.0%
E6, 16-18'	3,160	253	92.0%
F1, 18-20'	5,440	23,100	(325%)
F4, 0-2'	1,220	448	63.3%
F4, 16-18'	1,090	12,500	(1,050%)
E2, 0-2'	1,730	3,620	(109%)
E7, 2-4'	492	161	67.3%
F2, 14-16'	3,250	555	82.9%
E5, 18-20'	105,000	35,800	65.9%
F5, 16-18'	22,100	20,900	5.43%
F5, 18-20'	35,000	53,200	(52.0%)
E3, 14-16'	1,210	1,770	(46.3%)
E3, 16-18'	7,410	2,820	61.9%
A2, 0-2'	2,330	8,850	(280%)
A2, 2-4'	203	2,570	(1,170%)
A2, 16-18'	23,800	6,500	72.7%

[1] These data were used, in conjunction with the data presented in Table 2, to determine the mean percent removal of TRPH within the original treatment zone. The mean percent removal was calculated using the geometric mean, since the data are log-normally distributed.
[2] Parentheses around a value in this column indicate a percent increase, rather than a percent removal.

their concentrations were measured in only half of the soil samples. SVOC samples were extracted by EPA Method 3540 [2] prior to analysis by EPA Method 8270 [2]. VOC concentrations were determined using EPA Method 8240 [2].

Concentrations of individual SVOCs and VOCs in the soil samples were evaluated statistically using the same procedures described above for TRPH. Concentrations of several SVOCs exhibited statistically significant changes (at an 80 percent significance level) within the original and revised treatment zones. Statistically significant changes in SVOC concentrations within the original and revised treatment zones are presented in Table 4. None of the individual VOCs exhibited statistically significant changes (at an 80 percent significance level) within the original or revised treatment zone.

Several hypotheses may help explain the low contaminant removals measured during the demonstration. Because only a portion of the revised treatment zone reached the target temperature of 100 to 130°C, it seems most likely that the system did not achieve an adequate temperature. The low temperatures were at least partially due to problems with the electrical power available at the site. The design and operation of the SVE system, which is described in the Technology Description portion of this capsule, may have caused the contaminants to migrate downward out of the revised zone.

Technology Status

Information is currently available from two pilot-scale KAI RFH demonstrations: the Kelly AFB SITE demonstration documented in this capsule, and a demonstration conducted at Savannah River. KAI has conducted other tests for private clients, but the results of these tests are not available to the public. KAI has tentative plans for additional pilot-scale demonstrations. KAI also has long-term plans for larger-scale demonstrations investigating applicators that can travel the length of a horizontal or vertical borehole.

The cost of full-scale RFH treatment using a 200-kW generator is estimated to be $315 per ton for a site containing approximately 10,000 tons of contaminated soil. This cost estimate is based on a scale-up of the original treatment zone. The estimate includes costs associated with SVE, since SVE is an integral part of treatment using an RFH system. Major components of the cost estimate are equipment costs; startup and fixed costs; operating costs during treatment; supplies costs; consumables costs; facility modification, repair, and replacement costs; and site demobilization costs. The estimate does not include costs associated with analyses, site preparation, permitting, effluent treatment and disposal, or residuals and waste shipping, which are considered site-specific costs that will be assumed by the site owner or responsible party.

Table 4. *Summary of SVOC Removals*

Contaminant	*Mean Percent Removal in Original Treatment Zone*	*Mean Percent Removal in Revised Treatment Zone*
Benzo(b)fluoranthene	44[1]	40[2]
Benzo(a)pyrene	44[3]	43[2]
Bis(2-ethylhexyl)phthalate	55[4]	***[5]
Chrysene	***[5]	40[2]
Pyrene	***[5]	60[4]
Fluoranthene	***[5]	53[2]

[1] *Accepted at the 97.5 percent significance level.*
[2] *Accepted at the 80 percent significance level.*
[3] *Accepted at the 95 percent significance level.*
[4] *Accepted at the 90 percent significance level.*
[5] *No statistically significant change at the 80 percent significance level.*

Disclaimer

While the conclusions from this technology demonstration may not change, these data have not been reviewed by EPA Risk Reduction Engineering Quality Assurance personnel at this time.

Sources of Further Information

EPA Project Manager:

Laurel Staley
U.S. Environmental Protection Agency
Risk Reduction Engineering Laboratory
26 West Martin Luther King Drive
Cincinnati, OH 45268
(513) 569-7348

Kelly AFB Project Engineer:

Victoria Wark
SA/ALC/EMRO
305 Tinker Drive, Suite 2, Building 305
Kelly AFB, TX 78241-5915
(210) 925-1812

USAF Technical Program Manager, Site Remediation Division:

Paul F. Carpenter
AL/EQW-OL
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403
(904) 283-6187

USAF Contractor:

Clifton Blanchard
Brown & Root Environmental
800 Oak Ridge Turnpike, Suite A600
Oak Ridge, TN 37830
(615) 483-9900

Process Vendor:

Raymond Kasevich
KAI Technologies, Inc.
170 West Road, Suite 7
Portsmouth, NH 03801
(603) 431-2266

References

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2. U.S. Environmental Protection Agency, Test Methods for

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

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