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DOE Contract No. DE-AC05-98OR22700
Job No. 23900
April 3, 2002

Mr. W. Don Seaborg
Paducah Site Manager
U.S. Department of Energy
P.O. Box 1410
Paducah, KY 42002-1410

Subject: Transmittal of ***Certified for Construction Design Drawings and Technical Specifications Package for the Six-Phase Heating Treatability Study (TS) at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky*** (DOE/OR/07-1921&D2)

Dear Mr. Seaborg:

At the direction of the Department of Energy (DOE), 18 copies of the subject document are enclosed. Please forward 11 copies of the subject document to the following at the Commonwealth of Kentucky regulatory agencies: Ms. Gaye Brewer, Mr. Robert Daniell (7), Ms. Janet Miller, Mr. Steve Hampson, and Dr. John Volpe. Four copies are to be transmitted to the following at the U.S. Environmental Protection Agency: Mr. Jeff Crane and Mr. Carl Froede (3). The remaining three copies of each are for your use. For your convenience, suggested text for use in transmitting the documents to the regulatory agencies is also enclosed. Distribution is being made in accordance with the ***Standard Distribution List for Bechtel Jacobs Company LLC Primary and Secondary Documents (1/31/02).***

Submittal of this document completes the design phase of the TS. Bechtel Jacobs Company LLC looks forward to performing this technology demonstration at the C-400 building area. If you have any questions or need additional information, please contact Mark Gage of my staff at 5125.

Sincerely,

Gordon L. Dover
Paducah Manager of Projects

GLD:ll
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Secondary Document

Certified for Construction Design Drawings and Technical Specifications Package for the Six-Phase Heating Treatability Study at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky

I-04611-0155

CLEARED FOR PUBLIC RELEASE

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

This report includes the design for the planned installation of the Six-Phase Heating technology system for conducting a Treatability Study at the Paducah Gaseous Diffusion Plant for the U.S. Department of Energy. While use of this technology has been proven effective at other sites, a key objective of any resulting Treatability Study is to determine if this technology can be effectively installed within the local stratigraphy and that the operating system can successfully reduce the levels of contamination present at the selected location within the Paducah site facility. The planned Treatability Study represents a field test of the Six-Phase Heating technology in conditions more difficult than in previous applications. Consequently, it must be stressed that factors out of Science Applications International Corporation's (SAIC's) control (direct or indirect), including, but not limited to, variability in geology, distribution of contamination, levels of contamination, and performance of the subcontractor installing and operating the Treatability Study, could affect the performance of the technology. SAIC does not warrant, guarantee, or assume any responsibility for the installation or operation of the system or results of this Treatability Study.

DOE/OR/07-1921&D2
Secondary Document

Certified for Construction Design Drawings and Technical Specifications Package for the Six-Phase Heating Treatability Study at the Paducah Gaseous Diffusion Plant, Paducah, Kentucky

Date Issued—March 2002

Prepared for the
U.S. DEPARTMENT OF ENERGY
Office of Environmental Management

by
Bechtel Jacobs Company LLC
managing the

Environmental Management Activities at the
Paducah Gaseous Diffusion Plant
Paducah, Kentucky 42001

for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-98OR22700

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ABBREVIATIONS AND ACRONYMS

acfm	actual cubic feet per minute
AST	aboveground storage tank
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylene
BTU	British Thermal Units
C	Celsius
CCl_4	carbon tetrachloride
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CPVC	chlorinated polyvinyl chloride
dBA	decibels, A-weighted scale
DCE	dichloroethene
DNAPL	dense nonaqueous-phase liquid
DOE	U.S. Department of Energy
E-Beam	electron beam
ECD	electrolytic conductivity detector
Eh	oxidation-reduction potential
ES&HP	Environmental, Safety, and Health Plan
EPA	U.S. Environmental Protection Agency
eV	electron volt
F	Fahrenheit
FFA	Federal Facility Agreement
FID	flame ionization detector
FS	feasibility study
GAC	granular activated carbon
GC	gas chromatograph
gpm	gallons per minute
GWOU	Groundwater Operable Unit
H_c	Henry's Law Constant
H_2S	hydrogen sulfide
Hg	mercury
HCl	hydrochloric acid
HPO	hydrous pyrolysis oxidation
HU	hydrogeologic unit
Hz	hertz
IDW	investigation-derived waste
ISO	International Organization for Standardization
KAR	Kentucky Administrative Regulations
KPDES	Kentucky Pollutant Discharge Elimination System
kg	kilogram
kV	kilovolt
kW	kilowatts
LNAPL	light nonaqueous-phase liquid
MCL	maximum contaminant level
MIP	membrane interface probe
MTZ	mass transfer zone
MW	megawatt
NaOH	sodium hydroxide

ACRONYMS AND ABBREVIATIONS (continued)

NEMA	National Electrical Manufacturers Association
NH_3	amonia
O.D.	outside diameter
PCE	perchloroethene
PCU	power control unit
PFA	perfluoroalkyoxy-alkanes
PGDP	Paducah Gaseous Diffusion Plant
pH	hydrogen-ion concentration
PID	photoionization detector
PMCH	perfluoromethylcyclohexane
ppb	parts per billion
ppmv	parts per million by volume
psi	pounds per square inch
QAPP	Quality Assurance Project Plan
RGA	Regional Gravel Aquifer
RI	remedial investigation
ROI	radius of influence
SAP	Sampling and Analysis Plan
scfm	standard cubic feet per minute
SPH	Six-Phase Heating
STEL	short-term exposure limit
STR	Subcontract Technical Representative
^{99}Tc	technetium-99
TCA	1,1,1-trichloroethane
TCE	trichloroethene
TeCA	1,1,2,2-tetrachloroethane
TEFC	totally enclosed, fan cooled
TOC	total organic carbon
TSWP	Treatability Study Work Plan
UCRS	Upper Continental Recharge System
UPS	uninterruptible power supply
USEC	United States Enrichment Corporation
VR	vapor recovery
V	volts
VOC	volatile organic compounds
WAG	waste area group
WMP	Waste Management Plan

EXECUTIVE SUMMARY

This Design Drawings and Specifications Package has been prepared for the Six-Phase Heating (SPH) Treatability Study at the Paducah Gaseous Diffusion Plant in Paducah, Kentucky. The treatability study will provide quantitative treatment and cost data to assess the feasibility of deploying **SPH** as part of the remedial action for the Groundwater Operable Unit. The study will be consistent with the *Federal Facility Agreement* among the U. S. Department of Energy, the U.S. Environmental Protection Agency (EPA) and the Commonwealth of Kentucky (EPA 1998). The treatability study will be conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and will follow the guidance set forth in EPA's *Guide for Conducting Treatability Studies under CERCLA* (EPA 1992).

The primary objective of the SPH treatability study is to demonstrate the implementability of the SPH technology in the unsaturated and saturated zones of the Upper Continental Recharge System (UCRS) and in the underlying Regional Gravel Aquifer (RGA). A successful implementation will demonstrate that SPH can cost effectively heat soil and groundwater in both the UCRS and RGA, recover steam and the target contaminant vapors, trichloroethene in this case, and treat the recovered contaminant vapors.

A second objective of the study is to test the effectiveness of the Membrane Interface Probe (MIP) to detect volatile contaminants in the subsurface. A successful implementation of this technology will demonstrate that the MIP can provide a continuous profile of volatile contaminants versus depth in the UCRS. Results of the test would provide sufficient confidence that the technology would eliminate the need for continuous soil sampling to determine volatile organic concentrations in source areas both before and after treatment.

The treatability study will include the design, installation, and operation of one SPH array. A single SPH array consists of six power electrodes, a central neutral electrode, an electrical power control unit, temperature and pressure monitoring systems, a steam and contaminant vapor recovery (VR) system, and contaminant vapor and condensate treatment systems. The SPH system operates by applying electricity to electrodes that have been placed at specified depths in the subsurface. As power is applied to the electrodes, the soil matrix resists the flow of electricity between the electrodes causing the subsurface to be heated. Subsurface temperatures are increased to the boiling point of groundwater and targeted contaminants are volatilized. Steam and volatilized contaminants migrate upward and are collected in the vadose zone by VR wells. Steam is then condensed to water and contaminant vapors are processed by the vapor treatment system. Electrodes will be installed to a total depth of about 30 m (97 ft) below ground surface. This will place the bottom of the electrodes slightly below the base of the RGA. The SPH treatability study design will allow treatment of both the shallow UCRS and the underlying RGA, and it is intended to test the constructability, remedial effectiveness, and cost effectiveness of deploying the technology in the area adjacent to the C-400 Building.

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1. TREATABILITY STUDY DESCRIPTION

In August 1988, volatile organic compounds (VOCs) and radionuclides were detected in residential wells near the U.S. Department Energy's (DOE's) Paducah Gaseous Diffusion Plant (PGDP). The D2 version of the Groundwater Operable Unit (GWOU) Feasibility Study (FS) was issued August 2001 (DOE 2001). As part of this FS, it is necessary to understand the effectiveness of certain treatment technologies that are being considered for full-scale deployment based upon their applicability to specific site conditions. This document contains the Certified for Construction Design Drawings and Technical Specifications for the Six-Phase Heating (SPH) Treatability Study to be conducted at the C-400 Building.

The SPH treatability study at the C-400 Building will be conducted under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and will follow the U.S. Environmental Protection Agency's (EPA's) ***Guide for Conducting Treatability Studies under CERCLA*** (EPA 1992). The study will be consistent with the ***Federal Facility Agreement*** (FFA) among the DOE, EPA, and the Commonwealth of Kentucky (EPA 1998). This study will provide quantitative treatment effectiveness and technology cost data for evaluating the constructability, applicability, and performance of the SPH technology in remediating trichloroethene (TCE) source areas at PGDP. Additionally, the Membrane Interface Probe (MIP), developed by Columbia Technologies, LLC, will be studied to determine its effectiveness to define VOC concentrations in subsurface soils at PGDP.

1.1 GEOLOGY AND HYDROGEOLOGY

The depths to various lithologic units vary across the C-400 Building region. The depths presented in this design are approximate and actual depths will be determined or verified as the first new borings are installed. Similarly, the depths to groundwater vary considerably with season; however, consistent depths are used in this design for ease of understanding. All depths have been rounded to the nearest meter and nearest foot.

The PGDP overlies the southern extent of the ancestral Tennessee River. An 11-m (35-ft) thick sand and gravel deposit of the ancestral Tennessee River extends from beneath PGDP northward to the Ohio River. These coarse sediments form the shallow aquifer beneath PGDP, known as the Regional Gravel Aquifer (RGA). Immediately underlying the RGA is the Upper Cretaceous McNairy Formation. The upper portion of the McNairy Formation consists of interbedded silts, sands, and clay. The middle member, the Levings member, generally is a silty clay, while the lower McNairy Formation is primarily sand with some silts and clays.

This treatability study will be conducted near the southeast corner of the C-400 Building. The lithology at this location is extremely variable. The main hydrogeologic units (HUs) beneath the treatability study area consist of the Upper Continental Recharge System (UCRS), which is broken down further into HUs 1, 2, 2A and 3; the RGA (HU4 and HU5); and the McNairy Flow System. In the study area, the RGA and sands of the McNairy Flow System are separated by an approximately 3-m (9-ft) thick lens of interbedded silts, sands, and clay that act as an aquitard. Approximately 17 m (56 ft) of silt and clay, with horizons of sand and gravel lenses, covers the RGA. The groundwater flow system developed in these shallow sediments is called the UCRS. Groundwater typically is encountered in the UCRS at approximately 11 m (36 ft) below ground surface (bgs). The RGA potentiometric surface is encountered at a depth of approximately 16 m (53 ft) bgs. The RGA is saturated throughout and recharged primarily by vertical groundwater flow from the UCRS. Hydraulic gradients direct groundwater flow in the RGA laterally to the north where groundwater discharges into the Ohio River.

1.2 LOCATION OF TREATABILITY STUDY

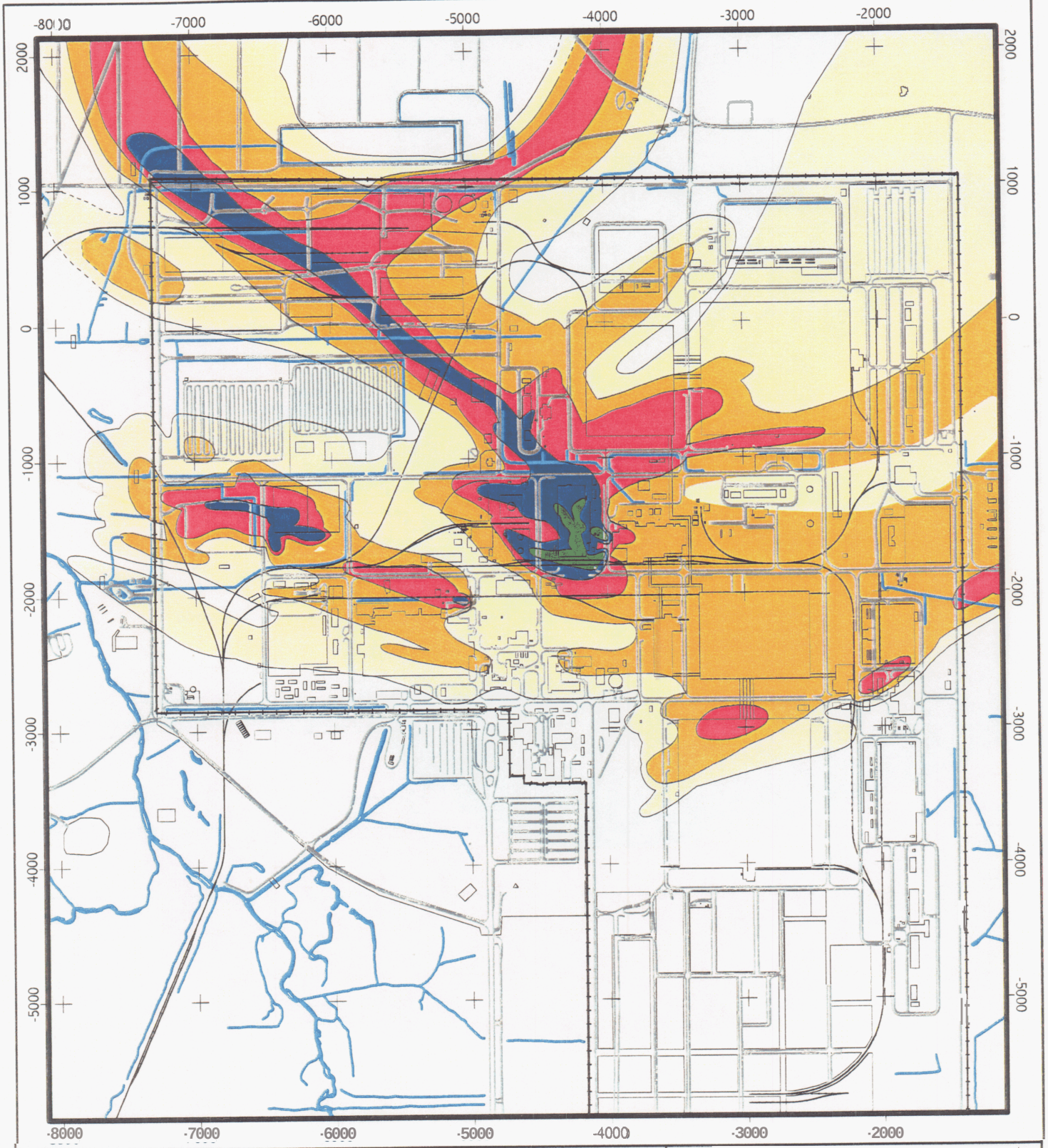
The extensive Site Investigations of 1989 through 1991 (CH2M HILL 1991; 1992) identified TCE and technetium-99 (^{99}Tc) as the primary groundwater contaminants that have migrated beyond the on-site secured area of the PGDP. Subsequent source unit and site-wide investigations have confirmed these observations. The data cumulatively define three main plumes of dissolved contamination. All three of the plumes are located in the RGA. Two of these plumes, currently identified as the Northwest Plume and the Northeast Plume, receive considerable contaminant loading from the C-400 Building area.

TCE was the primary organic solvent used in degreasing operations at the PGDP from the 1950s through the 1980s. The on-site use of TCE was discontinued in July 1993; thus, industrial processes can be discounted as continuing sources of contamination by TCE. The remaining sources of TCE to groundwater are mostly secondary accumulations in the subsurface and leaking burial grounds. TCE occurs as a dense nonaqueous-phase liquid (DNAPL), also known as free phase product, to a maximum depth of approximately 28 m (91 ft) bgs, which represents the base of the RGA. Dissolved levels of TCE far exceed the EPA drinking water standard of 5 μg/l in two of the plumes outside of the on-site secured area.

^{99}Tc was a fission product, impurity of reprocessed uranium derived from spent reactor fuel. The enrichment of recycled uranium at the PGDP occurred during three periods: 1952–1964, 1969–1974, and 1976–1977. The pertechnetate anion, TcO_4^-, the common oxidized state of ^{99}Tc at the PGDP, is highly soluble and has a low affinity to sorb or complex with the subsurface at the PGDP. Within most of the area impacted by the RGA groundwater contaminant plumes, ^{99}Tc levels are below the drinking water standard of 900 pCi/L. In the current CY 2000 plume maps, approximately 1,649 acres are interpreted within the combined plume boundaries as >25 pCi/L. Of that 1,649 acres, only 99 acres, or 6%, are interpreted as >900 pCi/L. The comprehensive review of groundwater data performed for the PGDP GWOU FS (DOE 2001) identified organic, inorganic, and radionuclide contaminants in the groundwater beneath the on-site secured area. In addition to TCE and ^{99}Tc, six other organic compounds appear to be migrating from the PGDP beyond the on-site secured area. These contaminants include the three TCE degradation products *cis*-1,2-dichloroethene, 1,1-dichloroethene, and vinyl chloride, plus carbon tetrachloride, chloroform, and benzene.

The Waste Area Group (WAG) 6 Remedial Investigation (RI) characterized the nature and extent of contamination around the C-400 Building (DOE 1999). The WAG 6 RI concluded that there are zones of TCE DNAPL in the UCRS and RGA adjacent to and beneath the C-400 Building. Appendix E of the *Treatability Study Work Plan for Six-Phase Heating, Groundwater Operable Unit, at Paducah Gaseous Diffusion Plant, Paducah, Kentucky,* DOE/OR/07-1889&D2/R1 (DOE 2002), is taken from the GWOU FS (DOE 2001) and presents a summary of the characterization data for the C-400 area DNAPL zones and documents the DNAPL conceptual models for the area. The relationship between the maximum (greater than 100,000 μg/l) concentrations of TCE and the C-400 Building is shown in Fig. 1.

The data suggest that the southeast C-400 DNAPL zones account for the majority of the mass of residual and pooled DNAPL. Given the high concentrations of TCE in the RGA groundwater, it is assumed that DNAPL has migrated through the UCRS and into the RGA. As part of the WAG 6 RI, UCRS soil was characterized and shown to be a residual source of DNAPL. To assist in developing the information needed to determine if full-scale implementation of SPH will be effective, the SPH treatability study is best centered on the area with the highest UCRS soil contamination levels and with high TCE levels in RGA groundwater (and possible DNAPL accumulation). This location is boring 400-200 (plant coordinates -4081 east, -1725 north), where TCE concentrations of 11,055 mg/kg were measured at 3 m (10 ft) bgs. To encompass boring 400-200, the SPH array will be located near the southeast corner of the C-400 Building as shown in Fig. 2.



LEGEND:

- TCE > 100,000 ug/L
- TCE 10,000 - 100,000ug/L
- TCE 1,000 - 10,000ug/L
- TCE 100 - 1,000ug/L
- TCE 5 - 100 ug/L

PGDP BOUNDARY
DOE BOUNDARY

500 0 500 1000 Feet

TRUE NORTH 20° PLANT NORTH

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee• Paducah, Kentucky• Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 1. Maximum TCE concentrations at PGDP in RGA groundwater.

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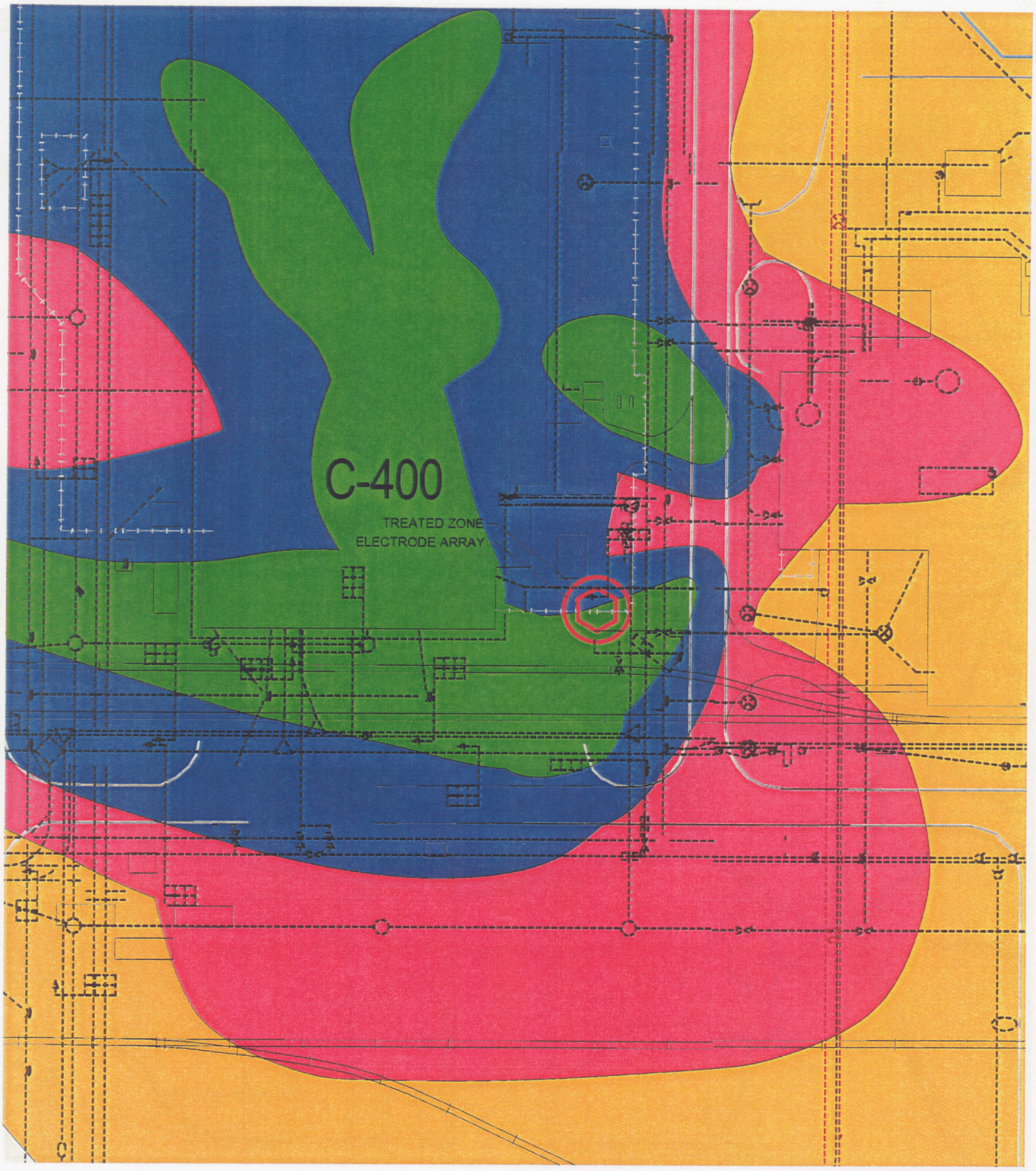

LEGEND:

- FENCE LINE
- ROAD
- RAILROAD
- UNDERGROUND UTILITY

TCE CONTOURS

- > 100,000 ug/L
- 10,000 - 100,000 ug/L
- 1,000 - 10,000 ug/L
- 100 - 1,000 ug/L
- 5 - 100 ug/L

- TREATED ZONE
- ELECTRODE ARRAY

TRUE NORTH 20° PLANT NORTH

50 0 50 100 Feet

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

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Fig. 2. Approximate location of Six-Phase Heating Treatability Study.

FIGURE No. c5ac90001sk109r1 a r
DATE 08-27-81

SAP (DOE **2002,** Appendix **A).** If the MIP performs well in the pre-test sampling characterization, the equipment will be remobilized to the site to conduct the post-test soil characterization. Soil samples collected from these borings and post-test groundwater samples from the multi-port groundwater monitoring wells will be analyzed, and the data will be compared to pre-test data.

A key consideration for any treatability study is whether the candidate technology tends to spread contamination. When the treatability study treatment cell is in the center of a large TCE-contaminated region, groundwater and soil samples taken outside of the treatment cell are expected to show TCE impact. It can be difficult to determine if any concentration variation at these external sampling locations is due to the spread of TCE from inside the treatment cell. Some researchers have attempted to perform a TCE mass balance to determine if the extracted mass of TCE is equal to the difference in mass estimates made before and after treatment. If the mass of extracted TCE is less than the difference between pre- and post-treatment mass estimates, a natural assumption is that TCE migrated out of the treatment cell during the study.

Mass balances are subject to the large uncertainties of ***in situ*** mass calculations. In addition, some TCE is likely to be degraded ***in situ*** during the heating process. Groundwater velocity in the **RGA** is about one ft per day. The soluble and nonvolatile chloride ion produced by ***in situ*** degradation of TCE typically is used to measure the mass of TCE degraded. However, the chloride ions may be swept from the treatment cell before they can be sampled. The result would be an unrealistically low calculation of the actual mass of TCE degraded.

Unfortunately, this treatability study will not provide data that will definitively indicate whether SPH caused any significant spreading of the TCE outside the treatment volume. Any heated liquid or steam that leaves the treatment region will carry thermal energy with it, and this thermal energy will be reflected as an increase in subsurface temperatures outside of the treatment region. However, two thermal effects can be anticipated in advance.

- A moderate amount of thermal energy will move out of the treatment region via thermal conduction. Thermal conduction can increase the temperature outside of the treatment region without any of the fluid flow that might spread TCE. The effects of thermal conduction are dependent on the time at elevated temperature; however, based on experience, measurable thermal conduction temperature increases are not expected to occur more than about ***6*** m (20 ft) beyond the treatment boundaries. Any temperature increases that are noted at distances greater than **6** m (20 ft) can be attributed to liquid or steam movement.

- The native groundwater flow velocity in the **RGA** is about one ft per day. This native groundwater flow presently is carrying dissolved TCE and will continue to do so during the treatability study. During the treatability study, downgradient locations also will show an increase in temperature as heated groundwater flows past.

The propensity of SPH to spread TCE at the PGDP can be inferred by using a combination of TCE concentrations and temperature data obtained during the treatability study. A decision tree can guide this inference (Fig. 3).

1.3.1 Current Status

Remedial activities at PGDP are conducted under a FFA among DOE, EPA, and the Commonwealth of Kentucky (EPA 1998). This treatability study is being conducted under CERCLA and follows the guidance set forth in the EPA's *Guidefor Conducting Treatability Studies under CERCLA* (EPA 1992).

1.3 SIX-PHASE HEATING TREATABILITY STUDY DESCRIPTION

The SPH process operates by applying electricity to electrodes that have been placed at selected depths in the subsurface. As power is applied to the electrodes, the soil matrix between them becomes an electrical resistance heater and subsurface temperatures rise as necessary to volatilize the target contaminants and convert groundwater to steam. Volatilized contaminants and steam migrate upward and are captured in the vadose zone by vapor recovery (VR) wells.

The treatability study will include the design, installation, and operation of one SPH array. A single SPH array consists of six power electrodes, a center neutral electrode, an electrical power control unit (PCU), pressure and temperature monitoring systems, a steam and contaminant VR system, and contaminant vapor and water treatment systems. The SPH system operates by applying electricity to electrodes that have been placed at specified depths in the subsurface. The treatability study is designed to test the effectiveness of the SPH technology in the complex hydrogeology at the C-400 Building. Electrodes will be constructed to a final depth of about 30 m (97 ft) bgs, and each will consist of six depth-discrete electrical resistance heating intervals covering the UCRS, the RGA, and the upper interbedded silt, sand, and clay layer of the McNairy Formation

To allow for the collection of operational data, the treatability study system will include 4 multi-port groundwater monitoring wells, 15 vacuum monitoring piezometers, and 59 subsurface temperature-monitoring points. Data will be collected from these sources before, during, and after heating.

The treatability study array will be set up at the C-400 Building as described in Sect. 4.5. Pre-test soil and groundwater samples will be collected, as described in the Treatability Study Work Plan (TSWP) Sampling and Analysis Plan (SAP), to document contaminant concentrations in the vicinity of the treatability study array (DOE 2002, Appendix A). Pre-test soil characterization will include use of the MIP to gather VOC concentration and soil conductivity data. As the electrodes heat the subsurface, volatile organics and groundwater will be converted to the vapor phase. These vapors will migrate upward to be recovered by VR wells and steam vents constructed within the electrode borings and by the steam vents located in the vacuum piezometer borings. Each electrode boring will contain two VR wells in the UCRS vadose zone and one steam vent located below the groundwater table (at the UCRSRGA interface). Each vacuum piezometer boring will include three vacuum monitoring points located at discrete depths in the vadose zone and a steam vent located below the water table at the UCRSRGA interface. Captured vapors and steam will be evacuated to the surface where the steam is condensed and the vapors will be adsorbed onto granular activated carbon (GAC) filters. Treated condensate will be recycled within the aboveground systems as makeup water for the SPH processes, and treated air will be released to the atmosphere.

Electrical resistance heating will continue for approximately 130 days (Appendix C); after which time, electrical resistance heating will be shut down and the treatability cell will be allowed to return gradually to ambient temperatures. During the first two weeks of cooling, the VR and vapor treatment systems will remain operational. The actual period of electrical resistance heating will depend upon how rapidly the system purges the test cell of contamination. Operations monitoring, described in Sect. 6.1.3, will produce the data needed to determine the actual electrical resistance heating time.

The treatability study will take place in the center of a larger contaminated region, and it is expected that there will be some recontamination from the surrounding regions after electrical resistance heating is shut down. This recontamination concern is heightened by the groundwater flow of the RGA, which has an estimated velocity of one ft per day. Due to recontamination effects, post-study samples will be collected as soon as practical after heating is shut down. Post-study groundwater samples will be collected within one week of shut down and post-test soil sample borings will be initiated within two weeks. Post-test sampling borings will be completed adjacent to the pre-test sampling borings, as described in the TSWP

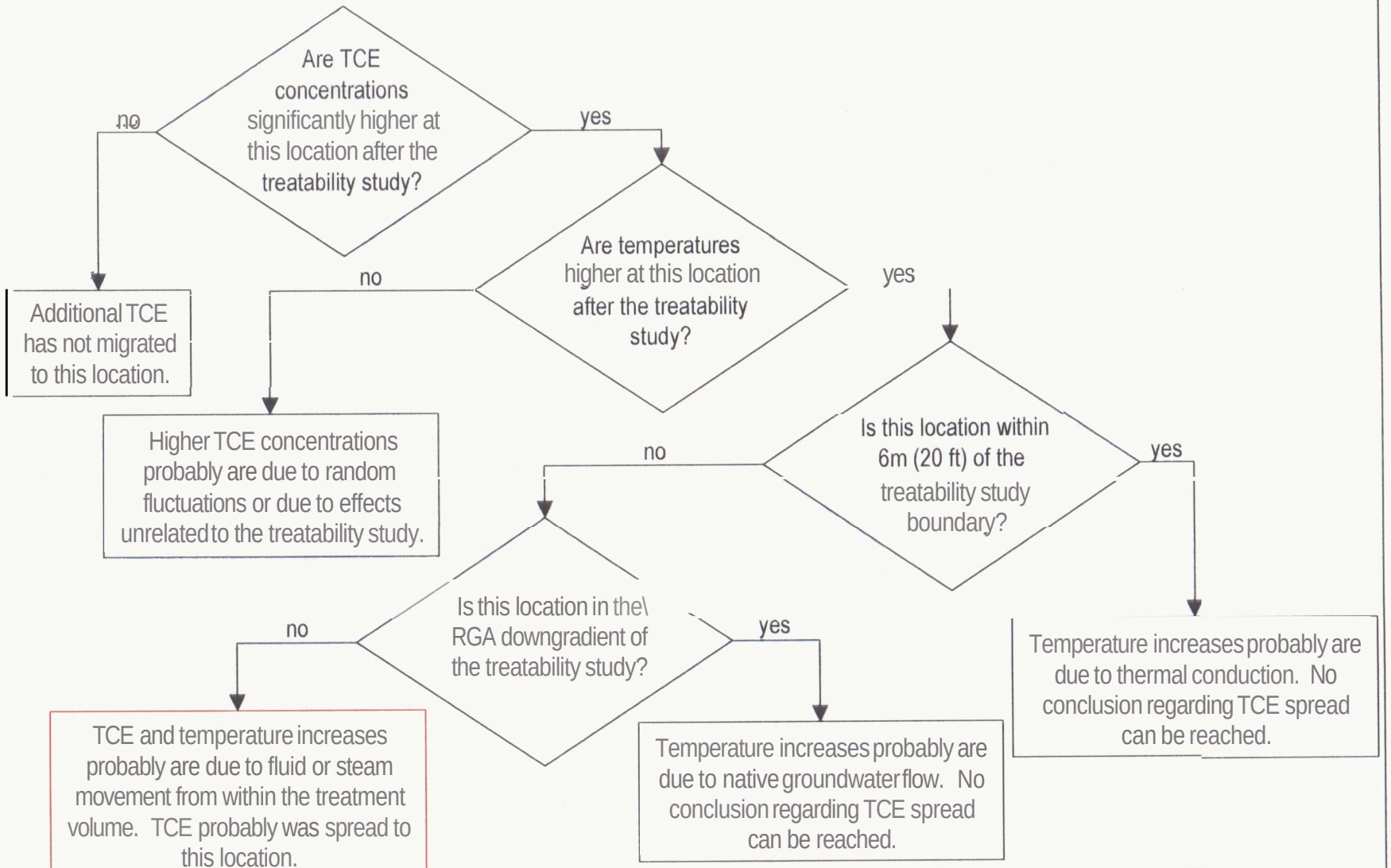


Fig. 3. Decision Tree to Determine Impact of Study on TCE Distribution.

U. S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

FIGURE No. approach.ppt
DATE 02-25-02

1.3.2 Regulatory Requirements and Notifications

All activities to be conducted during the treatability study will comply with the substantive requirements of federal and Commonwealth of Kentucky laws and regulations.

The general regulatory requirements and site-specific notifications necessary for these activities are briefly discussed in the following sections.

1.3.2.1 Utilities identification

Subsurface activities during the treatability study include the construction of the multi-port groundwater monitoring wells, SPH electrodes and **VR** wells, vacuum monitoring piezometers, and post-study soil characterization borings. A PGDP Excavation and Penetration Permit will be required prior to the initiation of any invasive subsurface activities. All invasive subsurface activities will be performed in accordance with the project-specific health and safety plan and the requirements of the excavation and penetration permit. All utilities will be located and marked. The influence of SPH on utilities is described in Sect. 5.3.2.

1.3.2.2 Electrical service

A connection to the plant electrical system will be required to complete the temporary electrical power connection for the SPH system and to connect the treatability study equipment to the temporary power source. The existing 13.8 kV distribution lines on the south side of Tennessee Avenue will be extended across the street to the SPH PCU. The SPH PCU will reduce and control the voltage at the proper levels for soil heating. Load details are provided in Sect. 5.3.3.

1.3.2.3 Well construction and sample borings

The drilling of borings and the construction of groundwater monitoring wells, SPH electrodes and VR wells, and vacuum monitoring piezometers will be performed in accordance with the requirements of 401 KAR 6:310. Within 30 calendar days of completing a groundwater well, the driller must file a well construction report with the Kentucky Division of Waste Management. Details of monitoring well construction are provided in Sect. 6.1.2. Details of electrode construction are provided in Sect. 4.5.4. Details of VR well design are provided in Sect. 4.7.1. Details of vacuum monitoring piezometer design are provided in Sect. 4.7.2.

1.3.2.4 Investigation-Derived Waste

The management and final disposition of investigation-derived waste (IDW) from the treatability study will be conducted in a manner that results in a minimization of waste generation, is protective of human health and the environment, and is in compliance with federal, Commonwealth of Kentucky, DOE, and PGDP requirements.

A variety of potentially contaminated and noncontaminated forms of IDW will be generated during the treatability study. All IDW from field activities will have the potential to contain contaminants associated with past operations and disposal practices including, but not limited to, volatile organics and radionuclides. Soil, groundwater, and materials in contact with soil or groundwater will be F001/F002/U228-listed waste. Notifications of planned IDW generating activities; preparation of waste generation plans; waste tracking; and waste sampling and analysis for waste characterization, handling, storage, transportation, and disposal will be performed as described in the Waste Management Plan (WMP) contained in Appendix C of the TSWP (DOE 2002).

1.3.2.5 Discharge of treated air

The SPH process will result in the collection of soil vapors containing VOCs. These soil vapors will be passed through the two GAC vessels placed in series. The VOCs will be adsorbed onto the GAC and the treated air will be discharged to the atmosphere in compliance with the substantive requirements of federal, Commonwealth of Kentucky, and DOE regulations. Details are provided in Sect. 4.9. GAC that has been contacted by soil vapors will be handled and disposed of as F001/F002/U228-listed waste.

2. TREATMENT TECHNOLOGY DESCRIPTION

2.1 SIX-PHASE HEATING

SPH is a remediation technology that uses electrical resistance heating in saturated or unsaturated soil to raise subsurface temperatures. Subsurface heating may be used for several remedial purposes, including contaminant volatilization, steam stripping, enhancing soil vapor extraction, and increasing biological degradation and chemical dechlorination reaction rates. SPH has been demonstrated as an effective technology for the removal of volatile and semivolatile contaminants from soil and groundwater (EPA 1999).

To implement the technology, an array of six power electrodes is placed into the ground so that the electrodes surround a targeted contaminated region. Each electrode then is connected to a separate power supply transformer to provide it with a unique phase of electrical current. Electrode spacing and electrical phases both are set 60° apart, producing **a** uniform ratio of voltage difference to the physical distance between electrodes. A typical SPH array is hexagonal in shape, with a neutral electrode located in the center. The neutral electrode makes it easier for the operator to balance the power between the other phases.

For this treatability study, the SPH array will be 9 m (30 ft) in diameter, effectively heating a subsurface region measuring 13 m (42 ft) in diameter. To treat larger areas, several arrays are constructed side by side and operated simultaneously. The vertical limits for SPH are set by the depth to which boreholes for electrode construction can be drilled. For the PGDP, the SPH system array is expected to treat approximately 3,900 m^3 (5,000 yd^3) of subsurface.

The SPH power electrodes conduct electrical energy to the subsurface and, for this treatability study, are designed to allow independent control of the energy input to six selected subsurface depth intervals. It is often advantageous to have independent control at several discrete subsurface depth intervals rather than operating the entire length of an electrode uniformly and simultaneously. Further details of the treatability study heating plan are provided in Sect. 4.6.

The subsurface intervals that are exposed to electrical resistance heating are called electncally conductive intervals. In the electrically conductive intervals, the surrounding borehole annulus is packed with a conductive material, such as graphite or steel shot, to increase the effective diameter of the electrode. In those portions of the subsurface where electrical resistance heating is not desired, the electrode construction materials are insulated and the surrounding annulus is filled with non-conductive materials such as sand, bentonite, or cement. At strategic depths in the electrode borings, impermeable seals are installed to prevent heated fluids or vapors from migrating up the annulus, or sand filters are installed to assist the VR process.

An SPH PCU is used to convert standard three-phase electrical power to six separate electrical phases. Each power electrode in an array is connected to one of the six electrical phases and, thus, will conduct current to the five other out-of-phase electrodes comprising that array. The PCU includes isolation transformers that force SPH current to flow between the electrodes only; it is physically impossible for

SPH current to flow to a distant electrical sink. When multiple arrays are used simultaneously at a site, they are configured so that electrodes in adjoining arrays are out-of-phase with each other and electrical current can flow from array to array. Resistance by the subsurface environment to this flow of electrical current uniformly heats the soil and groundwater between the electrodes. Because electrically conductive intervals can be installed to different depth intervals, and the application of energy to the different parts of the electrode field can be controlled, it is possible to heat separate subsurface zones either independently or in unison.

As the subsurface is resistively heated, contaminants are volatilized and soil moisture and groundwater are converted to steam. The production of steam during SPH operations effectively provides for the ***in situ*** steam stripping of VOC contaminants from the soil matrix. By raising subsurface temperatures above the boiling point of the mixture of targeted contaminants and groundwater, SPH significantly enhances the speed and effectiveness of physical contaminant removal. On its own, the **SPH** technology does not necessarily remove contaminants from the subsurface. Rather, it provides the physical conditions necessary to release the contaminants from groundwater and the soil matrix and to allow them to migrate up toward the surface where they are recovered by a VR system.

Heating the saturated UCRS will create numerous small steam bubbles in the relatively lower permeability sediments of this zone. Many of these bubbles will be so small that they will not have sufficient buoyancy to rise through the fine-grained sediments. However, the formation of small steam bubbles increases the effective vapor permeability of the sediments by providing a route that rising steam can travel through easily. Once this zone is heated to boiling, steam from lower depths can move upward by bridging from stationary bubble to bubble.

Once steam and volatile contaminants have been collected by the VR system, the steam is condensed, and a **GAC** vapor treatment unit adsorbs the volatile vapors. **As** the treatment area is cleaned, contaminant concentrations in the recovered soil vapors decrease. In a remedial cleanup, when these concentrations decrease by approximately 80% from peak concentrations (corresponding to approximately a 99% decrease at ambient temperatures), electncal resistance heating typically is stopped and interim groundwater and/or soil sampling is performed. Based upon the results of interim sampling, heating can be continued or post-remedial sampling can be conducted to document that the cleanup objectives for soil and groundwater have been achieved. For the C-400 Building treatability study, the planned period for electrical resistance heating is approximately 130 days. Due to the relatively high velocity of groundwater flow in the **RGA,** post-study characterization of groundwater and soil will be completed as soon as practical after heating is completed to minimize recontamination from surrounding regions. Post-study characterization of groundwater will be performed within one week of completing the heating period. Post-study characterization of soil will be performed about two weeks after completing the heating period.

SPH accelerates VOC remediation by the following principle mechanisms.

- SPH increases subsurface temperatures beyond the boiling point of most VOCs, causing them to transition to the vapor phase and rise toward VR wells placed in the vadose zone above the heated region.

- SPH boils a portion of the water in all soil types, regardless of permeability. The resulting steam sweeps VOC vapors out of low-permeability soil lenses and carries them upward to the vapor collection systems.

- **As** subsurface temperatures rise, the rates of naturally occurring biological activity and chemical reactions that cause ***in*** *situ* dechlorination are dramatically increased.

The volatilization properties of the target contaminants at the C-400 Building treatability study site favor heating as a removal method. Vapor pressures increase with temperature, resulting in a corresponding increase in the Henry's Law Constant (H,) for DNAPL constituents. For example, H_c values for TCE

have been found to increase by an order of magnitude when the temperature is increased from 20°C (68°F) to 90°C (193°F) (Heron et al. 1996).

The boiling points of the target contaminants are all below the boiling point of water (100°C at sea level pressure conditions). At sea level, the boiling points of the site-specific DNAPL constituents in air are TCE [87°C (189°F)]; *cis*-1,2-dichloroethene (DCE) [59°C (138°F)]; *trans*-1,2-DCE [48°C (118°F)]; and vinyl chloride [-13°C (9°F)]. However, when a VOC is immersed or dissolved in water, its boiling point is depressed, because a low solubility VOC/water mixture boils when the vapor pressure of the VOC, plus the vapor pressure of water is equal to the ambient pressure as described by Dalton's Law of Partial Pressure.

Once subsurface heating starts, the boiling point of various VOC/water mixtures is reached in the following order: VOCs in contact with water, pure DNAPL next, and then pure groundwater. This is advantageous for remediation because contaminated water will tend to boil off before uncontaminated water, reducing the time and energy required to complete treatment. During the treatability study, the most recalcitrant of the target contaminants will be TCE, which has a higher boiling point and is more soluble in water than *cis*-1,2-DCE, *trans*-1,2-DCE, or vinyl chloride.

All boiling points increase with pressure, so higher temperatures will be required to create boiling conditions with increasing depth below the groundwater table. The water solubility and the effects of depth below the groundwater table on the boiling points of the target contaminants are summarized in Table 1 for the C-400 Building treatability study site, where the groundwater table is located at approximately **16** m (53 ft) bgs.

Table 1. The effect of depth below groundwater on boiling temperatures"

Substance	Water Solubility[b] (mg/l)	Boiling temperature in air[b] (°C)	Boiling temperature at 53 ft bgs ("C) (potentiometric surface)	Boiling temperature at 97 ft bgs (°C)
Water		100 (212°F)	100 (212°F)	125 (257°F)
TCE	1,100	87 (189°F)	73 (163°F)	97 (207°F)
cis-1,2-DCE	800	59 (138°F)	**54** (129°F)	77 (171°F)
trans-1,2-DCE	600	48 (1 18°F)	**45** (1 13°F)	67 (153°F)
Vinyl Chloride	1	-13 (9°F)	-13 (9°F)	10 (50°F)

Notes:
"Dalton's Law of Partial Pressures.
[b]Weast et al. **1976**

Although volatilization usually is the primary removal mechanism for VOCs during SPH, some of the VOCs are degraded in place by in situ processes. These *in situ* processes include bio-attenuation, hydrolysis, hydrous pyrolysisoxidation (HPO), and reductive dehalogenation by zero valent iron.

The biodegradation of chlorinated VOCs is most commonly observed as an anaerobic process. Thermophilic bacteria (those that grow at high temperatures) degrade chlorinated VOCs at a much higher rate than typically is observed under ambient conditions. This mechanism is especially important at sites with high levels of total organic carbon (TOC), which provides a carbon source for co-metabolism. At PGDP, the subsurface contains very low levels of TOC and the bio-attenuation of TCE is likely to be observed only as a slight increase in *cis*-1,2-DCE concentrations as heating progresses.

Hydrolysis is a chemical substitution reaction in which hydrogen ions in water react with organic molecules, replacing chlorine atoms. Oxidizing conditions or available oxygen are not required for

hydrolysis. While hydrolysis will degrade VOCs at room temperature, it generally is slower than biodegradation except for compounds such as chlorinated ethanes. The rate of hydrolysis increases with temperature and the presence of clay soil types tends to accelerate hydrolysis. An example hydrolysis pathway is TCE → DCE → vinyl chloride → ethene (mineralization) (Weast et al. 1976).

Hydrous pyrolysis is the breaking apart of complex molecules into simpler units while dissolved in hot water. It generally is referred to as HPO to differentiate it from hydrolysis. HPO requires oxidizing conditions **or** dissolved oxygen. HPO is insignificant at room temperature but can become important at elevated temperatures. HPO probably is not affected by pH, but tends to be accelerated by the presence of clays. An example reaction is TCE $+ O_2 + H_20 \rightarrow CO_2 + Cl^- + H^+$ (mineralization) (Knaus et al. 1996).

Both hydrolysis and HPO are strongly affected by temperature as described by the Arrhenius Equation. In essence, each 10°C (18°F) increase in temperature will increase the reaction rates by a factor of two to four, depending on the activation energy for the reaction. The base of the RGA will be heated from a temperature of approximately 15°C (59°F) to a temperature of approximately 125°C (257°F). This temperature rise will increase the hydrolysis and HPO reaction rates by a factor between 2^{11} and 4" or by a factor between 2,000 and 4,000,000. Although the increase in degradation reaction rate with heating is impressive, it still might not be significant. If the TCE half-life at ambient temperature is very long, then even the best-case increase in degradation reaction rates still will be insignificant in comparison to TCE volatilization rates.

The electrode ,backfill consists of steel shot, which is a form of zero valent iron. The reductive dehalogenation process that takes place at the electrode backfill is the same as that produced by an iron-filing permeable treatment zone. Reductive dehalogenation is not likely to be a large mechanism for TCE mass removal. However, the presence of the iron in the electrode boreholes might provide a significant polishing mechanism for dissolved phase TCE and daughter products after SPH remediation has ended. Elevated temperatures also accelerate the rates for reductive dehalogenation reactions as described by the Arrhenius Equation.

The groundwater flow velocity in the **RGA** is about 1 ft per day and this flow presently carries dissolved TCE with it at a rate of about 360 kg per month (Appendix C). **As** the two sections of the RGA are heated to boiling, the TCE solubility will approximately double (Heron et al. 1996) and the dissolved TCE flux will increase during the 13-17 day heating periods. The increase in dissolved TCE concentrations have the potential to move an additional 89 kg (195 lb) of TCE from the treatment zone (Appendix C), or about 0.2% of the expected TCE mass in the treatment region. Water will be removed from the RGA as steam when it begins boiling. This water extraction must be replaced by inflowing groundwater and limits further dissolved TCE movement out of the treatment cell as the heating process continues.

Groundwater pumping is not used to limit the existing dissolved phase TCE movement during the treatability study due to the desire to test remediation without liquid phase groundwater extraction and the resulting potential for ^{99}Tc extraction.

As the groundwater is heated to boiling, its density will decrease by about 5% (Weast et al. 1976). This reduction in density will make the groundwater within the treatment cell relatively buoyant and give it a tendency to rise (convection). The tendency for the groundwater to rise is retarded by the depositional nature of sediments that provides a higher permeability along the horizontal axis than the vertical axis. When the convection flow is superimposed on the existing groundwater flow, the net result is that groundwater is likely to enter the treatment cell low on the upgradient side, rise within the treatment cell, and exit near the top of the RGA on the downgradient side.

The only additive required for SPH is a drip source of potable water that is applied to the vadose soil immediately surrounding the operational electrodes. This water addition prevents the soil adjacent to the

electrodes from drying out and becoming nonconductive. Most flowing aquifers, such as the **RGA,** contain sufficient recharge capacity to keep the electrodes moist and conductive throughout the heating process and water addition to the deeper sections of the electrodes is not required.

The components required to implement SPH are as follows:

- electrodes;
- VR wells;
- a steam and vapor collection system, including piping, a blower, and a condenser;
- a vapor treatment system;
- a SPH power control unit to condition power for application to the subsurface;
- data acquisition systems; and
- a computer control system for continuous remote control of power.

2.2 CURRENT STATE OF SPH TECHNOLOGY DEVELOPMENT

SPH has been applied at eight demonstrations and seven full-scale remediations. The technology has been successful in removing contaminants from open areas, as well as from areas obstructed by buildings and buried utilities. In addition, SPH has been successful in remediating a wide variety of soil types, including tight silts and clay. Because **SPH** remediates soil and groundwater by the passage of an electrical current, low-permeability soil types or heterogeneous lithologies do not hinder the process **(EPA** 1999). The previous deployments of the SPH technology are summarized in Table 2. The summary for each deployment includes the location of the project, the general lithology treated, the contaminants removed, and the length of time heating was applied.

Table 2. Summary of SPH technology deployments

Site	Lithology and depth bgs	Contaminants	SPH remediation period
Savannah River Site, SC	clay lens at 9-12m (30-40 ft)	PCE and TCE	Nov 1993
Niagara Falls AFB, NY	clay till to 3m (10 ft)	BTEX and TCE	May-Jun 96
Dover AFB, DE	sand, gravel 4-11m (15-35 ft)	PMCH	Feb-Mar 97
Chicago Manufacturer, IL	clay till to 12m (39 ft)	PCE and TCE	Aug 96 - Aug 97
Fort Wainwright, AK	sand, gravel to 6m (20 ft)	BTEX	Mar-Aug 98
Petroleum Refinery	sand to 8m (25 ft)	BTEX	Oct-Nov 98
Skokie, IL	clay till 1-7m (3-24 ft)	TCE and TCA	Jun 98 - Apr 99
Western Washington	silty sand to 6m (20 ft)	PCE and TCE	Feb-May 99
Fort Richardson, AK	heterogeneous to 12m (40 ft)	TeCA, PCE, TCE	Jun-Oct 99
Georgia Manufacturing site	silty clay 5-9m (18-31 ft)	LNAPL	May-Nov 99
Pesticide Manufacturer	clay to 6m (21 ft)	Dibromoethane	Apr-Jul 00
Launch Complex 34, FL	sand/silt/clay to 15m (48 ft)	TCE	Aug 99 - Jul 00
USAF Plant Four, TX	silt and gravel to 11m (36 ft)	TCE	Aug-Oct 00
Waukegan, IL	clay till to 12m (38 ft)	Methylene chloride	Dec 99 - Nov 00
Portland, OR	clay, gravel to 18m (60 ft)	TCE	May 00 – On-going
PDGP, KY	**clay, gravel to 30m (98 ft)**	**TCE**	

Notes:
PCE = perchloroethene; BTEX = benzene, toluene, ethylbenzene, and xylene; PMCH = perfluoromethylcyclohexane; TCA = 1,1,1-trichloroethane; TeCA = 1,1,2,2-tetrachloroethane; and LNAPL = light nonaqueous-phase liquid.

While silty and clayey soil types typically have lower water and air permeability values, they tend to be slightly more electrically conductive than quartz sand. This is because their mineral surfaces have

higher charge densities and capillary forces allow them to hold more water (Heron et al. 1996). Similarly, anaerobic dechlorination adds conductive chloride ions to the soil and groundwater around contamination "hot spots" making them more electrically conductive. Electrically conductive regions of the subsurface attract greater electrical current, heat faster, and boil more vigorously. Thus, SPH is a particularly effective method of heating less permeable soil lenses where DNAPL not only tends to pool but also is most difficult to remove. For this reason, SPH is as favorable in low-permeability material as it is in relatively higher permeability soil types or homogeneous sand and gravel soil matrixes (EPA 1997).

SPH has been used throughout the continental United States and Alaska and can be safely operated in all but the most extreme weather conditions. Successful SPH demonstrations have been performed at the Savannah River Site in South Carolina and the Dover Air Force Base in Delaware. Full-scale remediations of semi-confined aquifers have been accomplished at Fort Richardson, Alaska, (Operable Unit B) and at an electronics manufacturing site in Skokie, Illinois. Unconfined aquifer remediations include the cleanup of a shallow water table directly beneath an active shopping mall in western Washington and the staged heating approach is being applied in a deeper aquifer at an abandoned manufacturing site in Portland, Oregon.

The Savannah River project demonstrated the effectiveness of SPH for vadose zone remediation, while the Dover Air Force demonstration showed that SPH could boil a highly transmissive sand aquifer. At the Fort Richardson, Alaska, and Skokie, Illinois, sites, SPH was used to successfully remediate semi-confined aquifers comprised of tight glacial tills and clay. At the Portland, Oregon, site, SPH is being used to remediate an unconfined sand and silt aquifer. Because the targeted aquifer at the Portland site does not have an aquitard, a staged heating approach has been successfully used to establish a hot containment floor at a depth of **21** m (69 ft) bgs to ensure that DNAPL does not migrate into a lower aquifer. SPH now is being extended upward to clean the impacted aquifer and the vadose zone. At the western Washington site, a shallow, unconfined, sandy silt aquifer beneath an active shopping mall was cleaned to maximum contaminant levels (MCLs). To prevent interfering with mall business, the SPH system design had to contain steam and VOC vapors below the floor of the mall and allow shoppers to walk directly across the active electrode field.

2.3 SPH APPLICABILITY TO THE PGDP SITE

The PGDP treatability study site is unique, having a broad mix of lithologies and large depth interval of contamination. However, the successful SPH remediation of the four sites described in Sect. 2.2 demonstrates that SPH is likely to be effective in the geology and with the targeted contaminants at the PGDP site.

SPH is less sensitive to lithologic variations than are many other methods of remediation. The technology has been used in all of the soil types found at the PGDP in both saturated and unsaturated conditions. All four sites cited in Sect. 2.2 were contaminated with volatile organics; and clays, silts, and gravels were the dominant lithologies treated. At PGDP, interbedded silts and clays are the dominant lithologies from ground surface to approximately 17 m (56 ft) bgs. These shallow sediments comprise the UCRS. In contrast, the underlying RGA is predominantly gravel and sand. The cited SPH applications also show that the technology is effective at sites where remediation is complicated by the depth of contamination, the presence of DNAPL sources below the groundwater table, obstructions such as buildings and buried utilities, and by on-going site activities. Each of these remediation challenges exists at the C-400 Building site.

SPH has been shown to be effective in semi-confined aquifer settings, similar to the RGA. The 11-m (35-ft) thick sand and gravel deposit that is the dominant unit of RGA occurs at an average depth of 17 to **28** m (56 to 91 ft) below the C-400 area. The base of the RGA appears to be the vertical extent of DNAPL migration at PGDP, and all three of the off-site contaminant plumes that extend from PGDP are developed in the RGA. Because contaminant levels in the RGA are supported by source terms in the UCRS, the SPH technology will be tested in both the UCRS and the RGA during the treatability study.

2.4 MEMBRANE INTERFACE PROBE

To assist in the pre-test characterization and post-test assessment, a MIP, developed by Columbia Technologies, will be utilized to provide a direct indication of *in situ,* VOC concentrations within the study area.

The MIP/soil conductivity probe is 3.8 cm (1.5 in) in diameter and approximately 30 cm (12 in) in length. The probe is driven into the ground at the rate of one ft per minute using a direct push rig.

The soil conductivity portion of the tool utilizes a dipole measurement arrangement. An alternating electrical current is passed from the center, isolated pin of the soil conductivity probe to the probe body. The voltage response of the soil to the imposed current is measured across the same two points. The probe is reasonably accurate for measurement of soil conductivities in the range of 5 to 400 mS/m. In general, at a given location, lower conductivities will indicate sands, while higher conductivities are indicative of silts and clays. The conductivity contrast between sandy sediments and finer-grained materials is a result of the higher water saturation associated with the water that is bound to the fine-grained material.

The MIP portion of the probe was developed and patented by Geoprobe Systems, Inc. The operating principle is based on heating the soil and/or water around a polymer membrane allowing VOCs to partition (absorb) across the polymer membrane. Because the immediate area around the membrane is heated [80 to 125°C (176 to 257°F) operating temperature] and the membrane is thin, this movement across the membrane is very rapid. After diffusing across the membrane, the VOCs partition into the carrier gas, which sweeps the back side of the membrane. In roughly 35 seconds, the carrier gas stream travels through about 100 ft of inert tubing to reach the installed detectors.

COLUMBIA Technologies utilizes three detectors, a flame ionization detector (FID), a photo ionization detector (PID), and an electrolytic conductivity detector (ECD), mounted on a laboratory grade gas chromatograph (GC) (Shimadzu 14A). The output signal from the detectors then is captured by a MIP data logging system installed on a laptop computer. Data is displayed continuously in real time during each push of the probe. In addition, the data logs can be printed for display and analysis following the data logging run or exported to common spreadsheet software.

The FID detector is the most commonly used GC detector, responding linearly from its minimum detectable quantity of about 100 picograms to almost 100%. The FID response is very stable from day to day and is not susceptible to contamination from dirty samples or column bleed. The FID detector responds to any molecule with a carbon-hydrogen bond, but not at all, or poorly, to compounds such as H_2S, CCl_4, or NH_3. The carrier gas effluent from the GC column is mixed with hydrogen and then routed through an unbreakable stainless steel jet. The hydrogen supports a flame at the tip of the jet, ionizing the analyte molecules. **A** collector electrode attracts the negative ions to the electrometer amplifier producing an analog signal, which is directed to the data system input.

The PID detector consists of a special UV lamp mounted on a thermostatically controlled, low volume, flow-through cell. The temperature is adjustable from ambient to 250°C. The 10.6 electron volt UV lamp emits energy at a wavelength of 120 nanometers, which is sufficient to ionize most aromatics (benzene, toluene, xylene, etc.) and many other molecules (H_2S, hexane, ethanol) whose ionization potential is below 10.6 ev. Methanol and water, for example, have ionization potentials greater than 10.6ev and do not respond on the PID. Detection limits for aromatics are in the low picogram range (ppb) and because the PID is nondestructive, it is often run in series with another detector for multiple analyses from a single injection. Use of the PID is mandated in several EPA methods (8021, TO-14, etc.) because of its sensitivity and selectivity.

The ECD on the field GC consists of a sealed, stainless steel cylinder containing radioactive nickel-63. The nickel-63 emits beta particles (electrons), which collide with the carrier gas molecules, ionizing them in the process. This forms a stable cloud of free electrons in the ECD cell. When electro-negative compounds (especially chlorinated, fluorinated or brominated molecules) such as carbon tetrachloride and TCE enter the cell, they immediately combine with some of the free electrons, temporarily reducing the number remaining in the electron cloud. The detector electronics, which maintain a constant current (of about 1 nanoampere) through the electron cloud, are forced to pulse at a faster rate to compensate for the decreased number of free electrons. The pulse rate is converted to an analog output, which is transmitted to the data system.

2.5 CURRENT STATE OF DEVELOPMENT AND MATURITY OF MIP TECHNOLOGY

The MIP technology has been used at over 30 commercial and Department of Defense sites including Oceana Naval Air Station in South Carolina (for TCE), Warren Air Force Base in Wyoming (for chlorinated solvents and BTEX), Arnold Air Force Base in Tennessee, Aberdeen Proving Ground in Maryland, and Dover Air Force Base National Test Site in Delaware.

3. TREATABILITY STUDY OBJECTIVES

3.1 PRIMARY OBJECTIVE

The primary objective of the treatability study is to demonstrate the implementability and cost-effectiveness of the SPH technology to the unsaturated and saturated soil of the UCRS and to the groundwater of the **RGA. A** successful implementation will heat the soil and groundwater in both the UCRS and RGA to a temperature that allows steam and vapors containing TCE to rise and to be moved by the vapor recovery wells, treated by the vapor treatment system, and removed from the treatability study test cell. Within this primary objective, several operational parameters will be evaluated to determine the effectiveness of the treatability study system and the impact of the SPH technology on current PGDP operations. These parameters are described in Sect. 3.3.

This treatability study is not a remedial action, but an evaluation of a technology that may be deployed in the future as part of a groundwater remedial action with negotiated remedial action objectives. Because the treatability study will be conducted in the center of a larger TCE-contaminated area, diffusion and fluid mixing will introduce additional TCE into the treatment area during and after operations. This TCE influx makes it impractical to establish a specific clean-up goal for this treatability study. The system remedial effectiveness will be measured by comparing soil and groundwater analytical data collected before and after the treatability study. The sampling and monitoring strategy is discussed in Chap. 6.

3.2 SECONDARY OBJECTIVE

A second objective of the study is to determine the suitability of the MIP in detecting VOCs in the subsurface at Paducah. Successful implementation of this technology will provide a three-dimensional model of VOC accumulations both before and after operation of the SPH system. The technology also will attempt to provide direct indication of VOCs within the RGA and DNAPL accumulation at the RGA/McNairy contact.

3.3 OPERATIONAL PARAMETERS

In addition to measuring the remedial effectiveness of the SPH system, the following operational parameters of the SPH will be evaluated during the treatability study for each of three depth zones (unsaturated UCRS, saturated UCRS, and the RGA/McNairy):

- steam, VR, and temperature decay rates,
- temperature gradients throughout the test cell,
- TCE removal rates as a function of operational time and energy consumption,
- constructability of the SPH system in the C-400 Building area,
- construction and operation costs as a function of TCE mass removed or destroyed (cost-effectiveness),
- the effect of the SPH system on adjacent utilities and facilities, and
- operational impacts experienced by United States Enrichment Corporation (USEC).

4. CERTIFIED FOR CONSTRUCTION TREATABILITY STUDY DESIGN

4.1 SCALE OF TESTING

The treatability study will provide the performance data needed to determine the feasibility of the SPH technology for treating TCE sources at PGDP. The scale of the treatability study involves the integration and performance of all the components of a full-scale, multiple array SPH system in a single array field test.

4.2 VOLUME OF MATERIAL TO BE TREATED

The TSWP estimates that approximately 113,550 L (30,000 gal) of TCE currently are in the UCRS, and 570,750 L (150,000 gal) of TCE currently are in the RGA in the southeast comer outside of the C-400 Building (DOE 2002). The treatability study SPH system will consist of a single array and will treat only a small portion of the contaminated area. The depth of the SPH array will be about 30 m (97 ft) bgs, which is approximately 3 m (9 ft) below the base of the RGA. The diameter of the SPH array will be 9 m (30 ft). Based upon modeling and field experience, the strong effects of heating will extend beyond that diameter by approximately 40%. Thus, the actual treatment area will measure approximately 131 m^2 (1,414 ft') and the approximate treatment volume will be 3,900 m^3 (5,000 yd^3).

4.3 CRITICAL PARAMETERS

Critical parameters for the SPH treatability study are those operational parameters of the system and the physical and chemical parameters of the media being treated that have the greatest impact on the ability of the technology to meet the objectives and goals listed in Chap. 3. These critical parameters are as follows.

- **Soil and Groundwater Temperature.** For the SPH technology to be effective, the temperature of soil and groundwater throughout the treated volume must be raised sufficiently to drive groundwater and targeted contaminants to their vapor phases. For the treatability study, soil and groundwater temperatures must be 100°C (212°F) (or slightly less due to the applied vacuum from the VR system) at the top of the heated volume and 125°C (257°F) at the bottom of the heated volume, which is at 30 m (97 ft) bgs (Weast et al. 1976). (The monitoring frequency for subsurface temperatures is provided in Table 11, Sect. 6.1.3.8).

- **Treatment Time.** The treatability study is planned for 130 days of electrical resistance heating, but the actual duration of electrical resistance heating may be shortened or lengthened depending upon the rate at which the system removes TCE and water from the treated volume.

- **Soil Moisture Content.** Because subsurface heating is accomplished by the flow of electricity through soil moisture, efficient heating over the course of the treatability study is dependent upon the amount of moisture in the subsurface. The moisture content of soil adjacent to the electrodes must be maintained at levels that prevent it from drying out and insulating the electrodes. At present, the vadose zone at PGDP contains approximately 25 volume percent water. During the treatability study, the vadose zone soil moisture is expected to decrease to approximately 19 volume percent, well above the 5 volume percent required for effective electrical conduction (Appendix C). The moisture content of soil adjacent to the electrodes is not monitored directly, principally due to the effects of temperature on soil moisture monitoring equipment. However, the resistance of the electrodes is monitored and if the resistance increases by more than 20% from startup baseline resistance, the system operator can increase the rate of water addition at the electrodes to increase the moisture content of soil adjacent to the electrodes.

- **VOC Vapor Extraction Rate.** The rate of air extraction from the vadose zone must be greater than the production of contaminant vapors to prevent vaporized contaminants from escaping to the atmosphere or from condensing in the vadose zone. The maximum expected TCE evaporation rate is less than 2,000 pounds per day (lb/day). This is controlled by the SPH power input rate to remain within the effective capacity of the vapor treatment system. A TCE extraction rate of 2,000 lb/day equates to 4.0 standard cubic ft per minute (scfm) of TCE vapor (Appendix C). Based on experience at other SPH sites, the minimum design VR rate is 200 scfm in order to provide a margin **of** safety and to ensure vacuum influence over the treatment volume.

- **Impact to Surrounding Structures, Utilities, and Operations.** It must be possible to install the system at the C-400 Building site and to operate it with limited interference to site personnel and operations. **A** successful application of the technology will demonstrate that site operations could proceed adjacent to, or even directly over, the operating electrode field.

- **Vapor Treatment Criteria.** Emissions from the GAC vapor treatment system will be in accordance with criteria with which DOE and the Commonwealth of Kentucky air quality control board have agreed. In addition, an on-line VOC analyzer will be mounted in the GAC stack. This VOC analyzer will automatically shut down the SPH and VR systems if the emitted vapor exceeds one-half the permissible exposure limit for TCE. The permissible exposure limit for TCE is 100 ppmv, so the set point for the system shut down is 50 ppmv.

4.4 DESIGN REQUIREMENTS

The general input requirements for the preparation of a SPH remediation design include the following:

- site location and general site logistics, including nearby structures and site activity;
- buried underground utilities and obstructions;
- shape and depth of the impacted area;
- site geology;
- site hydrogeology, including depth to groundwater and groundwater flow rate;
- soil chemical characteristics including percent organic carbon content;
- soil resistivity;
- contaminant type(s) and remediation goals;

- the presence of low-volatility co-contaminants;
- soil and groundwater contaminant concentrations;
- desired remediation time frames;
- options for wastewater disposal; and
- selection of vapor treatment technology.

The site conditions most crucial to the design of the treatability study SPH system design are presented in Table 3.

Table 3. Site-specific conditions

Design input	Site-specific conditions or criteria
SPH array diameter	9.1 m (30 ft)
Approximate diameter of heated region	13 m (42 ft)
Total depth of heating	30 m (97 ft)
Total volume of subsurface heated	3900 m^3 (5,000 yd^3)
Depth to groundwater	Approximately 11 m (36 ft) in the UCRS
	Approximately 16 m (53 ft) in the **RGA**
Geological units	UCRS from 0 to 17 m (0 to 56 ft)
	RGA from 17 to 28 m (56 to 91 ft)
	McNairy starting at 28 m (91 ft)
	McNairy aquitard 28 to 30 m (91 to 100 ft)
Vadose zone soil type	Clay, silty gravel, and silty sand (UCRS)
Saturated zone soil type	Clay and silt (UCRS)
	Gravel and sand (RGA);
	Sand, silt, and clay aquitard (Upper McNairy Formation)
	Sand (lower McNairy Formation)
Primary contaminant types	TCE, *cis*-1,2-DCE, *trans*-1,2-DCE and vinyl chloride
Maximum TCE concentrations in soil	11,055 mg/kg at boring 400-200 at 2 to 3 m (6 to 10 ft) bgs
Maximum TCE concentrations in groundwater	Indicative of separate phase TCE in both UCRS and RGA
Final subsurface temperature	Boiling point of groundwater at depth
Groundwater conductivity	450 µS/cm
Soil resistivity	About 40 ohm-m (Appendix C)
TOC content of soil	UCRS 0.04% / RGA 0.02%
Site cover	Gravel, natural vegetation, and concrete
Site activity	Site is occupied and relatively active
Surface obstructions	Yes – several site features and a building
Subsurface obstructions and utilities	Yes – several underground utilities and buried obstructions

Source: DOE 1999

4.5 SPH SYSTEM DESIGN

4.5.1 Process Flow

During SPH operations, standard three-phase electncal power is taken from the utility grid and split by the SPH PCU into six separate electrical phases. Under control of the system operator, these six phases of electncal energy are delivered to the subsurface through the SPH power electrodes. **As** the subsurface resists the movement of the electncal current between electrodes, it is heated to the boiling point of site groundwater.

For the treatability study, electrical energy will be applied at six distinct depths to allow the UCRS, the RGA, and the upper interbedded silt, sand, and clay layer of the McNairy Formation to be heated individually. **As** these subsurface regions are heated, VOCs will be volatilized and steam stripped from the soil matrix and then will be collected in VR wells screened at two depths in the vadose zone portion of the

UCRS. A steam venting system in the electrode boreholes will assist the transport of steam and VOC vapors across the interface between the UCRS and RGA. A second steam venting system is installed at the bottom of the fifteen vacuum piezometers and will also collect any steam that might collect at the UCRS/RGA interface. In addition, a reserve vadose VR well will be available, as needed, in each vacuum monitoring piezometer boring. VR features are described in greater detail in Sects. 4.7, 4.7.1, and 4.7.2.

Once collected at the VR wells, or by one of the venting systems, steam laden with contaminant vapors is transported through the VR system header piping to the SPH condenser where soil vapors and volatilized VOCs are separated from the steam. The steam is condensed and then recycled as cooling water. The condenser operation is described in greater detail in Sect. 4.8.

Soil vapors and volatilized VOCs are routed from the condenser, through the VR blower, and into a GAC vapor treatment system where VOCs in the vapor stream are adsorbed. A process flow diagram for the SPH remediation system is presented as Drawing I5EC40000A001 of Appendix A. The condenser is the most complex part of the process flow diagram, and a detail of the condenser is presented as Drawing P5EC40000A004 of Appendix A.

4.5.2 SPH Power Control Unit

The SPH PCU adjusts the voltage applied to the electrodes for optimum subsurface heating. This equipment is manufactured specifically for use in SPH remediations. The SPH PCU selected for the treatability study is designed for 100% duty cycle and sized for a maximum power output of 950-kW at 60 Hz. Over the course of the treatability study, the average output from the SPH PCU will be approximately 65% of the rated capacity, based upon an 80% uptime factor at operations of 80% of rated capacity. The SPH PCU is capable of providing six separate, simultaneous outputs with voltages adjustable from 0 to 2,400 V. At PGDP, the applied electrode voltage is anticipated to vary between 300 and 550 V (Appendix C).

Power supply control and data acquisition are performed on a dedicated computer running the Windows™ operating system. Remote data acquisition software is used to collect and store temperature, power, voltage, current, and operations status data. Operations personnel can access the data acquisition system and download data or monitor and control the heating process either directly or remotely by telephone modem.

The PCU will operate at an average output of 620 kW. During various stages of the heating process, while all of the electrodes will be energized, power will be applied only at 3 to 4 of the discrete heating zones. Once the entire treatment volume has reached design temperatures, the 950-kW PCU will be capable of simultaneously energizing all the electrically conductive intervals in all of the electrodes. Energy requirements to complete the treatment study, including energy loss to the environment, are calculated in Appendix C and presented in Table 4.

4.5.3 SPH Electrode Design Theory

During the SPH process, the movement of steam becomes the driving mechanism for the transport of contaminant vapors in the subsurface. Because steam is produced *in situ* during SPH, and not injected under pressure, the only driving force for steam migration is gravity or buoyancy. The effect of gravity on steam below the water table is to force it directly upward toward the surface. The gravity driven forces of buoyancy are very strong, and unless the steam is trapped under a truly impermeable and continuous soil lens, it will find an upward path to the VR wells. Subsurface investigations in the C-400 Building area have not identified any soil lenses in the targeted heating volume that may be classified as either impermeable or continuous. In addition to the native buoyancy of steam, the upward movement of steam bubbles can be enhanced by directly heating the finer-grained soils to produce small steam bubbles to form a bridging aid as described in Sect. 2.1.

Table 4. Treatability study energy requirements“

Energy application rates	Amount of energy (kW-hr)
Heat-up treatment volume”	253,600 (107,100 for the UCRS, 146,500 for the RGA/McNairy)
Remediate VOCs	1,375,900
Heat spread by thermal conduction	224,600
Lost from soil surface to atmosphere	17,300
Energy required to heat the VR air flow	17,700
Lost to groundwater flow	30,700
Rainfall Percolation Cooling	2,800
Condenser and VR blower‘	91,600
Treatability Totals	**2,014,600**

Notes:
“Based upon an average SPH energy input of 620 kW.
’Energy required to heat the entire treatment volume to the boiling point of water at depth.
‘Allows time for startup and cool down periods.
Calculations from Appendix C.

Once steaming below the water table starts, heated water within the treatment zone rises and flows upward in the direction of steam movement. By the time this heated water has reached the top of the water table, VOCs have been removed by steam stripping. The SPH process results in the net extraction of water from the heated zones [about ***3.6*** gallons per minute (gpm) of water is removed as steam], and there is a slight tendency for groundwater migration in the upward direction due to steam extraction from the subsurface (Appendix C). The water that is removed from the subsurface as steam can be replaced only by groundwater flow in from the bottom and sides of the treatment area. The amount of water removed from the RGA as steam will be 200,000 to 250,000 gal, causing one to two pore exchanges of groundwater due to the remedial process. A further three pore exchanges of groundwater are expected due to the one ft per day of groundwater flow in the RGA. The SPH system is designed to treat the influx of dissolved TCE that results from these pore exchanges; however, the pore volume exchanges, due to groundwater flow, highlight the need for prompt collection of post-test groundwater samples after the end of heating.

At sites with contaminant impact to depths far below the ground surface and with complex lithologies, a staged heating approach can help steam move from deeper regions to the surface and can reduce the remote possibility of further downward DNAPL migration. Typically, DNAPL will migrate down through the soil matrix until it reaches a low-permeability zone or aquitard where it will “hang-up” or “pool” to create a DNAPL source region. To achieve the best remediation results, the subsurface should be heated from the top of the impacted zone to a depth known to be below the DNAPL source region.

During the treatability study, heating to the point of boiling will start at the top of the impacted zone and work downward to a depth slightly above the DNAPL source region in the RGA as described further in Sect. 4.6. This heating will initiate the movement of steam to the surface and establish upward migration pathways for DNAPL vapors once heating in the deeper DNAPL source region begins. Next, the depth directly below the DNAPL source region at the base of the RGA will be heated to above the boiling point of the DNAPL constituents. This provides a “hot floor,” or thermal barrier, to contain any possibility of further downward DNAPL migration. If any TCE DNAPL begins moving deeper, it will contact hot soil and groundwater and flash to buoyant vapor, stopping downward migration. After creation of the thermal barrier, the DNAPL source region at the base of the RGA can be heated to boiling. To accomplish this heating pattern, it must be possible to sequentially heat selected subsurface depths.

4.5.4 SPH Electrode Design

The treatability study will employ a single SPH array constructed of six power electrodes and one neutral electrode. Electrodes will be installed in 30-cm (12-in.) diameter boreholes, and each electrode borehole also will contain two VR wells and a steam venting system. Electrode depths will be set based upon field observations made during electrode construction so that the electrodes are terminated approximately 1 m (3 ft) above the first sand in the McNairy Formation. Site characterization data indicates that the top of this interface is the most probable location for pooled DNAPL sources. This will place the bottom of the electrode borings into the imbedded silt, sand, and clay layer of the upper McNairy Formation without penetrating the approximately 3-m (9-ft) thick aquitard. Across the treatability study area, the RGA/McNairy interface is found at approximately 28 m (91 ft) bgs, and the expected total depth of the electrodes is approximately **30** m (97 ft) bgs.

To treat the sediments in the study area, the electrode design for the treatability study employs six distinct electrically conductive intervals. By using six separate heating intervals, the subsurface can be divided vertically into six distinct heating zones that may be heated first individually and then simultaneously. The six subsurface zones to which electrical resistance heating will be directly applied are described in Table 5. The depths provided are the electrically conductive zones **of** the electrodes. The electrical current spreads out slightly in the vertical plane as it travels between the electrodes. This vertical spreading causes strong electrical heating to extend about 1 m (3 ft) above and below the electrode conductive intervals as shown in Table 5.

Table 5. Electrical resistance heating zones[a]

Zone	Depth below surface	Unit heated
1	2.5 to **4.5** m (8 to 15 ft)	Shallow Vadose UCRS (HU1)
2	5.2 ***to*** 11.3 m (17 to 37 ft)	Deep **Vadose** UCRS (HU2)
3	11.9 to 17.1 m (39 to 56 ft)	Saturated UCRS (HU2A & HU3)
4	17.7 to 23.2 m (58 to 76 ft)	Shallow RGA **(HU4** &HU5)
5	23.8 to 27 m (78 to 89 ft)	Deep **RGA** (HU5)
6	28 to 30 m (91 to 97 ft)	Uppermost McNairy Flow System

[a]Sequence of heating is described in Sect. **4.6 and** Fig. 4.

The SPH electrodes will be positioned across the treatability study area as shown on Drawing C5EC40000A005 of Appendix A. Electrode completion details are provided on Drawing E5EC40000A008 of Appendix **A,** and the design considerations for each element of electrode construction are summarized in Appendix B.

Each of the six electrically conductive zones will contain two metal electrodes for redundancy and the annular space surrounding the metal electrodes will be filled with steel or copper shot to expand the effective diameter of the electrodes. At depth intervals where electrical resistance heating will not be performed, the annular space is filled with either cement grout, bentonite, or sand. Bentonite seals are used to prevent the vertical movement of steam or contaminant vapors within the boreholes, while sand is used to enhance the performance of the VR wells and steam venting systems.

A pharmaceutical-grade Epsom salt (magnesium sulfate) solution will be added to each electrically conductive interval to hydrate the electrode construction materials. The application rate will be one gal of Epsom salt solution per ft of electrode. Epsom salt is edible and inert, and electricians commonly use it in the installation of subsurface electrical grounding and cathodic protection systems.

Electrical connections between the electrode cables and the power cables from the SPH PCU are made above grade at the electrode head. Connections are completed in weatherproof junction boxes for electrical isolation. Electrode head construction details are shown in Drawing E5EC40000A009 of Appendix A.

The following hardware will be installed in each electrode borehole.

- Twelve metal electrodes and associated electrical cables.

- A steam venting system consisting of a downhole steam separator located at approximately 6 m (19 ft) bgs attached to a 5-cm (2-in.) diameter epoxy fiberglass well casing that extends from approximately 10 to 27 m (34 to 54 ft) bgs. The well casing will provide a venting system to assist the recovery of steam and contaminant vapors from beneath the groundwater table and the UCRS/RGA interface. The casing will be screened both within the RGA, thereby below the groundwater table, and within the vadose portion of the UCRS. The screened casing will be connected through the downhole steam separator and the condenser to the VR system. The downhole separator will reduce the entrainment of liquid groundwater, which could contain dissolved ^{99}Tc. Each electrode steam venting system will have an independent control valve at the electrode wellhead.

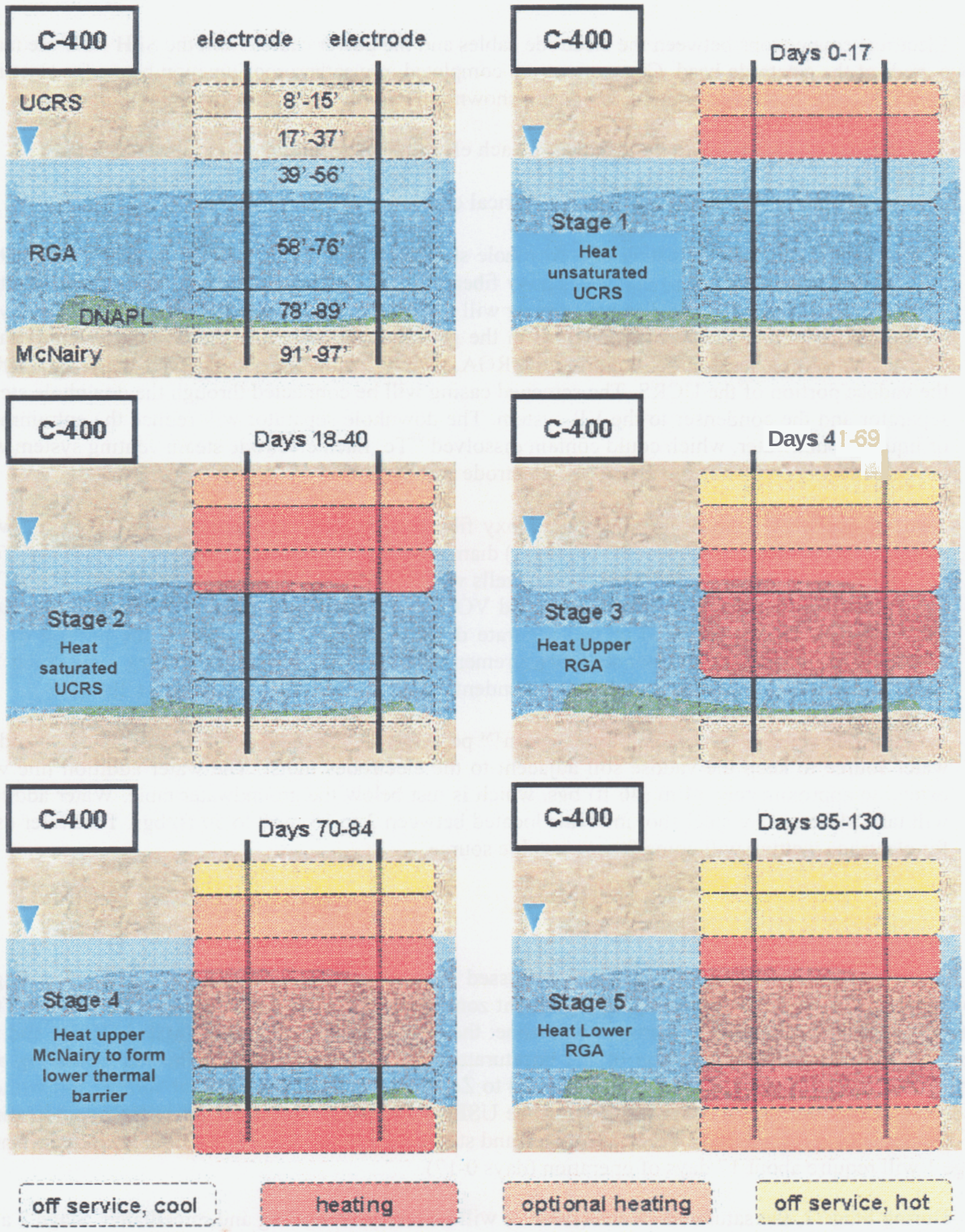
- Two VR wells. A 5 cm (2-in.) diameter epoxy fiberglass casing extending to 9 m (28 ft) bgs will serve as a deep VR well. A second 5 cm (2-in.) diameter epoxy fiberglass casing extending to 2 m (6 ft) bgs will serve as a shallow VR well. These wells will be connected through the condenser to the VR system and will be used to recover steam and VOC vapors generated by the SPH process. Because the VR wells will be screened at two separate depth intervals in the vadose zone portion of the UCRS, they will provide independent measurements of TCE concentration and flow rates. Each VR well will have a vacuum gauge and an independent control valve at the electrode wellhead.

- An electrode wetting system. A 3/8-in. Teflon™ perfluoroallqoxy-alkanes (PFA) tube will provide a water source to keep the vadose soil adjacent to the electrodes moist. The water addition line will extend to approximately 14 m (46 ft) bgs, which is just below the groundwater table. Water addition will take place in five steel shot intervals located between 2 to 15 m (8 to 50 ft) bgs. The water used for electrode wetting will come from a potable source.

4.6 SUBSURFACE HEATING PATTERN

The electrical resistance heating zones discussed in Sect. 4.5.4 will be energized in the five stages shown in Fig. 4 in order to remediate the treatment zone while attempting to determine the mass of TCE that is extracted from each key hydrogeologic zone: the unsaturated UCRS, the saturated UCRS, and the RGA. In Stage 1, the lower portion of the unsaturated UCRS (Zone 2) will be heated to boiling and remediated. During Stage 1, power is also applied to Zone 1, as needed, to heat near surface soil without exceeding design temperatures for any subsurface USEC systems. At the conclusion of Stage 1 heating, the unsaturated UCRS will have been remediated and steam flow to the VR wells will be well established. Stage 1 will require about 17 days of operation (days 0-17).

During Stage 2, the saturated UCRS (Zone 3) will be heated to boiling and remediated. Stage 2 also will establish a network of steam bubbles in the fine-grained lithology that will allow steam generated at deeper depths to migrate upward to the vadose zone by bridging from bubble to bubble. It will be very important for upward steam migration to keep Zone 3, which encompasses a tight soil lens at the groundwater table, energized and boiling during RGA remediation. Stage 2 will require about 23 days of operation (days 18-40).



U. S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 4. General subsurface heating pattern.

FIGURE No. subheating.ppt
DATE 92-22-02

During Stage 3, subsurface heating and remediation will be extended into the upper portion of the RGA (Zone 4), but will remain above the depths at which DNAPL concentrations of TCE are expected to be encountered (Zone 5). Stage 3 will require about 29 days of operation (days 41-69).

In Stage 4, the deepest zone (Zone **6)** will be heated to create the "hot floor" or thermal barrier in the first clay of the upper McNairy Formation immediately below the RGA. The hot floor consists of a soil region that is heated to 98°C (208°F), or above the boiling point of TCE at depth. If any TCE DNAPL is mobilized during remediation of the lower RGA (Zone 5), it cannot move down through the thermal barrier because it will flash into buoyant vapor upon contact with the hot soil. Stage 4 differs from the other heating stages; the other heating stages are heated and then boiled for a period in order to remediate them prior to proceeding to the next heating stage. The McNairy will be heated in Stage 4, but not boiled. Stage 4 will require about 15 days of operation (days 70-84). Boiling treatment of the McNairy will occur in conjunction with treatment of the lower RGA.

As soon as the McNairy reaches thermal barrier temperatures, heating will begin in the lower RGA (Zone 5) to remove DNAPL as quickly as possible. Finally, in Stage 5, the depth interval expected to contain DNAPL (Zone 5) will be heated to design temperatures. As the heating pattern progresses, zones that were heated in earlier stages will be kept at design temperatures by the intermittent application of power. Stage 5 will require about 45 days of operation (days 85-130).

The operator selects the active heating depth intervals by connecting the electrode cables for the appropriate depth zones to the power supply cable from the PCU. These connections are made and broken in the electrode head as shown in Drawing E5EC40000A009 of Appendix **A.**

Once subsurface heating is initiated, the PCU will be operated 24 hours a day, 7 days a week, except for temporary shutdowns to take interim progress samples and to perform system modifications or routine system maintenance. It is estimated that during the 130 days planned for electrical resistance heating, the PCU run-time efficiency will be greater than 80%.

4.7 VR SYSTEM DESIGN

VR from vadose zone soil is an established remediation technology that is commonly used to extract volatile compounds from unsaturated soil. During VR, a vacuum is applied to an extraction well to lower the pressure in the vicinity of the well. Lowering the pressure at the extraction well induces an advective flow of soil vapors from regions of higher pressure to the extraction point. This process can enhance the volatilization of contaminants and promote the diffusion of sorbed contaminants into soil pores where they can be extracted along with soil vapors. During the treatability study, VR will be used to remediate VOCs from shallow unsaturated soil in the UCRS and to recover VOC vapors and steam created by the SPH process.

A conservative VR system design assumes that subsurface vacuums decrease logarithmically with distance from the extraction points (Johnson et al. 1988; 1990). For set well spacing in a given lithology, VR radius of influence (ROI) can be enlarged only by increasing the applied vacuums at the wellheads. Thus, the VR system design for the treatability study is based upon the application of high-vacuums, which is 5 to 10 in. of mercury (in. Hg), at the vapor extraction points. Without direct field measurements of subsurface flow from an applied vacuum, calculation of expected VR ROI is not possible. Geological logs indicate that there is enough heterogeneity and sand stringers in the relatively tight UCRS, that an estimated ROI of **6** m (20 ft) for a VR well, under an applied vacuum of 5 in. Hg, can be considered conservatively low. At an applied vacuum of 10 in. Hg, a conservative estimate of VR ROI in the UCRS is 9 m (30 ft).

Design specifications for the vacuum blower and the vapor treatment systems used with SPH operations are based on the flow of air only. At startup of SPH, no steam is generated in the subsurface.

The blower exerts a vacuum on the VR wellheads and air in the subsurface flows towards the VR well screens. As SPH continues, a small amount of steam is generated. That steam rises into the vadose zone and is swept toward the VR wells by the air flowing to the VR well screens.

At the SPH condenser, steam is converted to water, thereby having no effect on the capacity of the VR blower regardless of the rate of steam production. The amount of steam generated during SPH is not, therefore, a component of the design specifications for the VR blower or the vapor treatment system. As SPH progresses, and steam production increases, steam in the vadose zone will continue to move into the VR well screens as it cannot migrate counter to the subsurface air flow created by the VR blower. As the remediation volume approaches full steaming, the vacuum applied by the blower to the VR wells may increase slightly. This increase is due to head losses resulting from the increased total volumetric flow through the piping system. The subsurface airflow pattern and vapor capture radii at the VR wells, however, do not change. A positive displacement blower automatically increases vacuum in order to pump a constant volume of air, and no operator action is required to adjust the applied vacuum as steaming begins.

The extraction of 200 scfm of air from the subsurface will be sufficient to provide complete recovery of steam and heated soil vapors during the treatability study. In the relatively tight vadose zone soil beneath the C-400 Building, vacuums of 5 to 10 in. Hg will be required to achieve capture radii of 6 to 9 m (20 to 30 ft) at each VR well. To ensure a conservative VR design, criteria for flow and vacuum have been set at 300 scfm and 10 in. Hg, respectively.

For a SPH remediation, VR piping must be heat resistant and is constructed of schedule 80 chlorinated polyvinyl chloride (CPVC). The temperature of the extracted steam/air mixture will be as high as 90°C (194°F). Schedule 80 CPVC is a good thermal insulator and, based upon experience, the exterior surface temperature of the VR header piping will remain below 50°C (120°F) and will not be a personnel hazard. The VR piping also must be sized for the combined flow of air and steam; thus, header pipe diameters are relatively larger than those used in standard VR systems. Header piping conveying the flow of a single VR well will measure 5-cm (2-in.) in diameter. Header piping diameter is increased to 3, 4, or 6 in. to carry the flow of multiple wells (Appendix C). A schematic of the VR header piping system is shown on Drawing P5EC40000A001 of Appendix A.

The vacuum loss between the condenser and the most distant VR wells is about 0.9 in. Hg at the expected combined flow of 200 scfm of air and 600 scfm of steam (Appendix C). Under full steaming conditions, and an air flow of 300 scfm, the vacuum drop across the SPH condenser is 0.5 to 1 in. Hg. If the maximum design vacuum of 10 in. Hg is applied to the subsurface, then the VR blower will need to generate a maximum vacuum approaching 12 in. Hg.

Soil vapor extraction will be performed using a 20-horsepower positive displacement blower (Gardner-Denver 1986). Positive displacement blowers are best suited for applications of high vacuum and relatively high flow. The blower inlet will be manifolded to the SPH condenser outlet and the blower outlet will be connected to the inlet of the vapor treatment system. Sampling ports and gauges will be supplied to measure vacuum, flow, and temperature at the blower inlet and pressure and temperature at the blower outlet. Vacuum, pressure, and temperature will be measured by gauge, while flow is measured by pitot tubes read with water-filled or digital manometers.

The VR wells will be extended above grade, and wellheads consisting of a 90" elbow and an instrument run will be constructed of CPVC pipe and fittings. The instrument run will be constructed of 3.12-cm (1.25-in.) CPVC to increase the accuracy of flow measurement. A thermocouple will be installed to measure the temperature of the extracted vapor. The instrument run also will include a quick-connect port to allow vacuum monitoring and vapor sampling. A ball valve is included on the VR blower end of the instrument run.

4.7.1 VR Wells

Two VR wells will be installed in each electrode borehole to capture VOC vapors and steam mobilized by the SPH process. Spacing between the 7 VR well clusters will average 5 m (15 ft) center-to-center and the expected ROI at each well is 6-9 m (20 to 30 ft) at applied vacuums of 5 to 10 in. Hg, respectively. VR well spacing for the treatability study is three to four times tighter than the maximum spacing distances determined using the conservative estimates of VR ROI in the UCRS at the design vacuums. Once captured, steam and vapors will be routed to the SPH condenser. To ensure complete capture of vapors and steam, the VR system has been over-designed in density of extraction points and applied vacuum.

VR wells will be constructed of 5-cm (2-in.) diameter epoxy fiberglass well casing and screen. Casing and screen will have threaded, flush joints, and screens will be plugged at the bottom. Each VR well will consist of two casings, one placed in the shallow portion of the UCRS vadose zone and one placed in the deep portion of the UCRS vadose zone. The screen interval on the shallow well will extend from 1 to 2 m (3 to 6 ft) and the screened interval on the lower well will extend from 7 to 9 m (23 to 28 ft) bgs. The screen slot size will be 0.05 cm (0.02 in.), and screened intervals will be surrounded by a sand filter pack or steel shot pack that extends 6 in. above and below the slotted sections. VR well completion details are outlined in Drawing E5EC40000A008 of Appendix A.

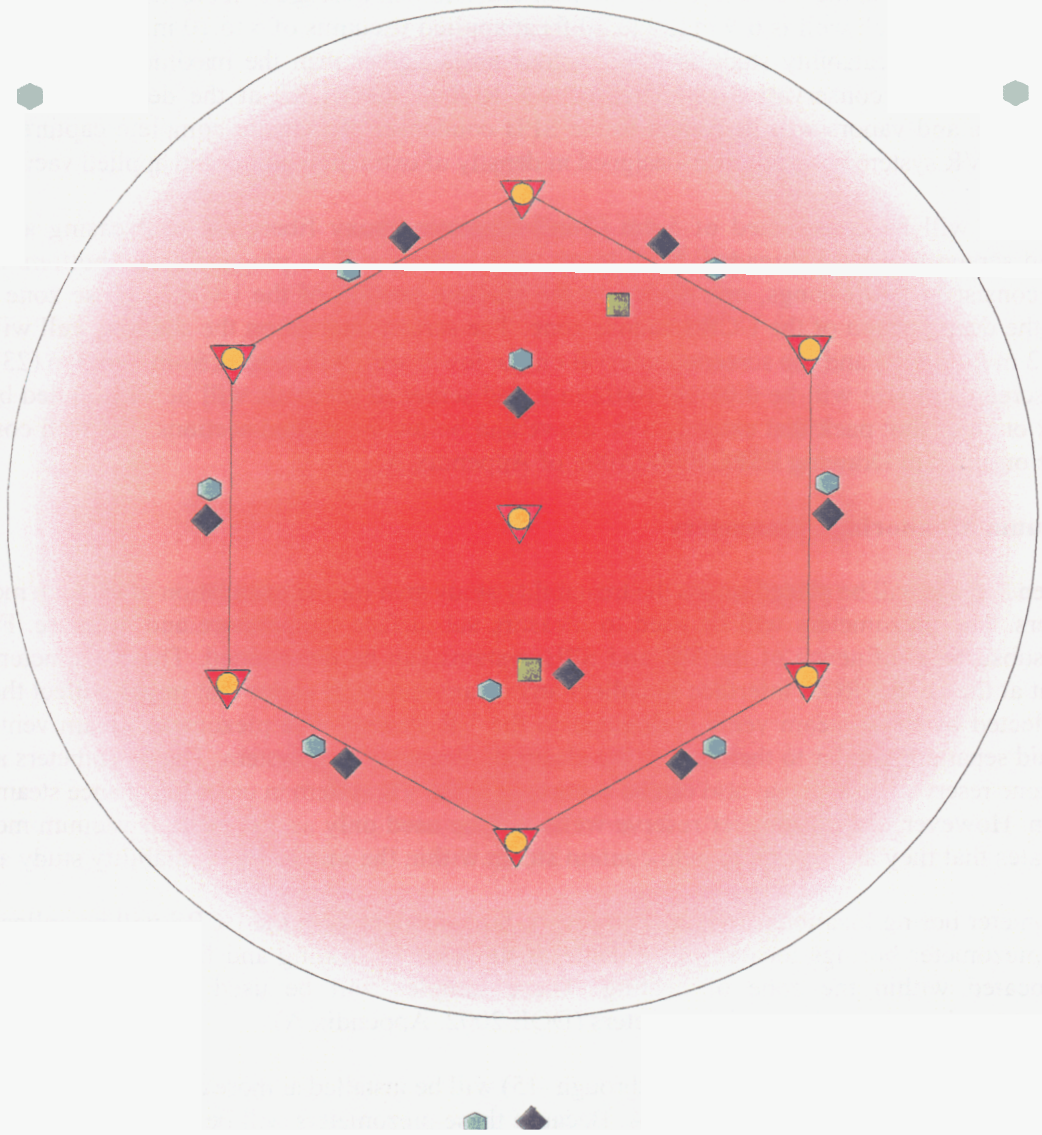
4.7.2 Vacuum Monitoring Piezometers

Fifteen borings will be placed across the treatability study area for the installation of vacuum monitoring piezometers. The piezometers will be used to measure subsurface temperature and pressure. From this data, the subsurface influence of the VR and SPH systems can be determined. The piezometers have a steam vent at the UCRS/RGA interface to collect any steam and TCE vapor that might collect there. Any steam collected by these steam vents is directed to the VR system. The piezometer steam vents have a vapor-liquid separator similar to that used in the electrode steam venting system. The piezometers also have a vadose zone reserve VR well that also can be connected to the VR system in order to enhance steam and VR in a region. However, the piezometer reserve wells will be used only as VR wells if vacuum monitoring data indicates that they are needed to help contain steam within the immediate treatability study area.

Piezometer boring locations are shown in Fig. 5. Soil samples from the UCRS will be collected from the three piezometer borings located just outside of the zone of heating and from the eight piezometer borings located within the zone of heating. These samples will be used to characterize baseline contaminant levels and geochemical parameters (DOE 2002, Appendix A).

An additional four piezometers (PZ-12 through -15) will be installed at more distant locations, as shown in Drawing C5EC40000A005 in Appendix A. Because these piezometers will be well outside the expected region of electrical resistance heating influence, soil samples will not be collected at these locations.

Construction details for the vacuum monitoring piezometers are shown on Drawing C5EC40000A006 of Appendix A. Piezometer borings will extend to at least 18 m (58 ft) bgs. Vacuum monitoring points will be installed at depths of 3 m (10 ft), 6 m (20 ft), and 10 m (33 ft) bgs, allowing subsurface vacuum to be recorded at three discrete depth intervals. The upper and middle vacuum monitoring points will be constructed of 1.27 cm (0.5-in.) O.D. sintered metal fittings measuring 3.5 cm (1.4 in.) in length. Each sintered metal fitting will be connected to a 0.64 cm (1/4-in.) O.D. PFA Teflon™ tube that runs to the surface. The lower vacuum monitoring point will be constructed of a 3.18-cm (1.25-in.) diameter well point constructed of No. 60 stainless steel gauze screen and measuring 90 cm (36 in.) in length. The well point will be connected to a 2.5-cm (1-in.) diameter galvanized steel pipe that runs to the surface. Vacuum monitoring points will be surrounded by a sand filter pack that extends 0.5 m (1.5 ft) above and below the points. The annular space between the vacuum monitoring points will be sealed with bentonite and grout.



Electrode

Vapor Recovery Wells

Vacuum Monitoring Piezometers

Multi-port Monitoring Well

Post-Test Soil Characterization Boring

Note: Locations of borings and wells are conceptual and may change due to actual field conditions.

0 5 10

Scale in feet

U. S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

SAIC
Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

Fig. 5. Location of borings.

FIGURE No. cell.ppt
DATE 07-13-01

The lower vacuum monitoring point also will serve, if needed, as a reserve VR well if vacuum influence measurements indicate that complete VR can not be assured within the SPH treatment area. Each piezometer boring also will contain a deep steam vent constructed in a similar manner as the steam vents in the electrode borings. The lower steam vent will extend to a depth of 16 m (53 ft) bgs and will recover steam from the RGA/UCRS interface. The steam vents will be equipped with pressure gauges and independent control valves at the wellheads and will be connected through the condenser to the VR system.

Each piezometer boring also will contain a 0.95-cm (3/8-in.) PFA Teflon™ tube that extends from the surface to a depth of 17 m (57 ft) and serves as a thermowell. The bottom of the thermowell will be capped. A single type T thermocouple will be periodically moved up and down in each thermowell, and temperatures can be monitored at various depths as desired by using hand-held instrumentation.

4.8 STEAM CONDENSER SYSTEM

Once any portion of the subsurface reaches the boiling point of water, steam generation will begin. As steam rises into the vadose zone, it is collected at the VR wells and routed to the SPH condenser. The skid-mounted SPH condensers are manufactured and sized to accommodate the largest SPH power supplies.

The SPH condenser separates soil vapors from steam, performs as a liquid/vapor knockout, air strips steam condensate prior to discharge or reuse, and provides automated condensate pumping functions. The vapor outlet of the condenser contains a liquid/vapor knockout system and includes a mist eliminator that is 99% efficient in removing droplets to a size of 10 microns. When connected to a vacuum blower, the pressure drop across the condenser is less than 0.5 pounds per square inch (psi), which is equivalent to approximately 1 in. Hg vacuum.

The expected volumes of steam, soil vapors, and condensate passing through the condenser during the treatability study are summarized in Table 6. Once the treatment volume is completely heated, the VR system will capture approximately 800 scfm of steam and soil vapors from the subsurface. This combined flow will be composed of 600 scfm of steam and 200 scfm of soil vapors. Approximately 2,100,000 L (560,000 gal) of water will be removed from the subsurface during the treatability study in the form of steam (Appendix C).

Table 6. Estimated flow rates and volumes of steam and condensate

Process Stream	Maximum Flow Rate"	Total Volume Over the Entire Study Period (gal)
Combined steam and vapor flow	800 scfm	NA
Steam from the subsurface	600 scfm	NA
Air and vapors from the subsurface	300 scfm	NA
Water recovered from the subsurface as steam	3.5 to 4 gpm	560,000 gal
Condensate recycled as cooling makeup water[b]	3.5 to 4 gpm	530,000 gal
Condensate recycled as electrode wetting water	0.2 gpm	30,000 gal

Notes:

"Flow rates achievable when the heated region is at design temperatures. (Appendix C)

[b]Exact amount depends on weather conditions.

NA = not applicable.

Steam extraction will remove water from the subsurface at a rate of about 3.6 gpm. When boiling the vadose UCRS, no groundwater inflow will occur. When boiling the saturated UCRS, little water inflow will occur due to the relative low liquid permeability of the UCRS and boiling likely will result in a few ft

of UCRS draw down. When boiling the RGA, the groundwater inflow rate will equal the water extraction rate as steam. This inflow will be superimposed on the existing groundwater flow regime of the RGA, which has an estimated native water flow velocity of about 1 ft per day.

The conditions within the steam condenser are a good application of Henry's Law. Based on Henry's Law (and borne out by experience at previous SPH sites), **99.6%** of the TCE vapor will remain in the vapor phase as it passes through the condenser. Only 0.4% of the TCE will become dissolved in the steam condensate (Appendix C).

The condenser is water-cooled. The heat that is removed from the steam in condensation is reflected in a temperature rise of the recirculation cooling water. The heat is then removed from the recirculation water using a cooling tower in which a portion of the recirculation water evaporates with each pass. Operations of the cooling tower are very similar to that of an air stripping tower. Condensate water is treated by passing it through a GAC VOC filter and a ^{99}Tc ion exchange resin before it is recycled to replenish the recirculation water lost to evaporation. Due to the energy balance, the amount of water that is evaporated from the cooling tower is almost exactly equal to the amount of steam that is condensed, and the exact balance depends on the atmosphere's relative humidity. During the day when the relative humidity tends to be lower, the condenser evaporates a little more water than it condenses; during the night and during rainy periods, the condenser tends to condense a little more water than it evaporates. A water tank will be used to store excess cooling water during high humidity periods and provide make-up cooling water for low humidity periods.

Vapor-liquid separators will be installed in the steam vents of the electrode borings and the vacuum monitoring piezometers to reduce the entrainment of liquid groundwater. Most water will be extracted in steam form, which is distilled and thus contains no dissolved minerals such as ^{99}Tc. However, the ^{99}Tc-adsorbing ion exchange resin used to treat the recovered condensate will provide a further safety measure.

4.9 VAPOR TREATMENT SYSTEM

Several vapor treatment options were considered for the SPH treatability study. Adsorption by GAC was selected as the preferred technology. The considered options are described below.

4.9.1 Adsorption

VOCs can be removed from vapor streams by adsorption onto GAC. Vapor phase carbon adsorption utilizes highly porous GAC as a medium for capturing the VOCs in the off-gas stream. Carbon adsorption systems typically consist of two or more sealed vessels filled with GAC, connected in series, and operated under positive or negative pressure. **A** primary advantage using adsorption technology to treat chlorinated contaminants is that there are no combustion processes involved; therefore, there are no associated emissions of particulates, hydrochloric acid (HCl), nitrogen oxides, or other potentially hazardous combustion by-products.

While GAC removes contaminants from the off-gas stream, it does not destroy them. The GAC must be replaced periodically and regenerated at an off-site facility permitted for this activity. The operating costs for carbon adsorption are primarily the expenses of GAC replacement and regeneration. Limitations of carbon adsorption arise from the fact that the GAC use rate is very sensitive to the concentration of VOCs in the treated vapor stream and to the total pounds of VOCs treated. High vapor moisture levels and high temperatures also adversely affect adsorption treatment systems, as these conditions lower the loading capability of **GAC.**

Contaminant and soil vapors are pulled from the VR wells, through the SPH condenser, and into the VR blower by vacuum. Upon exiting the VR blower, the vapor stream is cooled by an air-to-water heat

exchanger to temperatures approaching ambient conditions. This cooled vapor stream then is passed through two 20,000-pound GAC vessels connected in series and discharged through a stack to the atmosphere. System efficiency is monitored, and GAC change-outs scheduled, by sampling the vapor stream at the inlet of the first GAC vessel, between the vessels, and after the second vessel.

An on-line photoacoustic analyzer, which operates using photoacoustic infrared spectroscopy, will be installed in the stack discharge from the secondary activated carbon vessel. This photoacoustic analyzer will alarm and shut down the system, in the event that an out of compliance situation is monitored. The VOC adsorption zone consists of a thin band known as the mass transfer zone (MTZ) that moves through the carbon bed from the inlet to the outlet. When the MTZ reaches the bed outlet, "breakthrough" occurs. The adsorption process is exothermic and heat is released in the adsorption zone. The MTZ can become quite hot, in excess of 150°C (302°F) when high VOC concentrations are adsorbed onto fresh carbon (US Filter-Westates 2001); however, it is only the inch-thick MTZ that becomes hot, and the flow of air through the carbon vessel rapidly cools the upstream (loaded) carbon. The hot air exiting the MTZ is cooled, in turn, by the downstream carbon and exits the bed at a temperature only a few degrees above ambient.

In order to prevent excessive MTZ temperatures, the activated carbon vessels will be loaded twice. When a fresh GAC vessel is placed on service, the GAC inlet header dilution valve will be opened (see Drawing I5EC40000A001 of Appendix A). The centrifugal blower will draw 2,000 scfm of dilution air into the process stream to reduce vapor concentrations by about **90%** and allow the GAC to be loaded while maintaining a low MTZ temperature. When the primary GAC has broken through (i.e., the VOC concentration at the inlet of the secondary GAC vessel is 50% of the VOC concentration at the inlet of the primary GAC), the GAC inlet header dilution valve will be shut and the inter-GAC header dilution valve will be opened. The primary GAC will be loaded again with an undiluted process stream to maximize loading.

When the primary GAC vessel experiences breakthrough with undiluted air, the secondary GAC vessel will become the primary GAC vessel and a fresh GAC vessel, which will be stored onsite to facilitate rapid changeouts, will become the new secondary GAC vessel. The GAC inlet header dilution valve will be opened again to provide the initial loading of the new primary GAC. The loaded GAC vessel will be swapped for a fresh GAC vessel that will be stored onsite for the next changeout. A GAC vessel changeout is likely to be required every 4 to 20 days, depending on TCE extraction rates.

Carbon adsorption systems are readily available on a rental basis from qualified suppliers who provide GAC regeneration services at their licensed facilities. The systems are easy to install, have no moving parts, and require very little maintenance. The principal cost for operating an adsorption system is GAC regeneration and replacement. It is expected that the vapor stream from the treatability study will contain high concentrations of the targeted contaminants. The vapor stream will be cooled before it reaches the carbon vessels, and it should be possible to achieve GAC loading rates of 20-40 weight percent and reductions in VOC concentrations of over 95%. Thus, 2.5 to 5 pounds of GAC will be required for each pound of VOCs removed from the treated vapor stream (US Filter-Westates 2001).

Carbon adsorption systems provide high VOC capture rates, require minimal initial capital expenditures, and are easily installed. Once installed, costs for operations, labor, and maintenance are low, and the systems produce no combustion by-products. However, adsorption systems remove VOCs from the vapor stream but do not destroy them; thus, they create a waste form that requires off-site treatment. The amount of GAC needed to treat a given vapor stream represents the principal cost of an adsorption system. **GAC** use, and subsequently system cost, is directly proportional to the pounds of VOCs treated.

Carbon adsorption was selected for the SPH treatability study due to its reliability and relatively low cost based on the expected mass to be recovered from the treatment region. The lack of combustion byproducts is considered to be an added benefit.

4.9.2 Solvent Recovery

On-site solvent recovery systems can also be used to remove VOC contaminants from vapor streams. Solvent recovery systems use activated carbon to adsorb VOCs from the vapor stream, regenerate the carbon onsite, and produce a waste form that is a mixture of water and liquid phase VOCs. Typically, solvent recovery systems are capable of achieving VOC removal rates of greater than 95%.

Typically, these systems consist of three carbon adsorption vessels interconnected so that two may be used in series to treat the vapor stream, while the activated carbon in the third is being regenerated by steam. Once a carbon regeneration cycle is complete, the interconnections between the vessels switch and the vessel containing the newly regenerated carbon becomes the secondary treatment vessel; the secondary treatment vessel becomes the primary treatment vessel; and the carbon in primary treatment vessel is regenerated. **As** the process is repeated, steam condensate and recovered liquid phase VOCs are pumped from the system for storage and final disposal.

If solvent recovery had been selected for use in the treatability study, contaminant and soil vapors would be pulled from the VR wells, through the SPH condenser, and into the VR blower by vacuum. Upon exiting the VR blower, the vapor stream would be cooled by an air-to-water heat exchanger to temperatures approaching ambient conditions. This cooled vapor stream would be directed into the inlet of the solvent recovery system. **A** final, off-site, regenerated carbon vessel would be placed at the discharge of the solvent recovery unit for additional treatment polishing and to allow the solvent recovery unit to operate at higher loading rates. Treated vapors would be discharged directly to the atmosphere through a stack. VOC capture efficiency is monitored by sampling the vapor stream at the inlet and outlet of the solvent recovery system and at the outlet of the polishing vessel.

Solvent recovery system auxiliaries include an electrical connection and a boiler to produce steam. Condensed steam and liquid phase VOCs must be pumped from the system to storage tanks for proper disposal. The pumping and storage systems will require 110% secondary containment. Solvent recovery is an established vapor treatment technology that has been proven effective in applications similar to the proposed treatability study application. Solvent recovery units matching the treatability study design requirements are commercially available on a purchase basis.

Because solvent recovery is an adsorption technology, it does not provide on-site destruction of VOCs. **A** waste stream of water and liquid phase VOCs are generated and require storage and proper disposal. Once a solvent recovery system has been installed, however, operating costs are much less sensitive to the concentration of contaminants in the vapor stream or the total pounds of contaminants treated as compared to off-site, regenerated **GAC** systems. Solvent recovery systems are relatively complex and require more operating labor than GAC systems. They also require more energy than a GAC system and produce a liquid waste that requires proper storage and disposal.

Although solvent recovery was not selected for the SPH treatability study, it should be retained for consideration in full-scale remediation, especially if the study shows that high TCE masses are likely to be extracted.

4.9.3 Catalytic Oxidization

Catalytic oxidization uses a catalyst bed to initiate oxidative destruction of VOCs in vapor streams. The catalyst facilitates the oxidation process and allows combustion of VOCs to be accomplished at temperatures of 315 to 490°C (600 to 900°F) (Johnson-Matthey 1996). While the catalyst typically has a long life span, it can be quickly poisoned by lead, bismuth, mercury, silicon, arsenic, antimony, and phosphorous. Additionally, some organic compounds can mask the catalyst, lowering the destruction

efficiencies of targeted contaminants. An evaluation process would be necessary to select and size the most appropriate catalyst for the project, but commercially available catalysts are readily available for the treatment of the targeted contaminants.

If catalytic oxidation had been selected for use in the treatability study, contaminant and soil vapors would be pulled from the VR wells, through the SPH condenser, and into the VR blower by vacuum. Upon exiting the VR blower, vapors would be directed into the inlet of the catalytic oxidizer. These vapors would then be preheated to the catalyst's activation temperature to sustain the oxidation process. The required preheating temperature typically is between 315 to 430°C (600°F and 800°F) (Johnson-Matthey 1996) and is achieved with a natural gas or propane-fired preheat burner located in a combustion chamber upstream of the catalyst bed.

Dilution air is fed into the preheating system to maintain the total concentration of flammable contaminants at less than 25% of the lower explosive limit (Johnson-Matthey 1996). This also prevents damage to the catalyst bed from overheating. The maximum operating temperature of most chlorinated catalyst beds is approximately 490°C (900°F) (Johnson-Matthey 1996). The requirement for dilution air must be taken into consideration when sizing a catalytic oxidizer system for a given vapor stream flow rate. Because the targeted contaminants in the treatability study have low heats of combustion, it would be possible to introduce high concentrations of contaminants to a catalyst bed with a limited need for dilution air. VOC destruction efficiency is determined by sampling the vapor stream at the inlet and outlet of the oxidizer.

Oxidization of chlorinated organic compounds produces HCI vapors that require removal through the use of a scrubber installed immediately downstream of the oxidizer. Most scrubber systems consist of two stages: a wet quench (water spray) that cools the exhaust gases from approximately 430°C (800°F) to about 248°C (120°F) (Weast et al. 1976) and captures some of the HCI, and a countercurrent wash with a caustic solution [usually sodium hydroxide (NaOH)] that neutralizes the acid quench water and removes the remaining HCI by conversion to salt water (brine).

Scrubber auxiliaries would include a caustic solution holding and supply system, a brine bleed discharge line that removes excess brine from the scrubber sump, and an induced-draft fan that draws treated vapors from the scrubber and discharges them through the exhaust stack. Excess scrubber brine, which accumulates in the scrubber sump, would be pumped to storage tanks and held for reuse as electrode wetting water, reuse for PGDP water softener ion exchange resin regeneration, or disposal. The holding and pumping systems for the caustic solution and excess brine would include provisions for 110% secondary containment. The volume of brine produced is proportional to the TCE mass that is treated. It is estimated that between 20,000 and 80,000 gal (Appendix C) of scrubber brine would have been generated during the treatability study. Excess brine would contain 3% to 12% salt and no residual TCE. Scrubber brine would be characterized and treated accordingly. No discharge of excess brine could be made to any Kentucky Pollutant Discharge Elimination System (KPDES) outfall without permits from the Kentucky Division of Water.

Because catalytic oxidization operates at lower temperatures than thermal oxidation, it produces significantly lower levels of nitrogen oxides. However, some nitrogen oxides are produced during the catalytic oxidation process. Catalytic oxidation, like thermal oxidation, also may yield products of incomplete combustion, including dioxins. The use of an acid gas scrubber system helps to ensure that particulate matter, on which the products of incomplete combustion tend to condense, is removed from the exhaust stream. Dioxin emissions from the acid gas scrubber typically are below detection limits.

Catalytic oxidation is an established vapor treatment technology that has been proven effective in applications similar to the proposed treatability study application. Catalytic oxidation units matching the treatability study design requirements are commercially available on a purchase and, possibly, a rental

basis. Typically, an acid scrubber system must be designed and purchased separately for either purchased or rental units. Additional costs for catalytic oxidation include the following: connections for electrical power, supplemental fuel, and potable water; storage for caustic chemicals; on-going fuel and scrubber chemical use; and storage and disposal of brine. Monitoring of the exhaust stream may have to include a range of possible combustion products as well as the target contaminants, which could significantly increase sampling and analytical costs.

Catalytic oxidation offers on-site destruction of VOCs at high VOC destruction rates (over 95%). Once a catalytic oxidation system has been installed, the operating costs for treating a vapor stream that is low in fuel value are only slightly influenced by the concentration of contaminants in the vapor stream or the total pounds of contaminants treated. On the other hand, catalytic oxidation systems are relatively complex and require more operating labor and maintenance than either **GAC** or solvent recovery systems. Oxidizers also require more energy than the other vapor treatment options considered and the potential for oxidizers to produce combustion by-products must be taken into account when determining sampling and analytical methods, schedules, and costs.

Although catalytic oxidation was not selected for the SPH treatability study, it should be retained for consideration in full-scale remediation, especially if the study shows that high TCE masses are likely to be extracted.

4.9.4 Electron Beam

Electron Beam (E-Beam) Technology is an industrial emissions control process for destroying toxic emissions at factory sites. In addition, it can be used for on-site destruction of toxic vapors extracted from contaminated groundwater or soil. The heart of the system is a source of electrons, called primary electrons, which are accelerated by a high voltage to velocities approaching the speed of light.

When directed into a contaminated air stream, these primary electrons interact with air and other molecules, producing secondary electron emissions. The combined cloud of primary and secondary electrons collide with the contaminant molecules present in the vapor stream, breaking their chemical bonds. The resulting particles then oxidize in the air stream to form water and carbon dioxide. Any chlorinated VOCs present will form acid aerosols, which are converted into a disposable salt solution (scrubber discharge) by passing the E-Beam treated vapors through a caustic (NaOH) scrubber.

The E-Beam process has been developed under the trade name of Zetron™ by Tipaz, Inc., in cooperation with the DOE Lawrence Livermore National Laboratory (Tipaz 2000). The technology has not yet been established as a proven method for applications similar to the proposed treatability study application. An E-Beam system matching the treatability study design requirements would have to be constructed specifically for the project and would be available on a rental basis.

The E-Beam technology is particularly applicable to PGDP because it operates at ambient temperature and is effective in treating air steams having a high humidity and particulate content. By operating at ambient temperatures, the E-Beam does not produce the hazardous byproducts that can be generated by thermal and thermal-catalytic oxidization processes. Unlike vapor treatment technologies that rely on contaminant adsorption, such as activated carbon, capital and operation costs for an E-Beam system do not increase directly with the mass of VOCs treated.

E-Beam equipment has been successfully applied in several very important industrial applications, including television sets, x-ray equipment, medical sterilization, bridge and nuclear vessel inspection, narrow beam welding, curing of coatings and ink print, and various other chemical and film processing procedures. E-Beam equipment is well understood and is rugged, reliable, and safe. The E-Beam is completely

enclosed within lead shielding, which prevents any radiation from being emitted. *An* interlock system prevents operation of the E-Beam until the electron gun compartment door is closed. Radiation measurements are performed at startup and any time during operations to assure the safety of operators and maintenance personnel.

In addition to electrical power, E-Beam systems require sources of makeup water and NaOH for the scrubber unit. Makeup water would be supplied by condensate from the SPH condenser and by an on-site water supply, while a source of NaOH solution would be stored onsite. The holding and pumping systems for the NaOH solution would include provisions for 110% secondary containment.

The scrubber unit produces a brine solution that would require on-site storage and reuse as electrode wetting water, reuse for PGDP water softener ion exchange resin regeneration, or proper disposal. The holding and pumping systems for the scrubber discharge solution would include provisions for 110% secondary containment. The volume of brine produced is proportional to the TCE mass that is treated. It is estimated that between 20,000 and 80,000 gal of brine would be generated during the treatability study (Appendix C). The brine would contain 3 to 12% salt and no residual TCE. Brine from the scrubber would be characterized and treated accordingly. No discharges would be made to any KPDES outfall without permits from the Kentucky Division **of Water,**

Although electron beam oxidation was not selected for the SPH treatability study, it should be retained for consideration in full-scale remediation, especially if the study shows that high TCE masses are likely to be extracted. Intervening improvements and further operational experience with electron beam oxidation might make it the preferred alternative in the near future.

The performance specifications for a Zetron™ E-Beam vapor treatment system are provided in Table 7.

Table 7. Zetron™ System specifications

System parameter	Specification
System identification	Zetron™ Model 2-20
Air flow rate	500 scfm
Initial TCE concentrations	5,000 ppm
Final TCE concentrations	<50 ppm
Minimum TCE destruction efficiency	90%
Energy requirements	18 kW
Power requirements:	
2-20 System	3-Ph 60Hz, 208 VAC
Chiller	3-Ph 60Hz, 206/230 VAC
Scrubber	3-Ph 60Hz, 208 VAC
System Footprint	16-ft trailer

Source: Tipaz 2000

4.9.5 Cost Comparison of Vapor Treatment Options

The results of a preliminary cost comparison of the possible vapor treatment options for the treatability study are provided as Fig. **6.** Assumptions made in developing the preliminary costs for each vapor treatment technology are provided below.

General Assumptions for all treatment technologies

Number of treatment days:	130 days
Likely minimum pounds of TCE in treatment region:	25,000 lb
Likely maximum pounds of TCE in treatment region:	100,000 lb

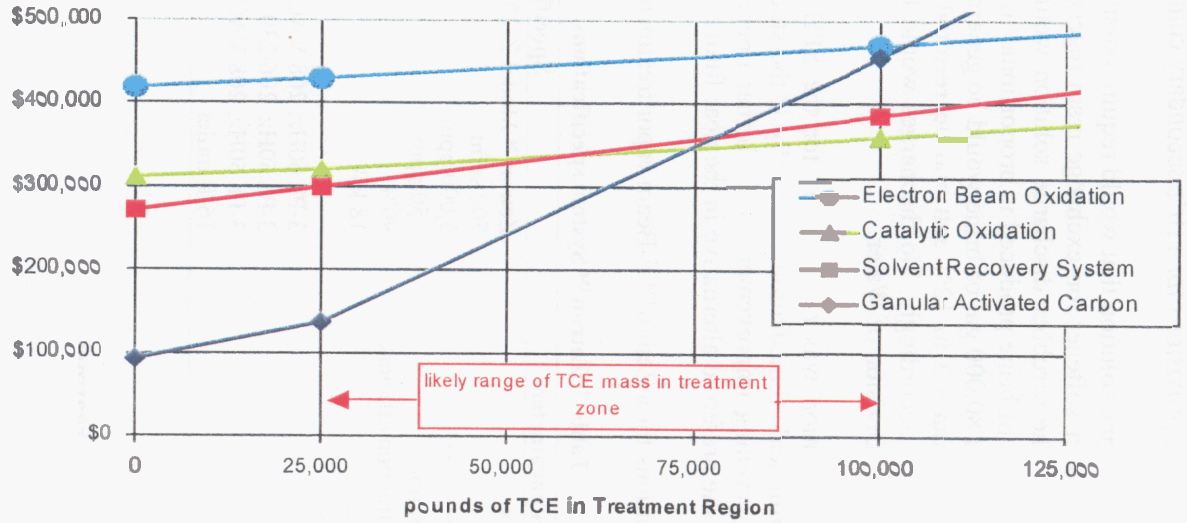


Fig. 6. Preliminary cost comparison of vapor treatment options.

U. S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER
US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

FIGURE No. cost.ppt
DATE 07-11-01

Carbon Adsorption with Off-Site Regeneration

Estimated mobilization and system set-up costs:	$60,000
Estimated weekly operations costs (not including GAC):	$600/wk
TCE mass loading (moderate TCE concentrations):	25%
TCE mass loading (high TCE concentrations):	30%

Solvent Recovery (Carbon with On-Site Steam Regeneration)

Estimated mobilization and system set-up costs:	$170,000
Estimated weekly operations costs (including unit rental and utilities):	$4,000/wk
Ratio of condensate water to TCE in system waste stream:	4 to 1
Estimated waste water disposal costs:	$1/gal
Estimated liquid phase TCE disposal costs:	$10/gal

Catalytic Oxidation with Acid Scrubber

Estimated mobilization and system set-up costs:	$120,000
Estimated weekly operations costs (including unit rental and utilities):	$9,000/wk
Estimated scrubber chemical costs per pound of TCE treated:	$0.20
Gallons of scrubber brine per pound of TCE treated:	1
Brine disposal costs:	$1/gal
Additional sampling and analytical costs:	Not determined

Electron Beam with Acid Scrubber

Estimated mobilization and system set-up costs:	*$85,000*
Estimated weekly operations costs (including unit rental and utilities):	$14,000/wk
Estimated scrubber chemical costs per pound of TCE treated:	$0.20
Gallons of scrubber brine per pound of TCE treated:	1
Brine disposal costs:	$1/gal

4.10 SYSTEM CONTROLS

System diagnostics, controls, and alarms are routed through the computer in the SPH PCU and the control panels of the SPH condenser and the VR blower. **A** GAC vapor treatment system does not require electrical power to operate, and is not included in the system control wiring. System diagnostics, controls, and alarms associated with the SPH PCU are accessed through the PCU computer. Emergency shut downs and automatic notification alarms are routed through the VR blower, the PCU, and the SPH condenser.

On-site and remote operators can turn the SPH PCU on or off, change the voltages applied to the electrical phases, reset some PCU alarms, and record temperatures throughout the SPH system. Voltage changes can be made immediately or by ramping up or down over set time intervals. Alarms are provided for transformer over-temperature, for current trips and faults, and for excessive voltage and current levels. The PCU main contactor can be closed only by operations personnel using the PCU control computer, and only authorized operations personnel can energize the electrode field.

Remote operators can determine if system faults or unwanted operating conditions exist inside the PCU or the electrode field. Most faults and undesired operating conditions can be corrected remotely by altering operating parameters or can be tolerated until the next scheduled site visit. More severe system faults may require portions of the electrode field, or the entire SPH PCU, to be shut down. Transformer alarms cause immediate shut down of the PCU and must be cleared by a site visit before the PCU can be reenergized.

Because steam collection and vapor treatment are vital operations functions, system alarms that do not originate in the SPH PCU are routed through the control panels of the VR blower and the SPH condenser. If the VR system stops for any reason, the SPH PCU is automatically shut down and an auto-dialer contacts operations personnel. A site visit then is required to correct the alarm condition and restart the VR blower before the SPH PCU can be reenergized. If there are no operating faults with the SPH condenser, it will continue to operate until it is shut down manually.

If the SPH condenser is unable to process steam or excess condensate, it will alarm. This alarm immediately stops the VR blower and halts steam collection and condensate production. Stopping the VR blower triggers a shut down of the SPH PCU and initiates the automatic notification auto-dialer.

The alarms associated with SPH PCU, SPH condenser, and the VR blower (along with the actions caused by each alarm) are identified in Table 8.

4.11 POWER AND MECHANICAL FAILURES

In the event of a site-wide power failure, all system equipment will shut down and the auto-dialer will contact operations staff by using an emergency battery pack for power. When power is restored, the SPH condenser and the VR blower will restart automatically. During a brief power failure (less than about 20 minutes), the PCU control computer will continue to operate, powered by an uninterruptible power supply (UPS). Following a brief power failure, the PCU can be restarted remotely if desired. Following an extended power failure, a site visit is required in order to restart the PCU control computer and resume SPH operation.

When the SPH PCU is shut down, the creation of steam in the subsurface stops instantly. Residual steam, however, remains in the subsurface and that steam continues to rise toward the surface. If the VR system is operating, residual steam is collected at the bottom of the vadose zone. If the VR system is not operating, a small flux of residual steam will enter the non-heated portion of the vadose zone and condense. This condensate will be remediated by the treatability study system once operations are restarted.

4.12 CONTROL OF VOCS

During the treatability study, the subsurface in the treatment area is under the vacuum influence of the steam and VOC VR system. This vacuum influence pulls steam and VOC vapors in the vadose zone to the extraction wells and removes them from the subsurface. While there may be apparent preferential pathways in the subsurface, such as the loose fill surrounding utility conduits, steam and VOC vapors still will migrate to the extraction wells. High air-permeability pathways, such as pipe chases, preferentially allow air to flow into the treatment area and steam and VOCs are unable to migrate out of the treatment area against this airflow. If the VR system stops, the SPH PCU is automatically shut down, and the creation of steam in the subsurface stops instantly. Once steam production stops, the driving force for steam and VOC migration out of the treatment area is removed. While steam and TCE vapor can diffuse several ft into cool soils adjacent and above the treatment zone during an extended VR system shutdown, these diffusing vapors are rapidly recovered when VR operation is resumed.

When the entire remediation volume is at boiling, the VR lines hold less than 0.5 L (1 pint) of water in the form of water droplets and steam. During operations, these lines are under vacuum, and a line rupture will not result in the venting of steam or VOC vapors.

An on-line photoacoustic analyzer in the stack will alarm and automatically shut down the VR system and the SPH PCU in the event that both the primary and secondary activated carbon vessel break through and emit VOC vapors to the atmosphere.

Table 8. System alarms and actions

Condition	Alarm	Action
Site-wide power failure		
	1. SPH PCU alarms. 2. Auto-dialer calls out.	1. All equipment stops running. 2. Operations staff is notified. 3. VR system restarts automatically. 4. SPH can be restarted remotely after brief (20 minute) power failures; site visit required following extended power failures.
SPH PCU – Major Fault		
Power Failure PCU transformer overheating Tap switch out of position Loss of power to PCU controls	SPH PCU alarms.	1. SPH PCU shuts down. 2. Problem seen in daily check. 3. Condenser remains operational. 4. VR remains operational. 5. Vapor treatment remains operational. 6. Alarm cleared remotely or by site visit
SPH PCU – Minor Fault		
Loss of an electrical phase Unbalanced electrical phases	No alarms.	1. All systems remain operational. 2. Problem seen in daily check. 3. Remote or on-site adjustments made.
SPH Condenser		
Power failure Fan failure High condensate level High/Low cooling water level Holding tanks overfill	1. Condenser alarms. 2. Auto-dialer calls out.	1. Condenser shuts down. 2. VR blower is shut down. 3. SPH PCU is shut down. 4. Vapor treatment remains operational. 5. Operations staff is notified. 6. Site visit required to restart systems if condenser fault does not auto-correct.
VR system		
Power failure Blower failure Blower overheating	1. VR blower alarms. 2. Auto-dialer calls out.	1. VR system shuts down. 2. SPH PCU is shut down. 3. Condenser remains operational. 4. Vapor treatment remains operational. 5. Operations staff is notified. 6. Site visit required to restart systems if blower fault does not auto-correct.
Vapor treatment system		
Breakthrough of primary GAC vessel	No alarms.	1. All systems remain operational; secondary GAC vessel automatically assumes adsorption duty. 2. Problem seen in daily check. 3. GAC vessel change-out required.
Vapor treatment system		
Breakthrough of primary and Secondary GAC vessels	On line stack photoacoustic analyzer alarms.	1. VR system shuts down. 2. SPH PCU is shut down. 3. Condenser remains operational. 4. Operations staff is notified. 5. Site visit required to change-out carbon vessels.
Electrode Field		
Electrode malfunction or failure Electrode overheating Loss of temperature in subsurface	No alarms.	1. All systems remain operational. 2. Problems seen at daily checks. 3. Perform on-site inspection.

A worst-case scenario is the loss of vacuum in the lines during steaming, either by design or by an accidental shutdown. In either case, steam in the lines will condense to form less than 0.5 L (1 pint) of condensate. This condensate will remain in the lines or flow back into the subsurface. Any VOCs in the condensate flowing back into the subsurface will be remediated by the system once it is restarted.

5. CONSTRUCTION REQUIREMENTS

5.1 CONSTRUCTION EQUIPMENT

In order to install the treatability study system, it will be necessary to complete soil borings for the placement of the electrodes/VR wells, multi-port groundwater monitoring wells, and vacuum monitoring piezometers. Borings also will be necessary for the collection **of** post-study assessment soil samples. **A** summary of the soil boring requirements is presented in Table 9.

Other necessary construction equipment includes a forklift to move materials.

Table 9. Summary of soil boring requirements

Activity	Boring" diameter	Boring; depth	Drilling method
7 – electrodes/VR wells	14 in.	30 m (97 ft)	10 1/4-in. ID auger – or Roto-Sonic with 12-in. casing
4 – monitoring wells	12 in.	35 m (110 ft)	8 1/4-in. ID auger – or Roto-Sonic with 12-in. casing
15 – piezometers	8 in.	18 m (58 ft)	4 1/4-in. ID auger
9 – post study borings	1 in.	18m (58 ft)	Direct Push Technology

"The effective diameter of a hollow stem auger boring is dependent on the soil type, producing the largest effective boring in clay soils and the smallest effective boring in flowing sands where native soils collapse against the stem.

5.2 TREATABILITY STUDY EQUIPMENT

The following is a list of the general equipment and materials needed for installation and operation of the treatability system.

- All-weather electronics cabinet
- Electrodes and associated components
- Soil VR wells and conveyance piping
- Groundwater monitoring wells
- Vacuum monitoring piezometers and conveyance piping
- SPH PCU with a dedicated computer and data acquisition software
- VR blower and conveyance piping
- Condenser and conveyance piping
- Post-VR blower heat exchanger, GAC vessels, and dilution air blower
- Stack photo-acoustic VOC analyzer
- Soil and groundwater sampling equipment
- Temperature sensors
- Temporary power supply
- Temporary potable water supply
- Telephone lines

- Pressure/vacuum gauges
- Hand-held monitoring equipment

5.3 SITE-SPECIFIC RECOMMENDED ACTIONS

5.3.1 Surface Structures

The area chosen for the SPH treatability study includes multiple structures related to current or former operations of the C-400 Building. The structures include an overhead crane system, a railroad track, a fence, below ground utilities, an unused, empty aboveground storage tank (AST), unused aboveground pipelines and pump associated with the AST, and loading dock structures. In order to install the treatability system in the area of highest contamination, the fence, as well as the aboveground pipe and associated airline connecting the pump system with the AST must be removed. The fence will be reinstalled after system installation is complete. The removal and reinstallation of the aboveground piping and fence will be coordinated by Bechtel Jacobs Company LLC.

5.3.2 Underground Utilities

The principal effects of SPH on underground utilities are thermal and not electrical. SPH has been performed at sites where metal utility conduits, phone lines, security control lines, and power lines have passed directly through the energized electrode field and no instances of electrical interference or damage have been reported. During SPH, electrical current can only flow between the electrodes. Metal objects, pipes, and wires that pass through the treated area at depths of less than 2 m (6 ft) do not develop significant applied voltages (greater than 1 V) and do not become energized. Because cathodic protection systems use direct current and the SPH system uses alternating current there is essentially no interaction between the systems, and cathodic protection systems will operate as usual.

As a safety precaution, underground utilities within 15 m (50 ft) of the treated area will be monitored by the project team for applied voltages as SPH operations are started. During the start-up process, a low initial voltage is applied to the subsurface and voltage measurements are performed on all adjacent underground utilities to ensure that they are not being energized. As start-up progresses, the voltage applied to the subsurface is increased slowly until the design voltage is reached. Voltage measurements on all adjacent underground utilities are performed repeatedly as the voltage to the subsurface is increased.

The top of the shallowest conductive zone is at 3 m (8 ft) bgs. Heating from this zone should not extend upward beyond 2 m (5 ft) bgs because the VR system will be removing steam at 1 m (3 ft) bgs. The subsurface to a depth of about 1 m (3 ft) will be cooled by the inflow of ambient air to the VR wells. As a safeguard, subsurface utilities that contain temperature sensitive components, such as insulation with 70°C temperature limits, will be monitored with thermocouples. If necessary, process control changes can be made to lower near-surface temperatures to limit thermal influence on sensitive utilities. For example, the use of the shallow heating zone is optional, and it can be discontinued if utilities could be harmed. The top of the next shallowest heating zone is at 5 m (17 ft) bgs; this is well below the depths associated with buried underground utilities.

5.3.3 Electrical Power Source

The PCU will require up to 1 megawatt (MW) of power for the treatability study. At least three electrical power poles need to be installed in the area adjacent to the SPH treatability study site. Electrical power will be obtained from the nearest available source at the time of installation, which is a nearby 13.8-kV electrical line on the south side of Tennessee Avenue. An independent air-switch isolation will be placed at

the tie-in point just south of the intersections of 11th Street and Tennessee Avenue on a newly installed 60-ft pole. Two subsequent poles of lesser heights will need to be installed to deliver electrical power to the PCU, one on the north side of Tennessee Avenue and one on the west side of 11th Street. The SPH PCU will reduce the supply voltage to the appropriate level to apply to the subsurface. The SPH team will provide any poles or lines required while USEC will be responsible for connecting the SPH system to the USEC power grid.

The subsurface heating load is pure electrical resistance. There is no "starting surge" with SPH such as is typically found upon starting large motors. During SPH, the load is quite stable, changing slowly over a period of days. Because the PCU operates at greater than an 80% power factor, it produces very little harmonic distortion. During the first day or two of start-up, the PCU will be operated at a lower power, while voltage surveys are performed on subsurface utilities and the power factor might drop to 50% due to voltage chopping by the silicon control rectifiers.

6. SAMPLING AND MONITORING

A detailed SAP is included in the TSWP (DOE 2002). The project specific SAP presents the basic strategies and procedures that will apply to soil, groundwater, and operational parameter sampling conducted in support to the SPH treatability study.

6.1 SAMPLING AND MONITORING STRATEGY

To evaluate the treatability study objectives **and** document the operational parameters presented in Sect. 3, sampling and monitoring will be performed in three phases: pre-heating baseline sampling, operations sampling and monitoring, and post-heating sampling. The overall treatability study sampling and monitoring strategy will focus on soil and groundwater in the UCRS, groundwater in the RGA, and soil and groundwater in the McNairy Formation. Chemical analytes will be sampled from subsurface soil and groundwater, the recovered soil vapor stream, steam condensate, and process wastewater.

The chemical analytes of interest are as follows:

- TCE and the TCE-degradation products: 1,1-DCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride;
- the organic compounds benzene, carbon tetrachloride, and chloroform;
- radionuclides; and
- metals.

Geochemical parameters of interest include the following:

- pH, oxidation-reduction potential (Eh), conductance, dissolved oxygen, alkalinity, and
- major cations and anions.

Operation parameters of interest include (collected for specific treatment zones where possible):

- subsurface temperatures,
- VOC recovery rate and total mass,
- steam recovery rate and total volume,
- power input to the subsurface,
- subsurface vacuum and air flow, and
- vapor treatment system efficiency.

As shown in Fig. 5, 35 borings are planned for the project. Four of the borings are for multi-port groundwater monitoring wells. One of the groundwater monitoring wells will be placed upgradient of the heating zone, two will be placed within the heating zone, and one will be placed downgradient of the heating zone. During the construction of these wells, thermocouples will be attached to the well casings to allow subsurface temperatures to be monitored at 3-m (10-ft) depth intervals. The two wells within the heated zone will have thermocouples over the entire depth of the wells, while the two wells outside of the heated zone will have thermocouples from 17-m to 34-m (55-110 ft) bgs only. When completed as multi-level groundwater monitoring wells, each well will have seven sampling ports. This will make each well equivalent to a multi-well cluster, and the four monitoring wells will result in **28** groundwater sampling points.

Construction of the SPH array will require seven borings for electrodes and each electrode boring will have a VR well cluster installed in it. Six of the borings will be placed in a roughly hexagonal arrangement, with the remaining boring placed in the center of the pattern.

Fifteen borings will be placed to construct vacuum monitoring piezometers to measure the amount of vacuum applied to the subsurface by the VR system, provide steam vents at the UCRS/RGA interface, and act as backup VR points. The eight piezometer borings within the heating zone and the three piezometer borings located just outside of the heating zone will be used to collect soil samples from the UCRS for characterization of pre-study contaminant levels.

At the conclusion of heating, nine borings will be installed to assist in determining residual contamination concentrations and technology performance. These borings will be adjacent to the piezometer borings where soil samples were collected to establish baseline contaminant levels. Assessment soil samples will be collected from the same depths as the baseline samples and analyzed for the same analytes and parameters tested for in the baseline soil samples.

6.1.1 Baseline Sampling

Both soil and groundwater samples will be collected as part of the baseline sampling effort. Soil samples from the UCRS will be collected from 11 of the 15 vacuum monitoring piezometers borings being drilled. Soil samples will be collected every 0.6 m (2 ft) from ground surface to the top of the RGA, which is at a depth of approximately 17 m (56 ft) bgs. Soil samples will be analyzed for VOCs, radionuclides, metals, and soil moisture. Baseline soil temperature profiles will be developed by collecting data from the thermocouples attached to the outside of the groundwater monitoring well casings.

Soil samples will not be collected from the RGA because the coarse texture of the gravel makes recovery of residual DNAPL difficult. Groundwater samples, therefore, will be the primary media used to indicate the magnitude of RGA soil contamination. Groundwater samples will be collected from seven subsurface intervals in each of four multi-port groundwater monitoring wells. Each well will sample one interval at the base of the UCRS gravel, five intervals through the RGA, and one interval in the first upper McNairy sand at an approximate depth of 34 m (110 ft). Groundwater will be analyzed for VOCs, radionuclides, temperature, pH, Eh, conductance, alkalinity, dissolved oxygen, and the concentrations of metals as well as major cations and anions, including chloride.

In each boring that extends to the base of the **RGA,** a soil sample will be collected across the RGA/McNairy Formation contact, or within the uppermost McNairy Formation, to aid in determining the presence of pooled DNAPL. Field analysis of these soil samples, based on reading of a PID or photoacoustic analyzer and direct observations, will be used to assess the local presence of DNAPL pools at the top of the McNairy Formation. This sample also will be submitted for laboratory analysis to quantify the TCE concentration. If a significant thickness of pooled DNAPL is present at a soil boring site based on field observations, the boring will be terminated at the top of the McNairy Formation.

6.1.2 Groundwater Monitoring Wells

Groundwater sampling will be performed using Solinst™ (Solinst Canada Ltd., Georgetown, Ontario) multi-port sampling systems. A multi-port sampling system was chosen over clusters of small-diameter sampling wells because the depth to groundwater, in conjunction with the steam temperatures requires that each sampling depth zone have a dedicated downhole pump. No small diameter, high temperature sampling pumps presently exist. The larger screen area of a 10-cm (4-in.) well will make the wells more plug-resistant and the use of multi-port sampling system will allow sampling from other intervals if one is plugged.

Each of the 4 multi-port groundwater monitoring wells will be constructed to allow sampling from 7 discrete intervals per well, providing a total of 28 sampling points. The locations of the monitoring wells are shown in Fig. 5. One of the groundwater monitoring wells will be placed upgradient of the heating zone; two of these borings are within the heating zone and one boring will be placed downgradient of the heating zone.

A 30.5-cm (12-in.) O.D. borehole will be used to construct the multi-port groundwater monitoring wells. The multi-port monitoring system will be installed inside a 10-cm (4-in.), schedule 40 stainless steel well casing placed to a final depth of 34 m (110 ft) bgs, which is below the upper interbedded sand and clay layer of the McNairy Formation. Design screened intervals are based upon the borehole geophysical logs from boring 400-038, and groundwater monitoring well construction details are summarized in Table 10 and shown in Drawing C5EC40000A007 of Appendix A.

Table 10. Multi-port groundwater monitoring well construction details

Well component	Depth interval (bgs)
4-in. well casing (flush joint, schedule 40 Type 316 stainless steel)	Surface to 34 m (110 ft)
Flush joint, schedule 40 Type 316 stainless steel end cap	34 m (110 ft)
6-in. CPVC oversleeve	Surface to 2 m (5 ft)
2-in. stainless steel flush joint riser pipe with a base plug	Surface to 34 m (110 ft)
0.6-m (2-ft) sections of slotted 0.010-in. flush joint stainless steel well screen	11.0 m (36ft)
	18.3 m (60 ft)
	20.1 m (66 ft)
	21.9 m (72 ft)
	24.4 m (80 ft)
	26.2 m (86 ft)
	32.3 m (106 ft)
0.15-m (0.5-ft) sampling ports	One at each screen interval
0.9-m (3-ft) well casing packers	Varies by location.
Concrete	Surface to 20 cm (8 in.)
Cement grout	0.2 to 9.8 m (0.6 to 32 ft)
Bentonite pellet seal[a]	9.8 to 10.4 m (32 to 34 ft)
Filter sand pack[b]	10.4 m to 12.8 m (34 to 42 ft)
Cement grout	12.8 m to 15.5 m (42 to 51 ft)
Filter sand pack (with no isolation seals between screens)	15.5 to 27.1 m (51 to 89 ft)
Cement grout	27.1 to 29.9 m (89 to 98 ft)
Filter sand pack	29.9 to 33.5 m (98 to 110 ft)

Notes:

[a]Bentonite will be free-flowing, high swelling, sodium based, Wyoming-type bentonite. High-density bentonite slurry will be a mixture of powered bentonite, and water. Bentonite will be mixed in a batch plant and the slurry will have a minimum of 30% solids by weight. Bentonite slurry will be placed with a side discharge tremie pipe.

[b]Filter pack material will have 100% by weight passing a No. 4 U.S. standard sieve and no more than 5% by weight passing a No. 50 U.S. standard sieve. Sand will be clean quartz sand and will be of rounded or subrounded particles.

Each groundwater monitoring well will be enclosed within a lockable, 46-cm (18-in.) diameter, steel protective casing, set flush with the ground surface. The casings for each well will be sealed and equipped with a pressure gauge and a pressure release valve.

6.1.3 Sampling and Monitoring During Operations

During the operation phase of the treatability study, several parameters will be measured to ensure optimum performance of the overall system and to determine the operating requirements and costs of the system. The parameters to be measured include the following.

- Energy usage will be recorded at the SPH PCU electrical meter to determine overall system energy requirements. Energy usage also will be recorded at the individual electrodes. The use of discrete electrically conductive intervals placed through the UCRS and the RGA formations will allow the energy input to each of these regions to be determined. Using the energy input, the steam production from each formation will be determined.

- Contaminant recovery, measured as the mass or volume of TCE recovered or the mass or volume of treatment residuals produced, will be monitored to assess the effectiveness of the system and to determine costs for contaminant removal. The mass of TCE will be determined by integrating vapor concentration measurements. This calculation can be cross-checked using the vapor treatment waste stream.

- Steam extraction rates and volume of condensate collected will be measured using a totalizer to track the progress of subsurface boiling and of energy input into the subsurface.

- Vacuum readings at the VR wellheads and the vacuum piezometers will provide information on how effectively the VR system is pulling vapor from the subsurface and its area of influence.

- Readings from thermocouples on the multi-port groundwater monitoring well casings and from the thermowells in the vapor monitoring piezometers will provide data on the soil heating profile as it develops.

- The VOC adsorption efficiency of the **GAC** vapor treatment system will be monitored. GAC usage will be totalized and a percent VOC loading will be obtained from the vendor prior to regeneration.

- Water addition at the electrodes w ill be recorded and addition rates and volumes calculated.

- The operating parameters of the system components, the SPH PCU, the condenser, the VR unit, and the vapor treatment system will be monitored so that maintenance, repairs, and adjustments can be accomplished to ensure optimum performance.

- Surface voltages and the induced voltages on metal objects and utilities will be extensively monitored at start-up and reviewed weekly during operation. Although these voltage surveys do not provide operational data, they are mentioned here in the interest of completeness.

6.1.3.1 Monitoring operations parameters

During operations, the control computer in the SPH PCU is accessed at least once every 24 hours using a modem. Access to the control computer may be made either locally or remotely by telephone modem. The control computer allows the operator to view a site map showing the relative locations of the PCU, the electrode field, the six zones of differing electrical phases, and selected temperature monitoring points.

The operator also can access tables where voltage, electrical current, and power readings are provided for all six electrical phase zones and where temperatures are given for selected thermocouples. These parameters can be reset remotely, and the reset results can be monitored in real time or through real time trending.

The SPH PCU is metered to measure the total amount of energy consumed throughout the treatability study. By instrumenting the individual electrically conductive intervals comprising each electrode, the amount of energy put into each interval can be determined. From this data, it will be possible to calculate the energy applied to the UCRS and **RGA** during the treatability study.

6.1.3.2 Sampling for VOC recovery

The recovery of contaminants from the subsurface will be evaluated by monitoring the extracted vapor and condensed liquid phase streams for flow rates and VOC concentrations. From this data, estimates of the rate of VOC removal and of the total mass of VOCs removed can be made. The extracted vapor stream represents the influent to the vapor phase treatment system, while the liquid condensate stream represents the discharge from the SPH condenser before it is used as makeup water. Monitoring of influent streams helps to track the general progress being made toward achieving the treatability goals and objectives (Chap. **3)** and is crucial in determining the interim groundwater sampling schedule. **As** the treatability study progresses, the concentration of VOCs in the extracted soil vapors increases as VOCs in the subsurface begin to be volatilized and then starts to drop as the subsurface sources of VOCs are remediated. During operation of the SPH and VR systems, monitoring of the influent to the vapor-phase treatment system will include, at a minimum, all of the following.

- Twice weekly measurements of vacuum, flow rate by pitot tube, and VOC concentrations: VOC concentrations will be determined using an FID, PID, or photoacoustic analyzer during twice weekly sampling. Measurements will be made after the condenser where the temperature is near ambient – no special sampling techniques are required.

- Weekly collection of Summa canister samples for detailed VOC constituent analysis: Summa canisters will be equipped to provide a 24-hour integrated sample.

- Monitoring at the discharge from the SPH condenser will include, at a minimum, totalizing condensate production and scheduled collection of condensate samples for laboratory analysis.

An estimate of the gross mass of contamination recovered from the subsurface by the **SPH** and VR systems will be calculated by time integrating the vapor- and liquid-phase concentration and flow data.

6.1.3.3 Sampling for vapor treatment system efficiency

The VOC adsorption efficiency of the vapor phase treatment system will be determined by measuring VOC concentrations at the inlet of the primary **GAC** vessel, at the inlet of the secondary GAC vessel, and at the final discharge. During operation of the SPH and VR systems, minimum monitoring of the **GAC** vapor-phase treatment unit will include:

- Twice weekly measurements of total VOC concentrations at the locations described above using **a** FID, PID, or photoacoustic analyzer;

- Weekly collection and analysis of Summa canister samples at the final discharge of the units for detailed VOC constituent analysis;

An estimate of the efficiency of the treatment system to adsorb VOCs will be calculated by time integrating inlet and outlet vapor concentrations and flow data. GAC vessel changeout when breakthrough occurs is described in Sect. 4.9.1.

6.1.3.4 Subsurface temperature monitoring

The SPH heating process is monitored by thermocouples and by the operating parameters of the **SPH** PCU. Thermocouples will be located in monitoring strings installed vertically into the subsurface at each multi-port groundwater monitoring well location. Each thermocouple string in the groundwater monitoring wells located within the treatment zone will contain 12 thermocouples on 3 m (10 ft) spacing from 2 to 34 m (5 to 110 ft) bgs. Each thermocouple string in the groundwater monitoring wells located outside the treatment zone will contain 7 thermocouples on 3 m (10 ft) spacing from 17 to 34 m (55 to 110 ft) bgs. These thermocouple strings will be monitored continuously using the SPH control system. Additionally, the 15 vacuum monitoring piezometers will each contain a thermocouple that can be moved up and down within the thermowell to monitor temperatures at any desired depth from surface to 17 m (57 ft) bgs. These thermocouples will be monitored by hand-held instruments on at least a weekly basis.

6.1.3.5 Groundwater sampling

Multi-port groundwater monitoring wells are located so that two are within the treatment zone, one is downgradient of the treatment zone, and one is upgradient of the treatment zone. These wells provide 28 groundwater sampling points. Groundwater wells will be sampled per the procedures and schedule presented in the TSWP SAP (DOE 2002, Appendix A).

6.1.3.6 Vadose zone monitoring

The vadose zone inside and surrounding the treatability study area will be monitored at 45 vacuum monitoring points to ensure that no VOC vapors are escaping the treatment area. Monitoring points are located so that vacuum measurements from within the upper, middle, and lower portions of the UCRS vadose zone can be collected. Measurements will be made during the start-up of the VR system, to confirm that the VR system has an adequate radius of influence (a minimum of approximately 2 m (8 ft) outside the treatment area) and then weekly during the treatability study to confirm that the VR system continues to operate properly.

6.1.3.7 Analytical requirements

During the treatability study, a fixed-base laboratory contracted through the Sample Management Office will perform most analyses. Specific analytical methods and procedures are described in the TSWP Quality Assurance Project Plan (QAPP) (DOE 2002, Appendix B). Certain parameters, such as dissolved oxygen, temperature, and conductance, will be measured in the field using appropriate field instruments such as field kits and in-line flow cells.

Waste characterization sampling will be conducted during the installation and operation of the SPH system. Waste characterization requirements are discussed in detail in the TSWP WMP (DOE 2002, Appendix C).

6.1.3.8 Sampling and monitoring locations and schedules

Two soil sampling events are planned during the treatability study. One sampling event will precede the installation of the SPH system to establish baseline conditions. The second soil sampling event will occur within two weeks after the heating phase of the treatability study is complete.

Four groundwater sampling events are planned during the treatability study. The first sampling event will establish baseline conditions prior to SPH operation. The second groundwater sampling event will occur when SPH operations are about 80% complete (near calendar day 104). The third groundwater sampling event will occur when SPH operations are about 90% complete (near calendar day 117) and will help to determine when to end **SPH** operation. The fourth groundwater sampling event will occur within one week after the heating phase of the treatability study is complete. Actual scheduling for the two interim groundwater sampling events will be based upon best estimates of progress of the system in removing contaminants from the subsurface.

Sampling and monitoring of the operating system will be ongoing throughout the treatability study. Typical sampling and monitoring events, the number of points sampled or monitored per event, and the methods and schedules used are summarized in Table 11.

Table 11. SPH system measurement and sampling schedule

Measurement or sampling event	Points	Method	Minimum frequency (See *"Notes"* below)	Measurement objective and reporting units
Vacuum:				
Vadose zone	45	Digital manometer	1	Verify vadose zone vacuum – in. H_2O
VR wellheads	14	Vacuum gauge	1	VR system performance – in. Hg
Steam vent heads	22	Vacuum gauge	1	General systems operations data – in. Hg
Before condcnscr	1	Vacuum gauge	1	General systems operations data – in. Hg
After condenscr	1	Vacuum gauge	1, 2, 3	VOC removal rates and totals – in. **Hg**
After VR blowcr	1	Digital manometer	1, 2	General systems operations data – in. H_2O
After heat exchanger	1	Digital manometer	1	General systems operations data – in. H_2O
Pressure:				
Condenser pump	1	Pressure gauge	1, 2	System operations check – psi
Temperature:				
Subsurface -wells	38	Type T thermocouple	5	Track remediation performance – "C
Subsurface -piezometers	15	Type T thermocouple	8	Track remediation performance – "C
VR wellheads	14	Type **T** thermocouple	8	Track remediation performance – "C
Condenser inlet	1	Type T thermocouple	5	Track remediation performance – °C
After condenscr	1	Temperature gauge	1, 2	Systems operations check – °C
After VR blowcr	1	Temperature gauge	1, 2	Systems operations check – °C
After heat exchanger	1	Temperature gauge	1	Systems operations check – "C
After primary GAC	1	Temperature gauge	1	Systems operations check – "C
Air & Vapor Flow:				
VR wellheads	14	Pitot Tube	2	VR system performance – approximate scfm
After condenscr	1	Pitot Tube	1, 2, 3	VOC removal rate – scfm
After dilution blower	1	Pitot Tube	1, 2, 4	Operations & treatment efficiency – scfm
Water Flow:				
Condenser makeup	1	Calibrated flow meter	5	Volume of water used – gpm
Waste discharge	1	Calibrated flow meter	5	Volume of condensate – gpm
VOC Sampling:				
VR wellheads	14	Tedlar or Summa	6, 10	VOC removal rate and totals ppm
After condenser	1	Note 9 and Summa	7, 10	VOC removal rate and totals ppm
After vapor treatment unit	1	Note 9 and Summa	7, 10	Abatement system efficiency ppm
Wastewater discharge	1	VOA vial	7, 10	Wastewater VOC concentrations mg/L

Notes:

1. Upon system startup, then weekly to ensure that baseline readings have not significantly changed.
2. Upon startup and when sampling for VOC concentrations.
3. When performing sampling for inlet VOC concentrations.
4. When performing sampling for vapor treatment system efficiency.
5. Continuous.
6. No VR wellhead samples are presently planned.
7. Per the sampling schedule of the Wastewater Discharge Authorization.
8. Weekly readings at various depths from the piezometer thermowells.
9. FID, PID, or photoacoustic analyzer.
10. Vapor emission contaminants will be reported as mg/L, ppm (V), or mg/m^3.

7. DATA MANAGEMENT PLAN

A project-specific Data Management Plan is presented in the TSWP (DOE 2002). The Data Management Plan was prepared in accordance with ES/ER-TM-88, *Environmental Data Management Implementation Handbook for the Environmental Restoration Program.*

The data management program for the treatability study manages the life cycle of project specific data from the planning of data needs for characterization and remediation decisions, through the collection, review, and actual usage of the data for decision-making purposes to the long-term storage of data. The data management process contains the following major activities: sampling and analysis planning, field preparation, field data collection, data review, data assessment, and data consolidation and use.

8. DATA ANALYSIS AND INTERPRETATION

Data analysis and interpretation will be performed in accordance with the QAPP presented as Appendix B of the TSWP (DOE 2002). The QAPP was prepared in accordance with QAMS-005/80 (EPA 1983); 10 CFR 830.120; crosswalked with the requirements of QA/R-5; and *Environmental Investigations Standard Operating Procedures and Quality Assurance Manual* (EPA 1996).

The results of the treatability study will be based upon the analysis and interpretation of measurements of several media and properties from the treatability study. In overview, the data must be sufficient to assess the following:

- key operating parameters,
- zone of influence,
- thermal performance,
- treatment performance, and
- cost effectiveness.

To reach these goals, the data must be collected from baseline and assessment measurements, as well as from measurements derived during the active operation of the SPH system.

8.1 SOURCES OF DATA

The data to be used in the evaluation of this treatability study will come from several different sources. Background data used to select the location of the SPH treatability study, as well as geologic and hydrogeologic data to support the design, were obtained chiefly from the WAG **6** RI Report (DOE 1999) and the FS for the GWOU (DOE 2001).

Baseline and assessment characterization of soil and groundwater contamination levels within the treatability study cell will be required to assess the mass of TCE removed during the study. Operations data are necessary, as well, for a complete assessment of system performance. Measurements of the physical properties of soil and groundwater in the treatability study volume will support the evaluation of the zones of influence of the SPH system components.

Both field measurements and laboratory analyses will be crucial to the assessment of the treatability study. Key analyses for the treatability study are summarized in Table 12.

Table 12. Key measurements during the Treatability Study

Medium	Property	Type of measurement	Timing of Measurement	Assessment
Soil	UCRS contaminant level	Laboratory	Pre-Study and Post-Study	TCE removal efficiency
	UCRS moisture	Laboratory	Pre-Study and Post-Study	Mass of steam generated
	UCRS and RGA temperature	Field	Operations	Heating efficiency Phase of TCE and water
	McNairy contaminant level	Field Laboratory	Baseline	Presence of DNAPL
Water	**RGA** contaminant level	Laboratory	Pre-Study, Operations, and Post-Study	TCE removal efficiency
Air	Vacuum	Field	Operations	VR zone of influence
Vapor	Contaminant level	Laboratory	Operations	TCE removal efficiency
	Volume	Field	Operations	Removal rate
Condensate	Contaminant level	Laboratory	Operations	TCE removal efficiency
	Volume	Field	Operations	Heating efficiency
Electricity	Power	Field	Operations	Applied energy
	Resistance	Field	Operations	Soil electrical resistance

8.2 BASELINE AND ASSESSMENT SAMPLING

Documentation of baseline soil and groundwater contamination levels within the treatability study cell is crucial to the assessment of treatment performance. Previous investigations have shown that conventional soil sampling and analysis techniques, with minor modification, are sufficient to characterize the residual DNAPL saturation within the UCRS. The collection, however, of meaningful water samples, even from the more permeable, water-saturated zones of the UCRS, remains problematic. Thus, contaminant levels in soil samples will be the primary measure of treatment performance in both the vadose zone and saturated UCRS. Contaminant levels in soil from the UCRS will be measured by standard laboratory methods.

In addition to the analyses of contaminant levels, baseline and assessment samples of UCRS soil will be tested for soil moisture. A plot of the percent contamination removal versus weight percent moisture removed will be used as an assessment of TCE removal (as a function of steam creation in the UCRS).

Conversely, the coarse-textured RGA sediments have not yielded adequate soil samples for analysis to support a meaningful assessment of DNAPL saturation. Although dissolved contaminant levels are only an indirect measure of DNAPL saturation, groundwater samples remain a more reliable indicator of DNAPL levels in the RGA than do soil samples. To support the baseline assessment of the treatability study, as well as the assessment of the progress of the study, groundwater from the RGA will be collected from monitoring wells installed within the treatability study cell.

While both soil and groundwater analyses yield quantitative data, both media samples are discrete volumes that, at best, can only approximate the in-place conditions. The primary means of analyzing the data will be comparison of the percent contaminant removal in adjacent samples. Bar graphs will be a primary means of presenting the data.

8.3 OPERATIONAL MONITORING

Several parameters will be measured during the operation of the SPH system to support an assessment of the effects of heating on selected properties of soil, groundwater, and DNAPL. These parameters will be tracked and grouped by the three major lithologic units: the vadose UCRS, the saturated UCRS, and

the RGA/McNairy. Records of applied power and mass of contaminants and water removed are key to the assessment of system performance. Measurement of condensate volume, applied/derived vacuum, and temperature can be used to assess the changing properties of the soil, groundwater, and DNAPL during the study.

Plots of applied power versus time, both as power use in kW, and cumulative energy applied to the soil as kW-hour, will be used to show trends during the operation period. These trends will be compared to changes in the mass removal rate by graphing pounds of contaminant removal versus time to monitor the performance of the treatability study. The trends of these parameters over time will be a key measure of the completion of the SPH system operations. Moreover, upon completion of operations, the cumulative energy applied to the soil will be a component of the assessment of the cost of the technology per volume of soil treated.

The primary means to assess the thermal performance of the treatability study will be a plot of temperature versus time, evaluated at discrete locations, through the depth of the treatability study cell, and along a radius extending from the center of the cell to the outside of the treated zone.

These data will provide a measure of the thermal properties of the soil, groundwater, and DNAPL media within the treatability cell, define the extent of the treatment zone, and monitor key occurrences, such as the initiation of boiling of DNAPL and water. The volume of soil heated above the boiling point of the DNAPL and groundwater will define the volume of treated soil for a comparison against the cost of the treatability study.

The definition of the developing extent of the heated volume can be compared to a plot of average phase resistance of the electrodes to qualitatively assess the effects of heating on the electrical resistance of the soil. The treatability study will measure the combined flow of steam from the cell and the pressure drop over which the flow of steam occurs. By plotting the resultant of dividing flow by pressure versus time, the trends are a qualitative assessment of changes in soil permeability.

The cost effectiveness of the SPH technology can be calculated several different ways. The method easiest to document is the total cost of the project divided by the volume or weight of contaminants recovered, to get a cost-per-unit volume or unit weight. However, if a comparison between the reduction of contaminants in the subsurface and the amount of contaminants recovered suggests that some contaminants were destroyed in place, a better value would be the total costs divided by the total reduction in contaminants. Some of the cost numbers for a TS are higher per unit volume treated than for a full-scale implementation because of economy-of-scale issues. Due to the complicated factors, the cost-effectiveness analysis will start with the simplest calculation, then develop numbers to account for those variations.

9. HEALTH AND SAFETY

The Environmental, Safety, and Health Plan (ES&HP) establishes the specific applicable standards and practices to be used during execution of the treatability study to protect the safety and health of workers, the public, and the environment. The ES&HP incorporates (directly or by reference) federal and state standards, pertinent consensus standards, and applicable contact requirements. The ES&HP will be developed and implemented in accordance with 29 *CFR* 1962.65, "Hazardous Waste Operations and Emergency Response." Additional specific health and safety requirements will be incorporated into the ES&HP for the field activities that comprise the treatability study through completion of activity hazard analyses.

The ES&HP will evolve as "lessons learned" are incorporated to continuously improve work processes while maintaining focus on the functions and guiding principles of the Integrated Safety Management System and the zero-accident performance philosophy. The ES&HP will be completed and approved before commencing fieldwork.

10. WASTE MANAGEMENT

An example project-specific WMP that addresses residuals that may be generated by this project is included as Appendix C in the TSWP (DOE 2002).

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APPENDIX A

CERTIFIED FOR CONSTRUCTION
TREATABILITY STUDY DESIGN DRAWINGS

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Design Basis
For Six-Phase Heating™ Treatability Study

This approval documents the acceptance of the attached "Technical Specifications" that form the design basis for the Six-Phase Heating™ Treatability Study and meets the intent of EPDI 4.49-01, "Project Specifications".

R. E. Scott, Manager of Engineering and Construction Services

3/28/02
Date

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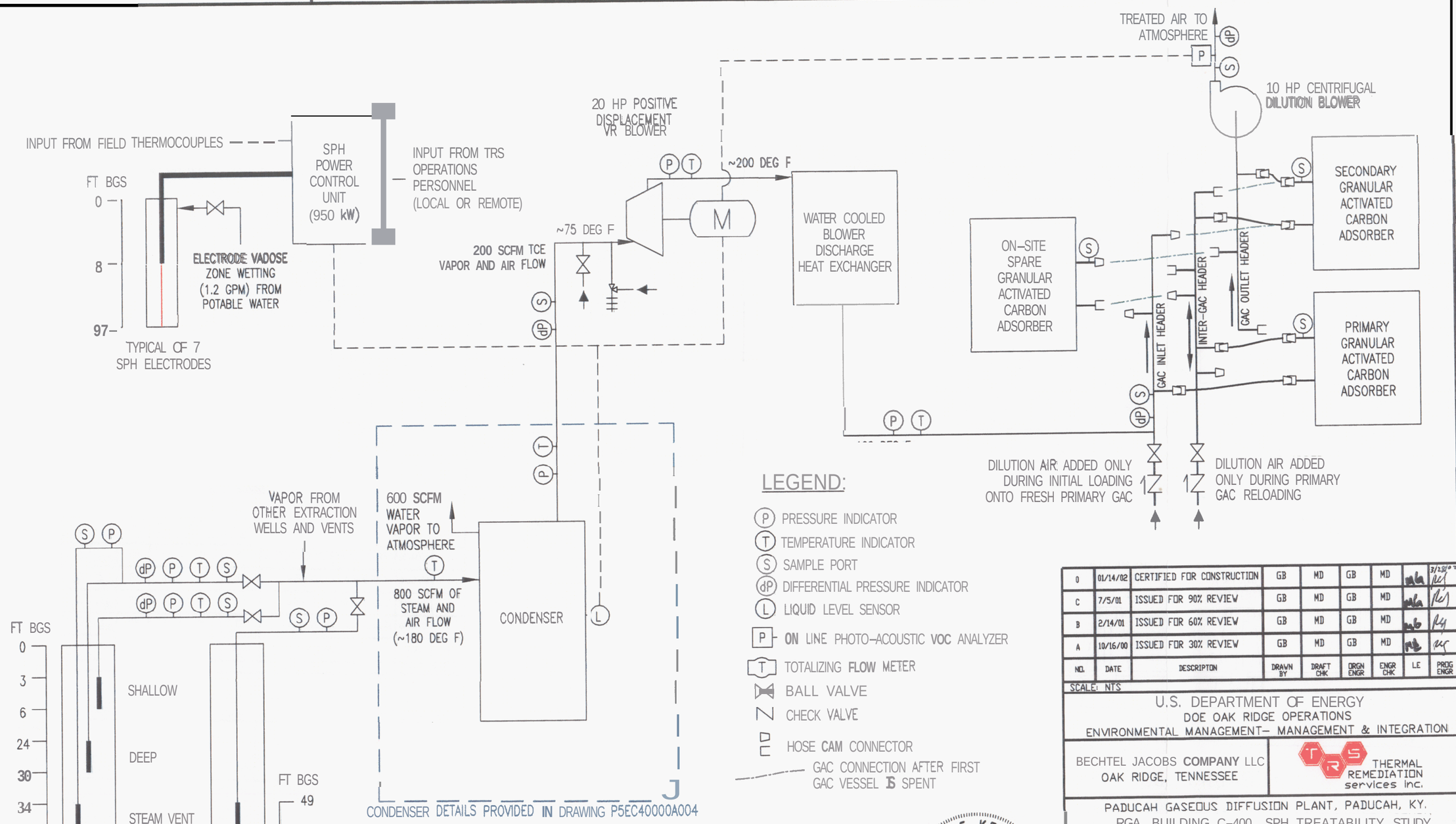

LEGEND:

- (P) PRESSURE INDICATOR
- (T) TEMPERATURE INDICATOR
- (S) SAMPLE PORT
- (dP) DIFFERENTIAL PRESSURE INDICATOR
- (L) LIQUID LEVEL SENSOR
- [P] ON LINE PHOTO-ACOUSTIC VOC ANALYZER
- [T] TOTALIZING FLOW METER
- BALL VALVE
- CHECK VALVE
- HOSE CAM CONNECTOR
- GAC CONNECTION AFTER FIRST GAC VESSEL IS SPENT

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER
Exp. 30 JUNE 2003

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	DRGN ENGR	ENGR CHK	LE	PROG ENGR
0	01/14/02	CERTIFIED FOR CONSTRUCTION	GB	MD	GB	MD		3/28/02
C	7/5/01	ISSUED FOR 90% REVIEW	GB	MD	GB	MD		
B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: NTS

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
RGA, BUILDING C-400, SPH TREATABILITY STUDY
PROCESS FLOW AND INSTRUMENTATION DIAGRAM

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR227000	PROCESS FLOW
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS
Bechtel Jacobs Company LLC

DRAWING NO. I5EC40000A001

REV NO. 0

DWG NO C5EC40000A005 SH1

BUILDING C-400

STORM DRAIN

PARKING LOT

13,000 OR 20,000 LB GRANULAR ACTIVATED CARBON (GAC) VESSEL

DILUTION BLOWER

WATER TANK

HEAT EXCHANGER

BLOWER

EXISTING TANK

SUMP

COOLING TOWER

CONDENSER

SPH POWER CONTROL UNIT

MW-155

MW-157

MW-156

11th STREET

COMMUNICATIONS JUNCTION BOX

MW405

MW406

MW407

MW408

400-201

400-202

400-200

PIV SUPERVISORY CIRCUIT (INACTIVE)

APPROXIMATE EXTENT OF REMEDIATION R = 21 FT

GANTRY FOOTING

13,000 OR 20,000 LB GRANULAR ACTIVATED CARBON (GAC) VESSEL

FIRE HYDRANT

13,000 OR 20,000 LB GRANULAR ACTIVATED CARBON (GAC) VESSEL

LOADING DOCK

DISABLED CRANE

STATE OF KENTUCKY GREGORY L. BEYKE 22085 LICENSED PROFESSIONAL ENGINEER

EXP. 30 JUNE 2003

LEGEND

- (#) PROPOSED ELECTRODE BORING
- (V) PROPOSED VACUUM PIEZOMETER
- 400-202 EXISTING SOIL BORING
- MONITORING WELL
- UNDERGROUND ELECTRICAL UTILITY
- UNDERGROUND SANITARY SEWER
- UNDERGROUND STORM DRAIN UTILITY
- UNDERGROUND SANITARY WATER UTILITY

0 15 30

SCALE IN FEET

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B	02/20/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: 1"=15'

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY - BUILDING C-400
PLOT PLAN

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
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CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS Bechtel Jacobs Company LLC

DRAWING NO.	REV NO.
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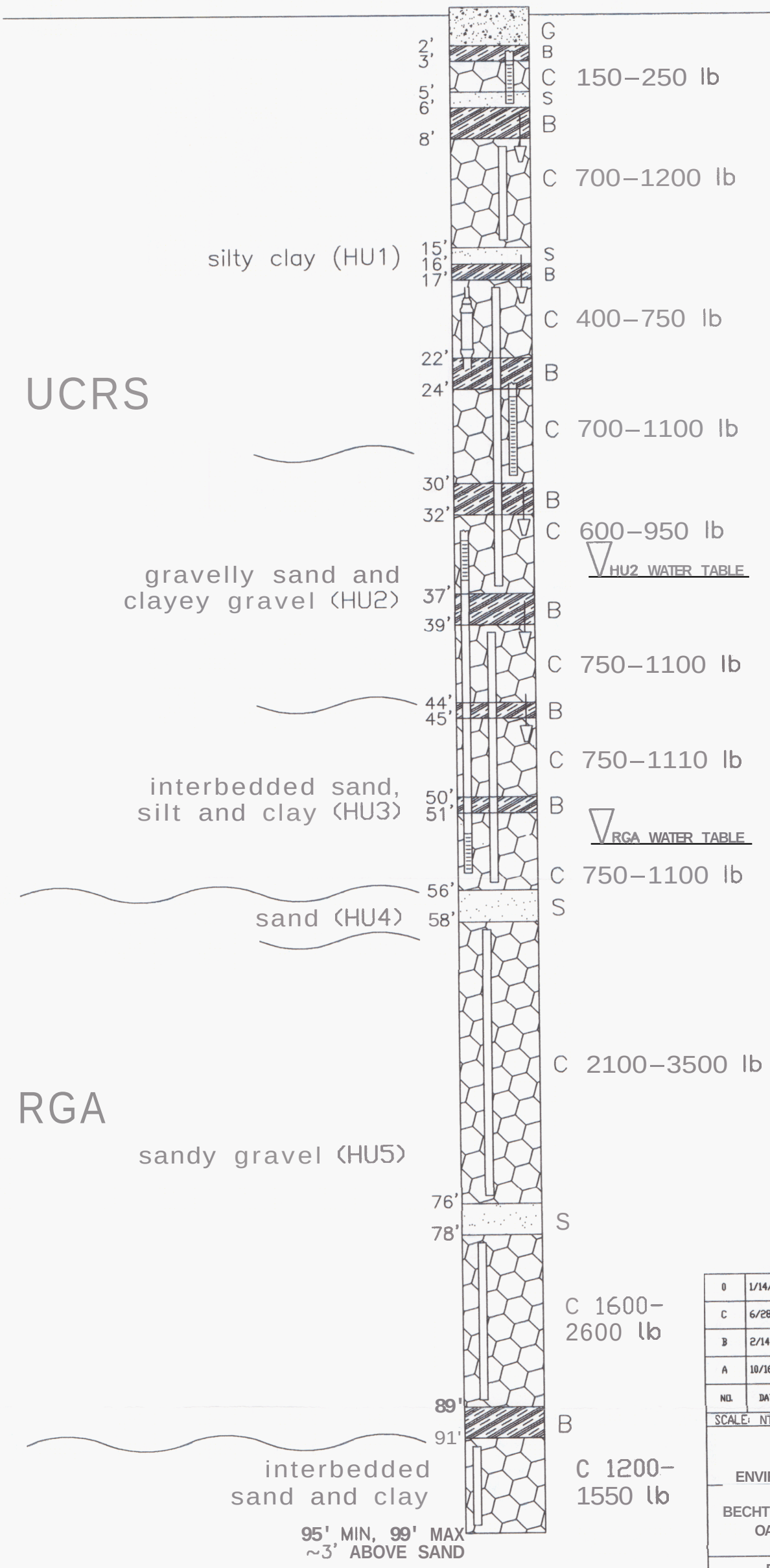

LEGEND

G = CEMENT GROUT
B = BENTONITE
C = CONDUCTIVE BACKFILL
S = SAND
= WATER DRIP
= ELECTRODE
= SVE WELL OR STEAM VENT
= STEAM SEPARATOR (DETAIL DRAWING P5EC40000A003)

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	DRGN ENGR	ENGR CHK	LE	PROG ENGR
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B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD	MG	Reg
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD	MG	Reg

SCALE: NTS

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DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY – BUILDING C-400
ELECTRODE COMPLETION DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
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CLASS No.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT
BECHTEL JACOBS Bechtel Jacobs Company LLC	DRAWING NO.	REV NO.
	E5EC40000A008	0

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PROFESSIONAL ENGINEER
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DWG NO E5EC40000A008 SH 1

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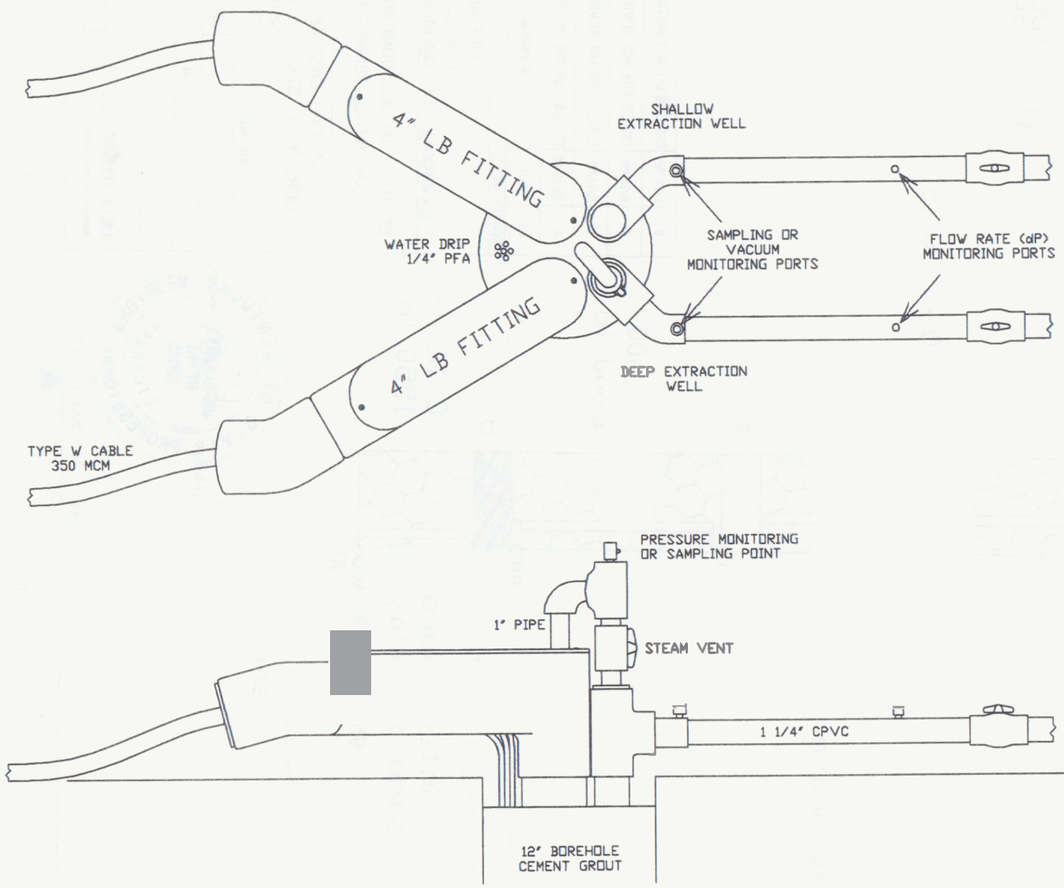

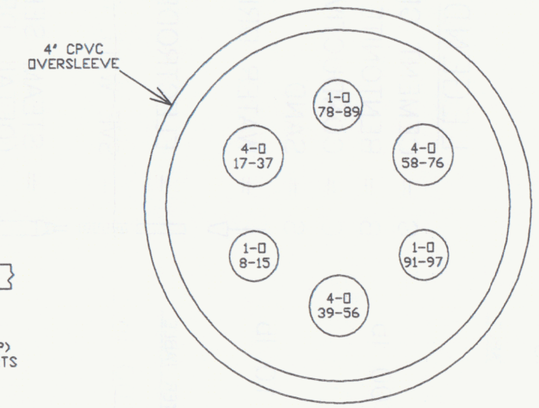

CABLE FILL DETAIL
(ALL CABLES TYPE KK FEP)

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B	02/20/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD	MG	RG
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD	MG	RG

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

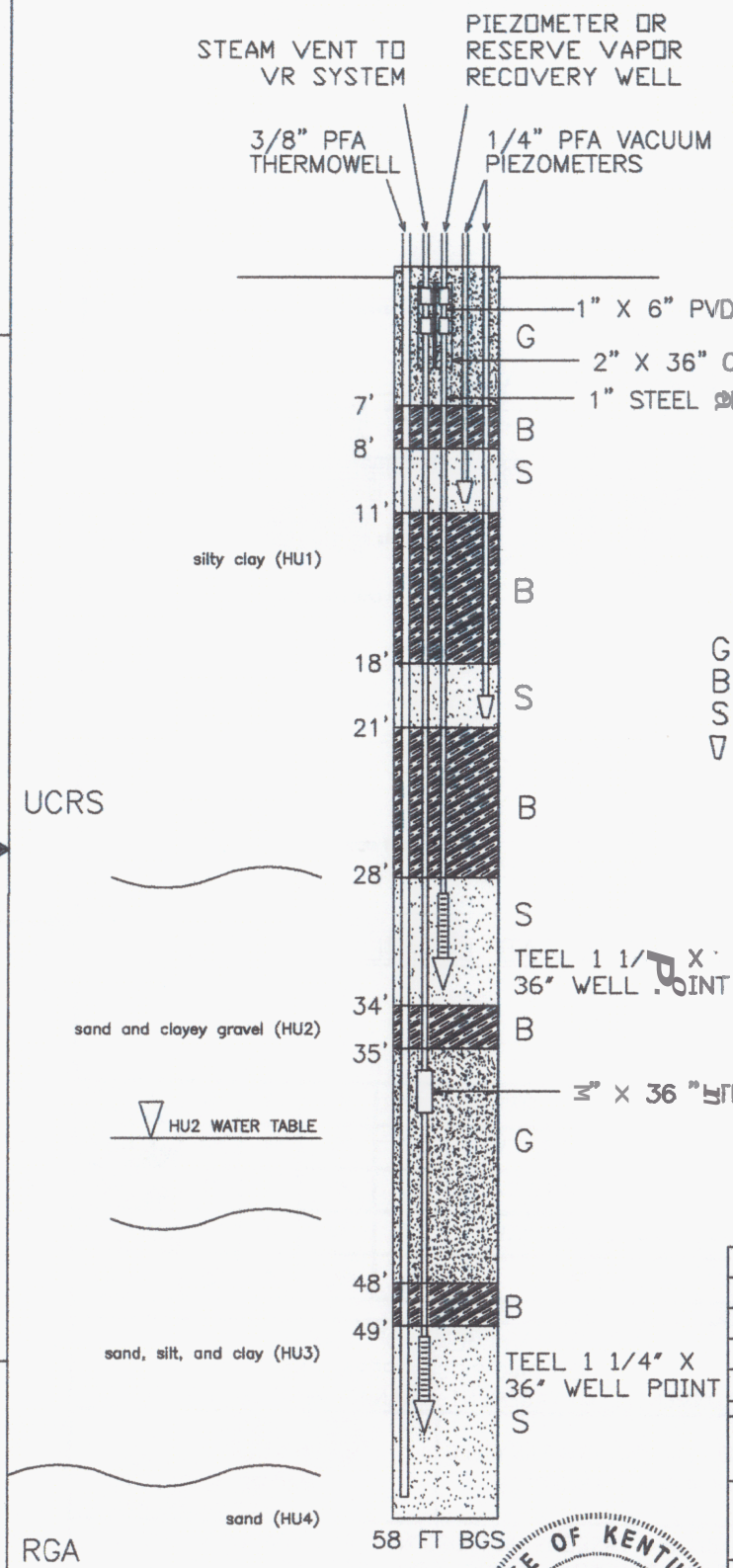
PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY – BUILDING C-400
ELECTRODE HEAD DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR227000	ELECTRODE HEAD
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT
DRAWING NO.		REV NO.
E5EC40000A009		0

BECHTEL JACOBS
Bechtel Jacobs Company LLC

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER
exp. 30 JUNE 2003

DWG NO C5EC40000A006 SH1



LEGEND

G = PORTLAND CEMENT GROUT
B = BENTONITE PELLETS
S = SAND
▽ = SINTERED METAL FILTER

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	DSGN ENGR	ENGR CHK	LC	PROG ENGR
0	1/14/02	CERTIFIED FOR CONSTRUCTION	GB	MD	GB	MD		
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B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: NTS

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY – BUILDING C-400
PIEZOMETER DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR22700	PIEZOMETER

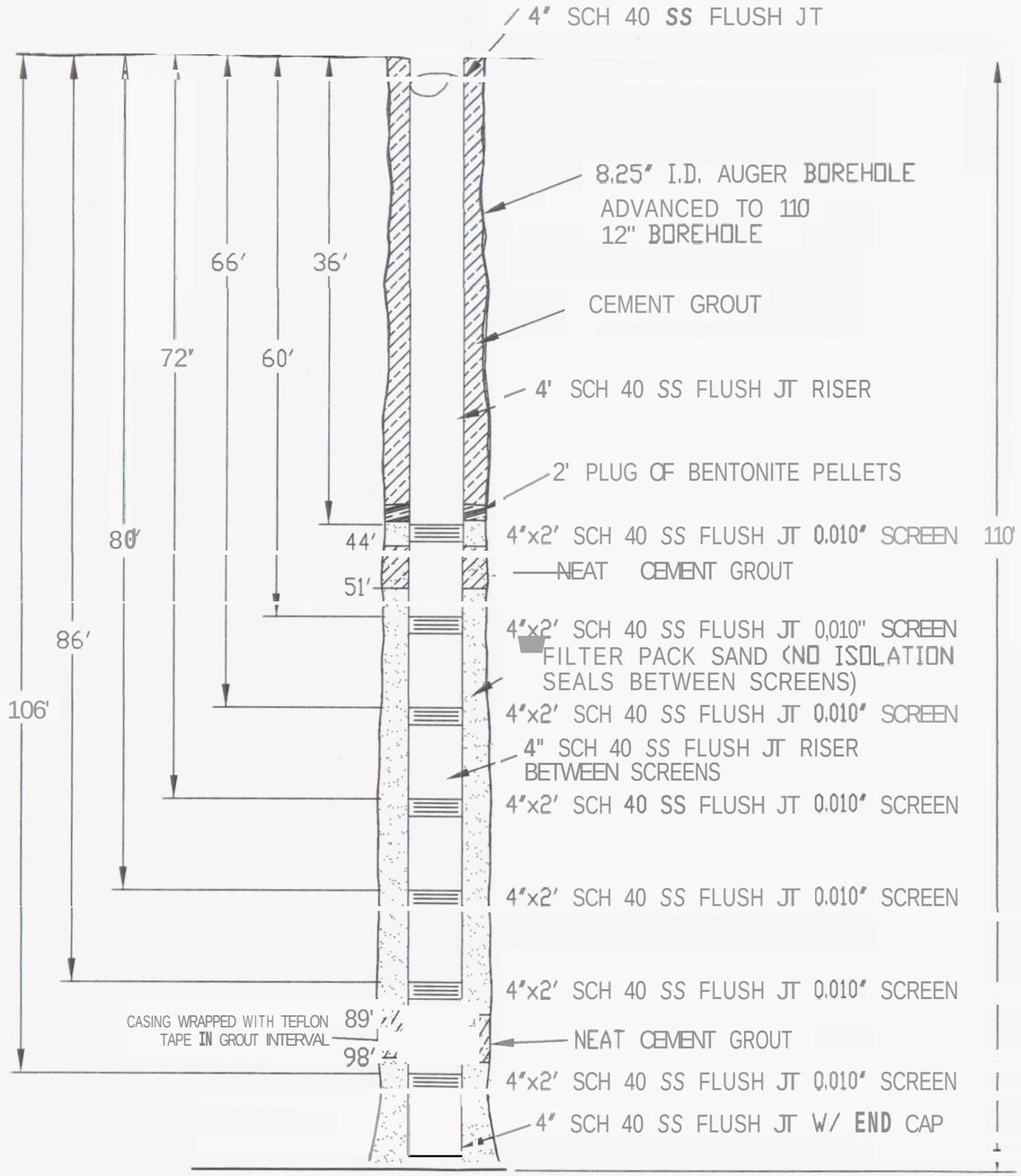
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

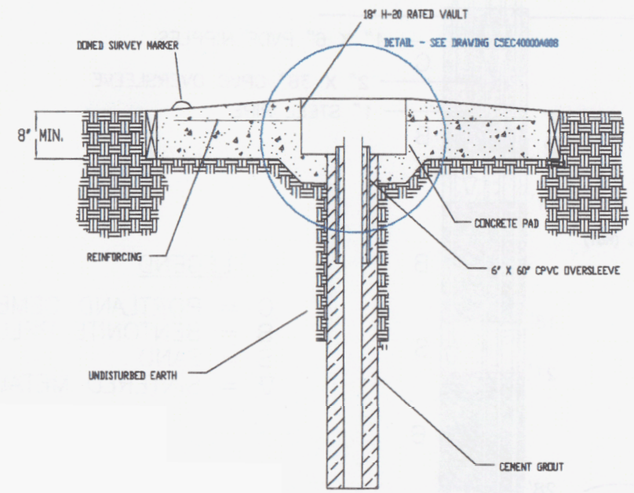
BECHTEL JACOBS Bechtel Jacobs Company LLC	DRAWING NO.	REV NO.
	C5EC40000A006	0

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER

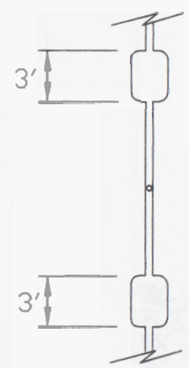
exp. 30 JUNE 2003

DWG NO C5EC40000A007 SH1





WELL CASING & PAD DETAIL



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B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: NTS

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ENVIRONMENTAL MANAGEMENT – MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
RGA, BUILDING C-400, SPH TREATABILITY STUDY
GROUNDWATER MONITOR WELL CONSTRUCTION

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR22700	MONITOR
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS Bechtel Jacobs Company LLC

DRAWING NO. C5EC40000A007

REV NO. 0

STATE OF KENTUCKY
GREGORY L. ...
22085
PROFESSIONAL ENGINEER
exp. 30 JUNE 2003

DWG NO. P5EC40000A001 SH1

EXISTING TANK

SUMP

PLANT -N-

MW406

400-201

MW407

400-200

CONDENSER

GANTRY FOOTING

APPROXIMATE EXTENT OF REMEDIATION R = 21 FT

LOADING DOCK

13,000 OR 20,000 LB GRANULAR ACTIVATED CARBON VESSEL

NOTE: STEAM VENTS AT PIEZOMETERS V-1 THROUGH V-8 ARE ALSO CONNECTED TO THE VAPOR RECOVERY HEADERS USING 1" STEAM HOSE (NOT SHOWN)

LEGEND

- (#) PROPOSED ELECTRODE BORING
- (V) PROPOSED VACUUM PIEZOMETER/STEAM VENT
- 400-202 EXISTING SOIL BORING
- PROPOSED MONITORING WELL
- UNDERGROUND ELECTRICAL UTILITY

0 8 16

SCALE IN FEET

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	ORGN ENGR	ENGR CHK	LE	PROG ENGR
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B	02/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: 1"=8'

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT - MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

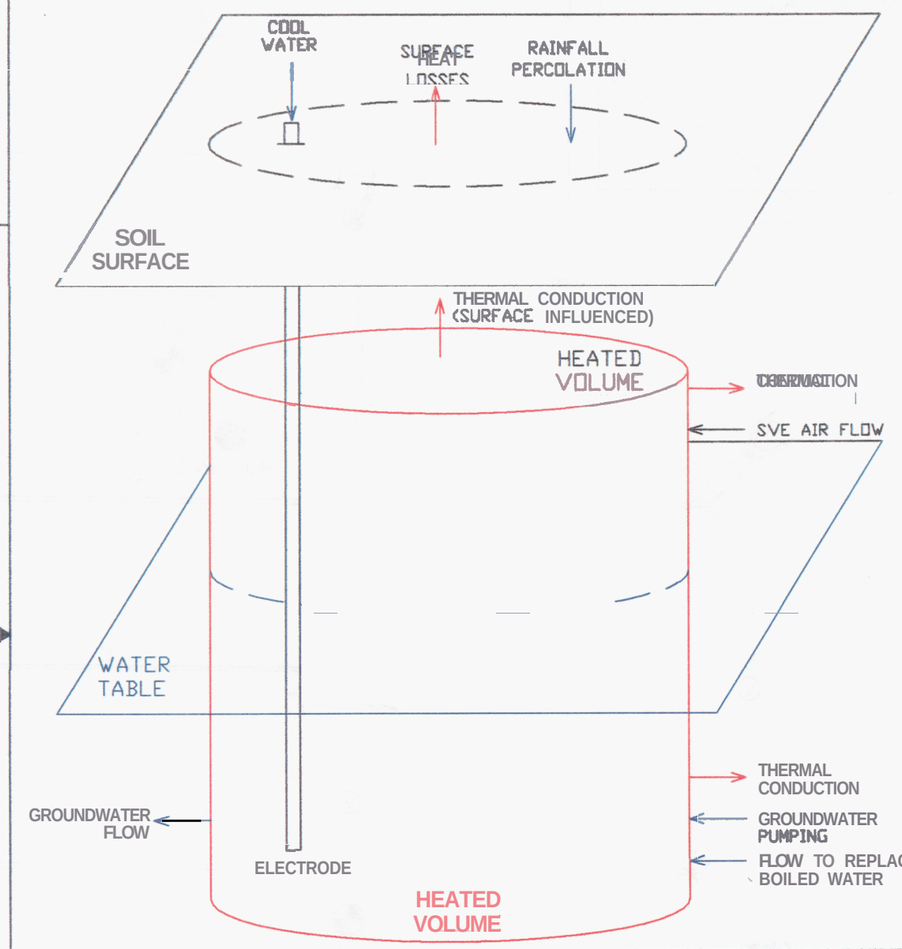
PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY - BUILDING C-400
PIPING PLAN

JOB NO.	DOE CONTRACT NO	CAD FILE NAME
23900	DE-AC05-98OR22700	PIPING
CLASS NO.	DLSC NO.	PLANT NO.
.0	C-400	PADUCAH GASEOUS DIFFUSION PLANT
	DRAWING NO.	REV NO.
	P5EC40000A001	0

STATE OF KENTUCKY GREGORY L. BEYKE 22085 LICENSED PROFESSIONAL ENGINEER

CVD: 30 JUNE 2003

DWG NO P5EC40000A002 SH 1



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B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: NTS

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ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY – BUILDING C-400
CONCEPTUAL HEAT FLOW MODEL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR22700	HEATFLOW

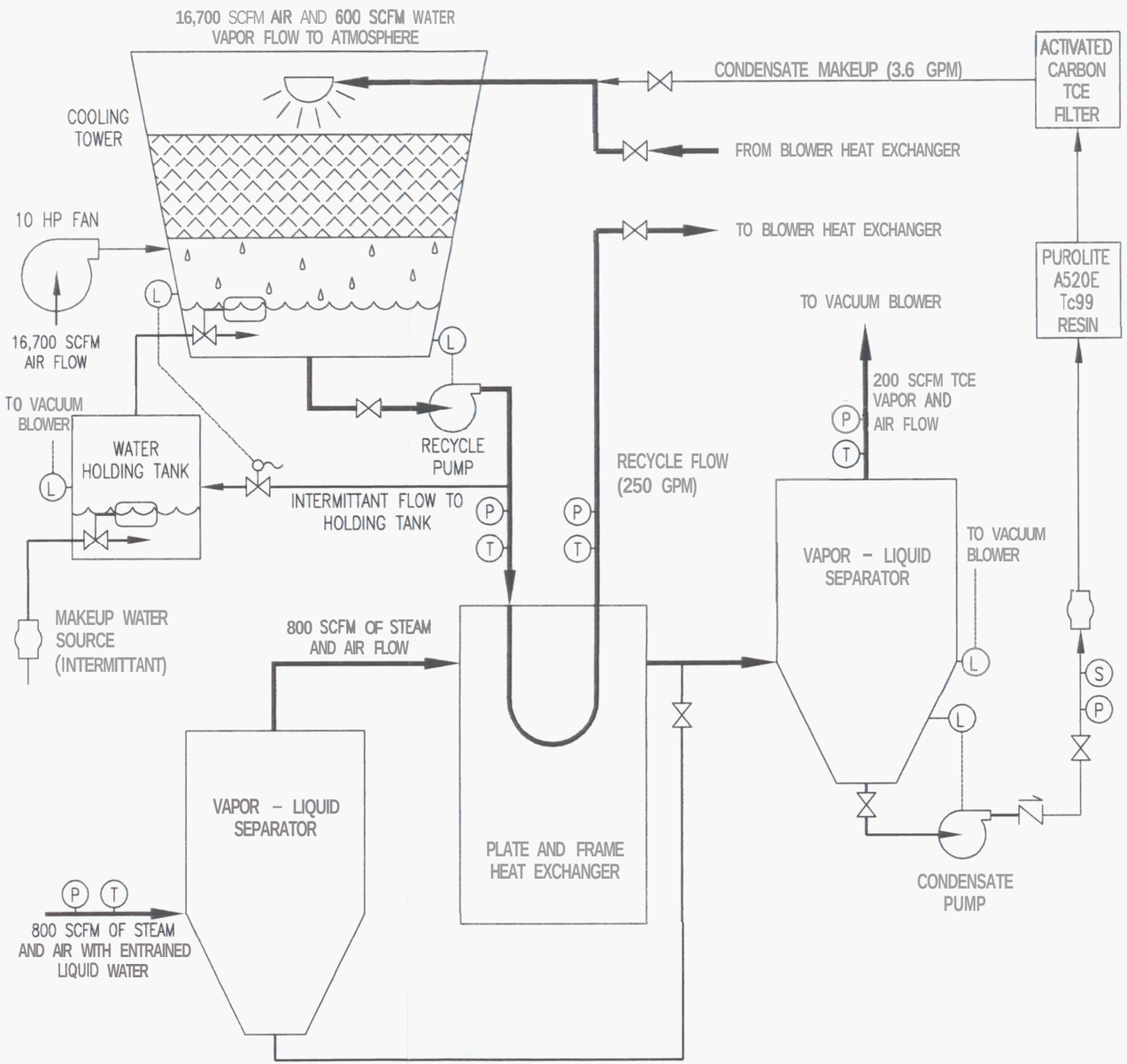
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS Bechtel Jacobs Company LLC	DRAWING NO.	REV NO.
	P5EC40000A002	0

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER

Exp. 30 JUNE 2003

DWG NO P5EC40000A004 SH1



LEGEND:

- (P) PRESSURE INDICATOR
- (T) TEMPERATURE INDICATOR
- (S) SAMPLE PORT
- NOZZLE
- TOTALIZING FLOW METER
- BALL VALVE
- CHECK VALVE
- (L) LIQUID LEVEL SENSOR
- FLOAT VALVE

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	ORGN ENGR	ENGR CHK	LE	PROG ENGR
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B	02/20/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD	[illegible]	[illegible]
A	10/16/00	ISSUED FOR 30% REVIEW	GB	HD	GB	MD	[illegible]	[illegible]

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ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services Inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY - BUILDING C-400
CONDENSER PROCESS DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR227000	CONDENSER PROCESS

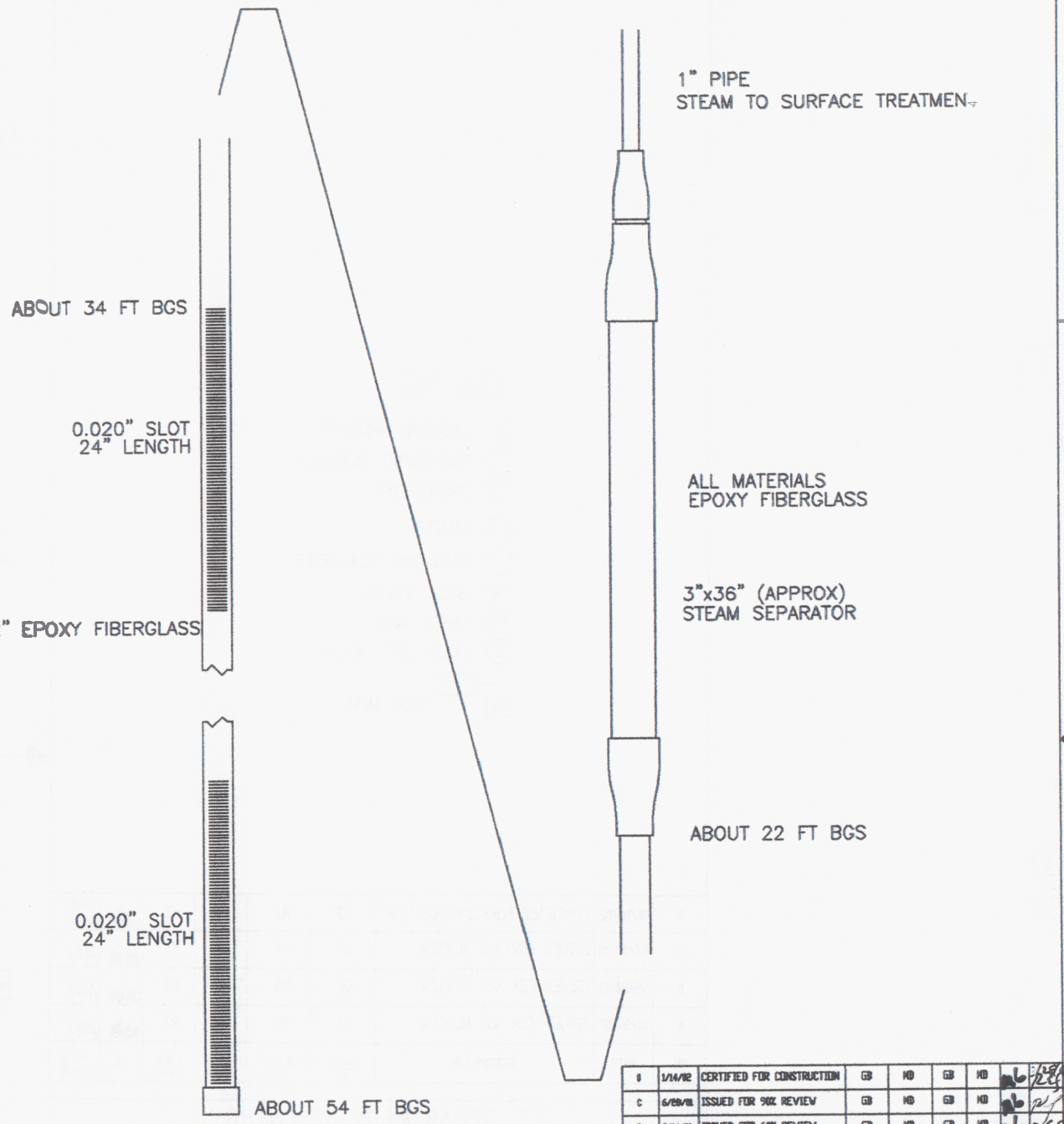
CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS

BECHTEL JACOBS
Bechtel Jacobs Company LLC

DRAWING NO.	REV NO.
P5EC40000A004	0

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER
exp. 30 JUNE 2003

DWG NO P5EC40000A003 SH1



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B	2/14/01	ISSUED FOR 60% REVIEW	GB	MD	GB	MD		
A	10/16/00	ISSUED FOR 30% REVIEW	GB	MD	GB	MD		

SCALE: NTS

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY, BUILDING C-400
STEAM SEPARATOR DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR22700	STEAM_SEP

CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS Bechtel Jacobs Company LLC	DRAWING NO.	REV NO.
	P5EC40000A003	0

STATE OF KENTUCKY
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22085
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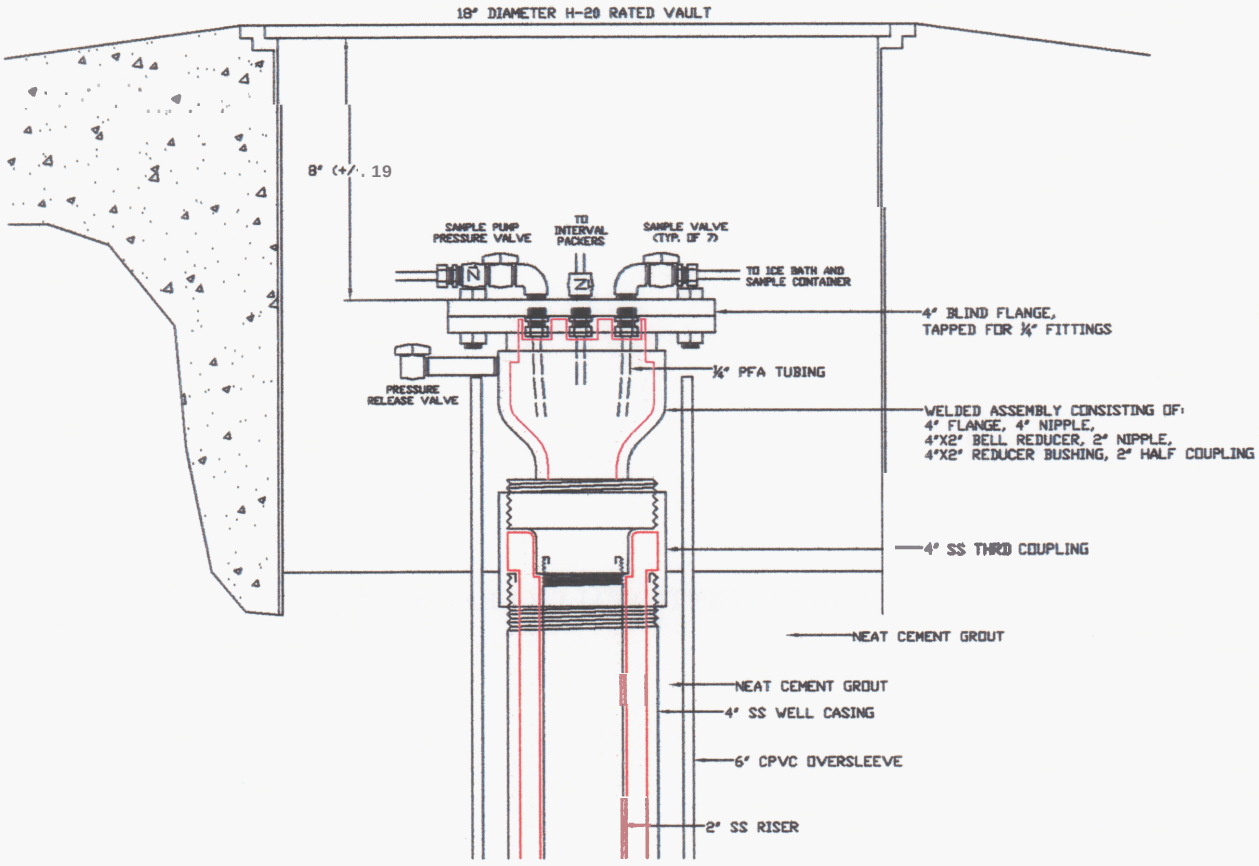
PROFESSIONAL ENGINEER

exp. 30 JUNE 2003

DWG NO C5EC40000A008 SH1



DENOTES PRIMARY PRESSURE BOUNDARY
DENOTES BACK-UP PRESSURE BOUNDARY
IF PACKER SYSTEM DEVELOPS LEAK

NO.	DATE	DESCRIPTION	DRAWN BY	DRAFT CHK	DSGN CHK	ENGR CHK	LE	PROJ ENGR
0	1/14/02	CERTIFIED FOR CONSTRUCTION	GB	MD	GB	MD		

SCALE: NTS

U.S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
ENVIRONMENTAL MANAGEMENT– MANAGEMENT & INTEGRATION

BECHTEL JACOBS COMPANY LLC
OAK RIDGE, TENNESSEE

THERMAL REMEDIATION services inc.

PADUCAH GASEOUS DIFFUSION PLANT, PADUCAH, KY.
UCRS/RGA, SIX-PHASE PILOT STUDY – BUILDING C-400
MONITOR WELLHEAD DETAIL

JOB NO.	DOE CONTRACT NO.	CAD FILE NAME
23900	DE-AC05-98OR22700	MONITOR WELLHEAD

CLASS NO.	BLDG. NO.	PLANT NO.
U	C-400	PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS Bechtel Jacobs Company LLC

DRAWING NO.	REV NO.
C5EC40000A008	0

STATE OF KENTUCKY
GREGORY L. BEYKE
22085
LICENSED
PROFESSIONAL ENGINEER
exp. 30 JUNE 2003

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APPENDIX B

ELECTRODE ELEMENT DESIGN CONSIDERATIONS

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Depth Interval (bgs)	Electrode Element Design Consideration
28 to 30 m (91 to 97 ft)	This deepest electrode zone heats the interbedded sand and clay at the top of the McNairy formation. This electrode zone will be the second to last zone placed on service and is intended to provide a "hot floor" to prevent the downward migration of DNAPL as the lower RGA and the RGA/McNairy interface is heated. At this depth, the boiling temperature of water is about 125°C and TCE will boil at about 97°C. The flow of electrical current between the electrodes fans out slightly, and this effect allows the 28 to 30 m (91 to 97) ft electrode zone to treat the depth zone from about 27 to 31 m (88 to 100) ft bgs.
27 to 28 m (89 to 91 ft)	This bentonite layer separates the 28 to 30 m (91-97 ft) electrode zone from the 24.2 to 27.1 m (78–89 ft) electrode zone. Bentonite is a moderate electrical conductor and a minor percentage of the electrical power that is applied to the 28 to 30 m (91-97 ft) electrode zone is likely to leak through the bentonite layer to the overlying zone. The exact amount of power spreading or "cross-talk" can be determined during operation. Although bentonite is not an ideal electrical separator, it was selected for this depth to retard the potential for DNAPL to move from the base of the RGA down through the electrode boring during the interval between installation and operation
24 to 27 m (78 to 89 ft)	This is the lower RGA electrode zone. This electrode zone will be the last zone placed on service, and heating in this zone will not start until after the upper McNairy reaches 97°C. The boiling temperature of water at this depth is about 120°C and TCE will boil at about 92°C.
23 to 24 m (76 to 78 ft)	This sand zone separates the 24 to 27 m (78 to 89 ft) electrode zone from the 18 to 23 m (58 to 76 ft) zone. Clean quartz sand is a good electrical insulator and minimizes electrode cross-talk. Sand also is preferred from a permeability standpoint, and in conjunction with the permeable steel shot backfill, it provides a permeable steam pathway from the base to the top of the RGA.
18 to 23 m (58 to 76 ft)	This electrode zone heats the upper RGA. The boiling temperature of water at this depth is about 112°C and TCE will boil at about 84°C.
17 to 18 m (56 to 58 ft)	This sand zone separates the 18 to 23 m (58 to 76 ft) electrode zone from the 12 to 17 m (39 to 56 ft) electrode zone.
12 to 17 m (39 to 56 ft)	This important electrode zone heats the top few feet of the RGA and the saturated portion of the UCRS. Heating this region creates small steam bubbles in the relatively lower permeability sediments of the saturated UCRS. The formation of small steam bubbles increases the effective vapor permeability of the sediments by providing a route that steam can travel easily through. Once this zone is heated to boiling, steam from lower depths can move upward by bridging from bubble to bubble. In addition to improving the permeability of the saturated UCRS, a steam vent is provided at about 17 m (54 ft) bgs. This vent provides a direct route from the top of the RGA to the vadose zone for steam that has traveled up through the permeable electrode construction materials or for steam that enters the electrode at the top of the RGA. The boiling temperature of water at this depth and shallower is about 100°C and TCE will boil at about 73°C.
13 to 14 m (44 to 45 ft) 15 to 16 m (50 to 51 ft)	These are thin bentonite layers internal to the 12 to 17 m (39 to 56 ft) electrode zone. The purpose of these bentonite layers is to provide seals in the electrode borehole and prevent electrode drip water from moving straight down to the RGA without moistening UCRS soils.
11 to 12 m (37 to 39 ft)	This bentonite layer separates the 12 to 17 m (39 to 56 ft) electrode zone from the 5 to 11 m (17 to 37 ft) electrode zone.

Depth Interval (bgs)	Electrode Element Design Consideration
5 to 11 m (17 to 37 ft)	This is the electrode zone for the lower unsaturated UCRS. At the bottom of the electrode is the upper steam vent. The deep VR well is located in the middle section of this electrode zone. This depth was selected to prevent choking off the VR well by water in the HU2 lithologic unit. The application of vacuum on this section of borehole will encourage water evaporation from the adjacent soil by vacuum desiccation. This drying will reduce the electrical conductivity of the adjacent soil and limit the power input of the middle electrode section. This is an acceptable trade-off that allows the same borehole to be used for both heating and VR. Electrical current from the over-and underlying electrode sections will fan out to help treat soil in the 7 to **9** m (24 to 30 ft) bgs depth interval. Although the co-location of VR wells with the electrodes limits the power that can be applied at that specific depth, the VR well does receive beneficial enhancements from the electrode. The drying of soil adjacent to the borehole increases gas-phase permeability and improves VR rates. The ***in situ*** steam separator is located in the upper section of the electrode, well above the water table to ensure that the separator will not flood under applied vacuum, unless the HU2 water table raises to about 9 m (30 ft) bgs.
6 to 7 m (22 to 24 ft) 9 to 10 m (30 to 32 ft)	These are bentonite layers internal to the 5 to 11 m (17 to 37 ft) electrode zone. The purpose of these bentonite layers is to isolate the vacuum desiccation effects of the deep VR well.
4 to 5 m (15 to **16** ft) 4 to 5 m (16 to 17 ft)	This zone separates the 5 to 11 m (17 to 37 ft) electrode zone from the 2 to 5 m (8 to 15 ft) zone and is composed of both sand and bentonite layers. The sand provides optimal electrical resistance and the bentonite layer enhances the electrode wetting system.
2 to 5 m (8 to 15 ft)	This is the uppermost electrode zone, heating the shallow unsaturated UCRS. The use of this shallow zone is optional and is based on the temperatures measured on the fire system control wiring that passes through the treatability study area. If subsurface temperatures adjacent to the control wiring approach rated limit for the wire insulation (70 to 90°C) this electrode zone will be disconnected from the SPH power system. When this zone is disconnected from SPH power it will be reconnected as a neutral zone to lessen induced voltage in the near surface region. Therefore the 4 to 5 m (15 to 16 ft) interval is comprised of sand to reduce electrode cross-talk.
1 to 2 m (5 to 6 ft) 1 to 2 m (6 to 8 ft)	This zone separates the 2 to 5m (8-15 ft) electrode zone from the permanent neutral zone located from 1 to 2 m (3 to 5 ft) bgs. This zone is composed of both sand and bentonite layers. The sand provides optimal electrical resistance and the bentonite layer prevents vacuum desiccation of the 2 to 5 m (8 to 15 ft) electrode zone. The sand layer also is used to enhance shallow VR efforts.
1 to 2 m (3 to 5 ft)	This is a permanent neutral zone to lessen induced voltages in the near surface region. The shallow VR well is located in this zone, and the underlying sand layer, in conjunction with the permeable steel shot, provides a filter pack for the VR well screen.
0 to 1 m (2 to 3 ft)	This thin bentonite layer is used only to prevent cement grout from intruding into the shallow VR well filter pack during construction
0 to 1 m (0 to 2 ft)	This neat Portland cement grout serves as the vacuum seal for the shallow VR well. It will not be impacted by heat or drying because it is pure cement.

APPENDIX C

DESIGN CALCULATIONS

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Design Calculations

Preparer: The individual who performed the engineering calculations and assembled the calculation package.

Gregory Beyke, Preparer

Reviewer: The individual, assigned by the Project Manager, who is responsible for verifying the accuracy, applicability, and methodology of the calculations.

Walter Richards, Reviewer

Approved by:

Gregory Beyke, PE
Lead Engineer

The purpose of this calculation package is to determine the relevant parameters for a SPH Treatability Study to be performed at southeast corner of Building C-400 at the Paducah Gaseous Diffusion Plant. Abbreviations and reference lists can be found in main body of the design to which this calculation package is attached.

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ENERGY BALANCE

Site remediation requires the removal or *in situ* destruction of a significant portion of the VOCs that are present in the subsurface. The principal removal mechanism is evaporation, while VOCs can be destroyed *in situ* through hydrolysis, biodegradation, and hydrous pyrolysis oxidation. Hydrolysis is the principal mechanism for the *in situ* destruction of many important VOCs including: methylene chloride, carbon tetrachloride, halogenated alkanes, and most pesticides. The hydrolysis half-life of most of these compounds is less than one day at 100°C (adapted from Jeffers et al. 1989).

The PDGP is contaminated with TCE. The rate of *in situ* hydrolysis is not likely to be significant for TCE, and it is conservative to assume that all other forms of *in situ* destruction also will be insignificant. This assumption simplifies design calculations by allowing evaporation to be considered the primary method of contaminant remediation during the SPH treatability study. The following discussion relates to the energy balance and remediation parameters presented in Table C.1.

In order to evaporate sufficient TCE from the treatability study cell to reach the treatability study cleanup goals, it is necessary to input sufficient boiling energy to remove both TCE and by-product steam. The ratio of TCE vapor production to steam production is governed by the following factors:

- The percentage TCE reduction desired in soil and groundwater;
- The physical characteristics of TCE - especially boiling temperature and water solubility (which together incorporate Henry's Law constant);
- The concentration of total organic carbon (TOC) in the subsurface - TOC preferentially adsorbs VOCs in comparison to water;
- The presence of co-contaminants, especially low-volatility hydrocarbons such as oil and grease - these compounds slow VOC evaporation through Raoult's Law.

In addition to the boiling energy that is required, sufficient energy must be input to the subsurface to bring the treatment volume to the boiling temperature and to account for heat losses by various mechanisms. The calculation of the energy to bring the treatment volume to boiling is straight forward (line B116), and the following assumptions are included in the calculation.

- The density of dry soil is 85 lb/ft^3.
- The heat capacity of dry soil is 0.2 BTU/lb/°F (this value is remarkably constant for all soil types).
- The heat capacity of water is 1 BTU/lb/°F (by BTU definition).
- Water provides 40 volume percent of the saturated zone.

However, the calculation of heat losses is not trivial. Drawing P5EC40000A002 of Appendix A is provided as a reference for the following discussion. The principal heat loss mechanisms during SPH are as follows:

- Thermal conduction (to the vadose and saturated zones);
- Electrical energy deposited outside of the treatment zone (indistinguishable from thermal conduction);
- Groundwater pumping, which not only removes hot water from the treatment volume but also encourages the inflow of cool water from the sides and bottom of the treatment volume;

Table C.1. Energy balance and remediation parameters

	A Parameter	B Value	C Notes
	Site Name:	Paducah	
	State:	KY	
	Geometry		
4	Is this a single array pilot test?	yes	
5	Treatment Area (sq. ft.):	1,400	=IF(B4="yes",ROUND(B55^2*PI()/2,-2),10,000)
6	Treat Sequentially as # Sections:	2	Note 1
7	Shallow Extent of Treatment (ft):	5	Site Parameter
8	Deep Extent of Treatment (ft):	98	Site Parameter
9	Treatment Volume (cu ft):	130,200	=B5*(B8-B7)
10	Treatment Volume (cu yd):	4,800	=ROUND(B9/27,-2)
11	"Excavation" Mass (tons):	6,900	=ROUND(B5*B8*100/2,000,-2)
12	Heat Loss Surface Area (sq. ft.):	13,732	=B5*2+(B8-B7)*PI()*SQRT(B5)
13			
14	**Hydrology/Lithology**		
15	Depth to Water (ft):	39	Depth to HU2 water table.
16	Portion of T.V. that is Saturated (%):	1	=MAX(0,MIN(1,(B8-B15)/(B8-B7)))
17	Water Flow Velocity (ft/day):	1	Average over the saturated zone. (DOE 1999)
18	Vadose Soil Type:	silt	Non-critical site parameter
19	Saturated Soil Type:	gravel	Non-critical site parameter
1	Site Name:	Paducah	
2	State:	KY	
3	**Geometry**		
20	Vadose Volume Percent Water (Y_0):	25%	=IF(B18="gravel",0.1,IF(B18="sand",0.15,IF(B18="silt",0.25,IF(B18="clay",0.3,0.25))))
21	Does Rainfall Percolate through?	yes	Non-critical site parameter
22	Annual Rainfall (in.)	44	=LOOKUP(B$2,'State Data'!A$3:A$53,'State Data'!C$3:C$53)
23	Organic Carbon Content (%):	0.04%	Site Parameter (DOE, 1999)
24	Are flowing sands present?	yes	Site Parameter
25	**Contamination**		
26	Controlling Contaminant:	TCE	
27	Boiling Temperature at 1 atm (°C):	87	=LOOKUP(B26,VOCs!A4:A34,VOCs!B4:B34)
28	Water Solubility (mg/l):	1,100	=LOOKUP(B26,VOCs!A4:A34,VOCs!C4:C34)
29	Clean-up Difficulty (TCE=1)	1	Note 3
30	initial Max. Soil Contam. (mg/kg):	11,055	Site Parameter
31	Average Contamination (mg/kg):	2,211	=B30/5
32	Contaminant Mass (pounds):	28,787	=B31*B9/10,000
33	Final Max. Soil Contam. (mg/kg):	288	Note 2
34	Soil Clean-up Percent:	99%	=1-B33/B30
35	Initial Max. Water Contam. (µg/l):	700,000	Site Parameter
36	Final Max. Water Contam. (µg/l):	7,000	Note 2

Table C.1. Energy balance and remediation parameters (continued)

	A Parameter	B Value	C Notes
37	Water Clean-up Percent:	99%	=1-B36/B35
38	Overall Clean-up Percent:	99%	=MAX(B34,B37)
39	Is this a Fuel?	no	Site Parameter
40	Any Low Volatility Co-contaminants'!	no	Site Parameter (DOE. 1999)
41			
42	**Temperatures**		
43	Initial Temperature (°C):	13	=LOOKUP(BS2,'State Data'!AS3:AS53,'State Data'! BS3:BS53)
44	Initial Temperature (°F):	55	=B43*1.8+32
45	Ave. Heated Temperature (°C):	111	=(100*MAX(MIN(B15-B7,B8-B7),0)+(100+SQRT(MAX(B8-B15,0))+0.16*MAX(B8-B15,0))*MAX(MIN(B8-B15,B8-B7),0))/(B8-B7)
46	Ave. Heated Temperature (°F):	232	=B45*1.8+32
47	Temperature at Bottom of T.V. (°C):	125	=100+1.75*MAX(B8-53,0)^0.7
48			
49	**Electrodes**		
50	Electrode Diameter (in.):	12	Site Parameter
51			Note 3
52			Note 3
53	Array to Electrode Ratio (D/d):	30	Note 3
54	Distance between Electrodes (ft):	15	=B55/2
55	Array Diameter (ft):	30	=2*ROUND(B51/24*B53,0)
56	Number of Electrodes:	7	=MAX(ROUND(B5/(B54^2)/0.866-1,0),7)
57	Total Depth of Electrode (ft):	97	=B8-1
58	Depth to Top of Electrode (ft):	8	=MIN(B7+ROUND(B55/10,0),B15+ROUND(B55/10,0))
59	Electrode Drill Cuttings (tons):	27	=ROUND(B50^2*PI()/576*B57*B56/20,0)
60	Subsurface Neutral Used'?	yes	Site Parameter
61	Conductive Zone Steel Shot (ft):	74	=B57-B58-15
62	Total Steel Shot Required (lb):	113,000	=IF(AND(B63=0,B60="yes"),ROUND(B56*(B61+2)*(B50^2)*PI()/4/144*270,-3),ROUND(B56*B61*(B50^2)*PI()/4/144*270,-3))
63	Conductive Zone Graphite (ft):	0	
64	Total Graphite Required (lb):	0	
65	Electrode Saturation (%):	65%	=MAX(0,MIN(1,(B57-B15)/(B57-B58)))
66	Water Addition Required'?	yes	Site Parameter
67	Total Water Addition Rate (gpm):	0.60	=B99/6
68			
69	**Power Input**		
70	Max. Power Based on Section (kW):	890	Note 3
71	Max. Power of Power Supply (kW):	950	Site Parameter
72	Power Input (kW):	618	=IF(B71*0.65<B70,B71*0.65,B70)
73	Amperes at 480V, 3 phase:	1,150	=ROUNDUP(B72*1000/SQRT(3)/480/0.65,-1)
74	Amperes at 12.4kV, 3 phase:	45	=ROUNDUP(BS72/SQRT(3)/12.4/0.65,0)
75	Amperes at 13.8kV, 3 phase:	40	=ROUNDUP(BS72/SQRT(3)/13.8/0.65,0)
76	Groundwater Conductivity (µS/cm):	450	Site Parameter (DOE 1999)

Table C.1. Energy balance and remediation parameters (continued)

	A Parameter	B Value	C Notes
77	Initial Vadose Resistivity (ohm-m):	39	Note 3
78	Initial Saturated Resistivity (ohm-m):	41	Note 3
79	Overall Resistivity - r (ohm-m):	40	=B78*B65+B77*(1-B65)
80	Cylindrical Resistance - Rc (ohms):	1.9	=B79/PI()/(B57-B58)*3.28*LN(B53+SQRT(((B53)^2)-1))
81	Fringe Resistance - Rf (ohms):	41	=B79/PI()/B51*12*3.28*(1-(1/(2*B53+1)))
82	Phase Resistance - R (ohm):	2.0	=B80*B81/(B80+B81)*1.1
83	Initial Electrode Voltage:	473	=SQRT(B72/0.8*1,000*B82/2/B56*B6)
84	Initial Amps per Electrode:	233	=B72/0.8*1,000/B83/B56
85			
86	**Vapor Extraction / Air Injection**		
87	Vapor Extraction Required?	yes	Site Parameter
88	VE Steam and Air Flow (scfm):	830	=B90+B89
89	VE Steam Flow (scfm):	630	=IF(B45>99,ROUND(B99*8.34/0.0764*29/18,-1),0)
90	VE Air Flow Rate (scfm):	200	=IF(B87="yes",ROUND(B72/3.5+25,-1),0)
91	Vapor Extraction Horsepower:	20	=IF(OR(B18="sand",B18="gravel"),IF(B90/24<30,ROUNDUP(B90/120,0)*5,ROUNDUP(B90/240,0)*10),IF(B90/12<30,ROUNDUP(B90/60,0)*5,ROUNDUP(B90/120,0)*10))
92	Average Extraction Rate (lb/day):	222	=B32*B38/B137
93	insulating Surface Cover Used?	no	=IF(B90>10,IF(B7<2,"yes","no"),"no")
94	Air Injection Used?	no	Site Parameter
95	Air Injection Flow Rate (scfm):	0	
96	Air Injection Horsepower:	0	
97	Groundwater Extraction Rate (gpm):	0	Site Parameter (DOE, 1999)
98	Average Rainfall (gpm):	0	=IF(B21="yes",B22*B5/12*7.48/365/24/60/B6,0)
99	Ave. Condensate Prod. Rate (gpm):	3.6	=B100/(B137-B135*B6)/24/60
100	Total Condensate Production (gal):	562,600	=ROUND(B126*3.41/8.34,-2)
101			
102	**Average Heat Spreading/Loss Rates**		
103	Soil Conduction During Heat-up (kW):	49	=(MAX(B12*(B45-B43)/D104*(1-B16)-B108/2,0)+MAX(B12*(B45-B43)/D104*B16-B110/2,0))/B6^0.95
104	Soil Conduction During Boiling (kW):	30	=(MAX(B12*(B45-B43)/D105*(1-B16)-B108,0)+MAX(B12*(B45-B43)/D105*B16-B110,0))/B6^0.95
105	Soil Surface Loss - Heat-up (kW):	0.1	=B5*(B45-B43)/D106
106	Soil Surface Loss - Boiling (kW):	6.6	=MAX(B5*(B45-B43)/D107-B104*B5/B12,B105)
107	Electrical Power Outside T.V. (kW):	39	=B12*3/B9*0.2*B72
108	VE or Air Injection Cooling (kW):	6	=MAX(B90,B95)*(1.2*(B45-B43)-0.039*(B45^2-B43^2)+0.00103*(B45^3-B43^3))/760*0.0764*1000/3410
109	Groundwater Flow Cooling (kW):	11	=B17*0.1*B9/SQRT(B5)*B16*60*(B46-B44)/24/3410/B6
110	Groundwater Ext. Cooling (kW):	0	=IF(B16>0.01,MAX(B97*8.34*(B46-B44)*60/3410-B111,0),0)
111	Rainfall Percolation Cooling (kW):	1	=B98*8.34*(B46-B44+5)*60/3410
112	Total Heat-up Spreading/Loss (kW):	77	=B103+B105+SUM(B107:B111)/2
113	Total Boiling Spreading/Loss (kW):	94	=B104+B106+SUM(B107:B111)
114			
115	**Energy Density Required**		
116	Energy to heat-up T.V. (kW-hr/cu.ft.):	1.95	=((B46-B44)*(85*0.2+60*(B20+B16*(0.4-B20)))/3410)
117	Energy to Boil VOCs (kW-hr/cu.ft.):	10.6	Note 3

Table C.1. Energy balance and remediation parameters (continued)

	A Parameter	B Value	C Notes
118	Moisture Boiled in Remediation (v/o):	59%	=B117*3410/980/62.5
119	Vadose Moisture Removed (v/o):	22%	=(1-B16)*B117*3410/980/62.5
120	Electrode Wetting Moisture (v/o):	13%	=B67/7.48*24*60*(B137-B6*B135)/2/B9/MAX(1-B16,0.05)
121	Moisture Restored by Rainfall (v/o):	2%	=IF(B21="yes",B137/B6/365*B22/12/MAX(5,MIN(B8-B7,B15-B7)),0)
122	Final Vadose Moisture Content (%):	19%	=IF((B20-B119+B120+B121)>B20,B20,B20-B119+B120+B121)
123			
124	**Energy Required (kW-hr)**		
125	Energy to Heat-up T.V.:	253,600	=MAX(ROUND(B116*B9,-2),ROUND(B116*B5*(B8-B15),-2))
126	Energy to Boil VOCs:	1,375,900	=ROUND(B117*B9,-2)
127	Energy Spread by Conduction:	224,600	=ROUND(B103*24*B135*B6+B104*24*B136*B6+B107*24*B137,-2)
128	Soil Surface Heat Loss:	17,300	=ROUND(B105*24*B135*B6+B106*24*B136*B6,-2)
129	Energy in SVE Air Flow:	17,700	=ROUND(B108*24*(B$137-B6*B$135/2),-1)
130	Energy Flow with GW:	30,700	=ROUND(B109*24*(B$137-B6*B$135/2),-2)
131	Energy Ext. with GW:	0	=ROUND(B110*24*(B$137-B6*B$135/2),-2)
132	Rainfall Percolation Cooling:	2,800	=ROUND(B111*24*(B$137-B6*B$135/2),-2)
133	Total Energy Required (kW-hr):	1,923,000	=ROUND(SUM(B125:B132),-3)
134			
135	Time to Heat-up each Section (days):	10	=B125/(B72-B103-B105-B107-B108/2-B109/2-B110/2-B111/2)/24/B6
136	Time to Boil each Section (days):	55	=B126/(B72-B104-B106-B107-B108-B109-B110-B111)/24/B6
137	Total Est. Treatment Time (days):	130	=B6*(B135+B136)
138	Treatment Time for Bid (days):	130	Site Parameter
139	Total Treatment Time (weeks):	19	=B138/7
140	Total Energy for Bid (kW-hr):	1,927,000	=ROUND(B72*B138*24,-3)
141	Time/Energy Safety Factor:	0%	=(B140-B133)/B133
142			
143	**Remediation by Heating Only**		
144	Time at Final Temperature (days):	0	
145	Power to Maintain Temp (kW):	55	=B104+B106+B108+B109+B110+B111
146	Energy to Maintain Temp (kW-hr):	0	

- Soil VR efforts, which bring cool air into the treatment volume. Although evaporative cooling is the major energy effect from VR efforts, it can be ignored in the design calculations since evaporation is the desired goal of SPH. Only the small heat capacity of the air itself needs to be considered;

- Flowing groundwater carries hot water away from the treatment cell and provides an input of cool water along the sides and bottom of the cell;

- Rainfall percolation provides cool water to the treatment volume; and

- Electrode wetting provides cool water to the treatment zone.

While the thermal conductivity of soil is remarkably constant for all soil types at about 0.97 BTU/hr/ft°F, thermal conduction is affected by the following factors:

- The rate of heat-up of the treatment volume (faster heating leads to increased thermal conduction rates);

- The length of time the treatment volume is boiled (the longer the boiling time, the slower the rate of thermal conduction);

- The difference between boiling temperature and ambient temperature;

- How closely the treatment volume approaches the soil surface (the closer the approach, the faster heat conducts to the constant-temperature surface);

- The VR airflow rate (air flowing into the treatment volume restores heat carried out by thermal conduction); and

- The groundwater pumping rate plus the inward flow groundwater from the surrounding aquifer to replace boiled groundwater (both of which restore heat carried out by thermal conduction).

The time-variant nature of thermal conduction and its interaction with other variables make calculation of the rate of thermal conduction difficult. **A** number of different scenarios have been analyzed using numerical modeling in order to determine the sensitivity of the various inputs. Using this sensitivity analysis, thermal conduction heat flows can be estimated using direct calculations, providing the results shown (lines B 103 through B 106).

The distribution of electrical power is well defined. By SPH convention, the edge of the treatment zone (the region of thorough heating) is defined at the square root of **2** times the electrode radius. The depth interval of the treatment zone is defined as extending 20% of the array radius above and below the electrode conductive interval(s). However, some electrical energy is deposited in soils outside of the treatment volume. In practice, this energy is indistinguishable from thermal conduction (line B 107).

The other heat losses are relatively easy to calculate provided that double counting is avoided (lines B108 through B111).

The total energy required then is the sum of the energy required to bring the treatment volume to boiling, plus the energy lost as heat, plus the energy required to boil the groundwater to achieve the treatment study goals. The distribution is shown in Fig. C.1.

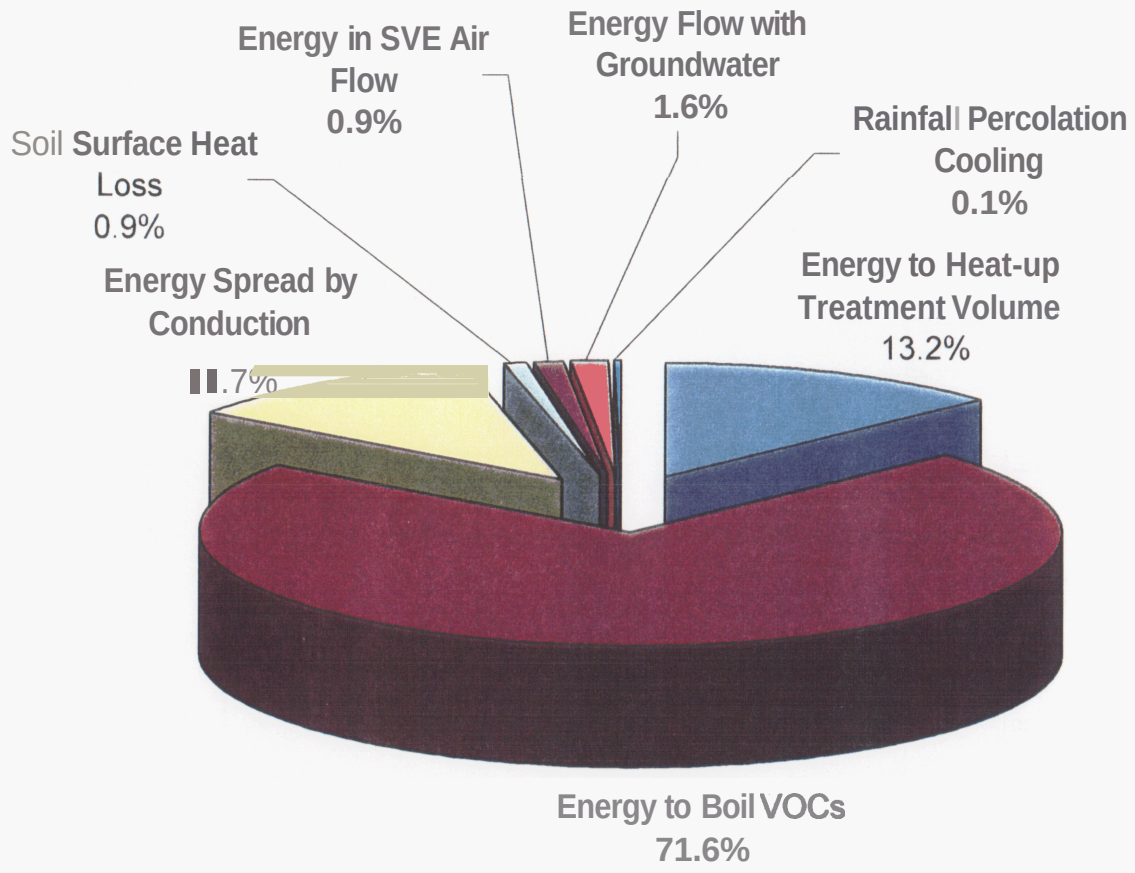

Fig. C.1. SPH energy distribution in subsurface.

U. S. DEPARTMENT OF ENERGY
DOE OAK RIDGE OPERATIONS
PADUCAH GASEOUS DIFFUSION PLANT

BECHTEL JACOBS COMPANY, LLC
MANAGED FOR THE US DEPARTMENT OF ENERGY UNDER US GOVERNMENT CONTRACT DE-AC-05-98OR22700
Oak Ridge, Tennessee • Paducah, Kentucky • Portsmouth, Ohio

Science Applications International Corporation
P.O. Box 2502
Oak Ridge, Tennessee 37831

FIGURE No. dist.ppt
DATE 07-11-01

Head Loss in VR Piping

A schematic of the VR piping system is presented in Drawing P5EC40000A001 of Appendix A. The head loss in the CPVC VR piping is summarized in Table C.2.

The formula for Column H of Table C.2 is =B+J*(C*2.53+D*1.35+E*2.08+F*5.37+G*5)
(adapted from Harrington Industrial Plastics 2000)

The formula for Column M of Table C.2 is =(H/100)*I^2/((J*(1-(K+40)/880))^4.8655)*(30/(30-L))/1460
(adapted from Perry et al. 1984)

Table C.2. Head loss in VR piping

	B	C	D	E	F	G	H	I	J	K	L	M
		number of:										
Section	dist. (ft)	90L	45L	thru T	side T	bush.	equiv. pipe (ft)	flow (scfm)	nom. pipe dia. (in.)	pipe sched	discharge vacuum (in. Hg)	vac. loss (in. Hg)
Analysis to Far Southwest Well VR5												
KOP to north branch Tee	20	1	2	1			64	790	6	80	12.0	0.15
north branch Tee to south branch Tee	3				1		35	451	6	80	11.8	0.03
south branch Tee to VR3 Tee	10	1		2		1	57	339	4	80	11.8	0.18
VR3 Tee to VR4 Branch Tee	5			1		1	26	226	3	80	11.6	0.15
VR4 Tee to VR5 Tee	33				1		49	113	3	80	11.5	0.07
VR5 Tee to instrument run	2	2				1	22	56	2	80	11.4	0.05
instrument run to well VR5s	4					1	10	56	1.25	80	11.4	0.25
vac at far well (VR5)											11.1	
Analysis to Far Northwest Well VR6												
north branch Tee to VR2 Tee	11	1		2		1	58	339	4	80	11.8	0.18
VR2 Tee to VR1 Tee	20			1		1	41	226	3	80	11.7	0.23
VRI Tee to VR6 Tee	17			1			23	113	3	80	11.4	0.03
instrument run to well VR6s	4					1	10	56	1.25	80	11.4	0.25
vac at far well VR6											11.2	
Analysis to Well VR4												
VR4 Branch Tee to VR4 d/s Tee	18		3		1		46	113	3	80	11.5	0.06
VR4 d/s Tee to instrument run	1	1				1	16	56	2	80	11.4	0.04
instrument run to well VR4s	4					I	10	56	1.25	80	11.4	0.25
vac at VR4											11.1	
Analysis to Well VR7												
south branch Tee to VR7 d/s Tee	20	I	2	1		1	45	113	2	80	11.8	0.45
VR7 d/s Tee to instrument run	1	1		1			10	56	2	80	11.4	0.03
instrument run to well VR7s	4					1	10	56	1.25	80	11.3	0.25
vac at VR7s											11.1	

The head loss to distant wells VR5 and VR6 was calculated first. Since VR6 had higher applied vacuum, wells VR1 and VR2 were ignored. Head loss calculations then were made for wells VR4 and VR7.

VOC Boiling Temperatures

Dalton's Law describes the boiling temperature of minimally soluble VOCs. When in contact with water, a VOC will boil when the vapor pressure of the VOC plus the vapor pressure of water is equal to the ambient pressure. The boiling temperature of various VOCs at depth can be calculated using the method of numerical integration.

Although the boiling temperature of the VOC at depth is of interest, it is not a critical parameter for site remediation, since the temperature of the subsurface will be increased to the boiling temperature of pure water. The method of boiling point calculation is not described further.

Maximum Expected TCE Concentration in Condensate

Based on a maximum expected TCE concentration in vapor of 74.2 mg/l (see above) and a Henry's Law Constant of 0.4169 (Howe et al. 1987), the maximum expected TCE concentration in condensate is 178 mg/l, or 16% of the TCE solubility limit of 1,100 mg/l (Weast et a1.1976).

Electrical Consumption by Vapor Recovery Equipment

The VR blower has a 20 hp motor. The condenser has motors totaling 14.5 hp. The dilution air blower has a 5 hp motor. It is unlikely that these motors will average greater than 90% of their capacity. The total electrical load of the VR equipment is

$$(20\text{hp} + 14.5\text{hp} + 5\text{hp}) * 90\% * 0.7457 \, {}^{\text{kW}}\!/_{\text{hp}} = 26.5\text{kW}$$

The expected duration of the remediation is 130 days. An additional 14 days of VR operation should be included to account for VR operation just prior to and just following SPH. The total energy consumed by the VR equipment is

$$26.5\text{kW} * (130\,\text{days} + 14\text{days}) * 24 \, {}^{\text{hr}}\!/_{\text{day}} = 91{,}600\text{kW} - \text{hr}$$

TCE Movement as Dissolved Phase (order of magnitude calculation)

The groundwater flow velocity in the RGA is about 1 ft per day (DOE 1999).

The treatment zone is about 42 ft across and the RGA is about 35 ft in thickness, providing a cross-sectional area of 1,470 ft^2. Assuming that 26% of the volume consists of interconnected pores that support water flow (Todd 1980), the water flow rate out of the treatment zone is about 380 ft^3/day.

The solubility limit of TCE is 1,100 mg/l (Weast et al. 1976)

The present dissolved-phase TCE migration is about

$$380\ ft^3/day \times 28.32\ l/ft^3 \times 30.3\ days/month \times 1{,}100\ mg/l \div 1{,}000{,}000\ mg/kg = 360\ kg/month$$

The solubility of TCE approximately doubles as the site is heated to boiling (Heron et al. 1996). The average increase during the heating phase is 1,100mg/l ÷2 = 550 mg/l. About 15 days will be required to heat the RGA to boiling temperatures.

The additional TCE mass that will move out of the treatment cell during heating is then

$$380\ ft^3/day \times 28.32\ l/ft^3 \times 15\ days \times 550\ mg/l \div 1{,}000{,}000\ mg/kg = 89\ kg$$

TCE Vapor Production Rate and Vapor Concentration

The maximum expected TCE evaporation rate is less than 2,000 lb/day. This is controlled by the SPH power input rate to remain within the vapor treatment unit capacity.

The vapor density of TCE is 4.5. The density of air is 0.0764 lb/ft^3 (Weast et al. 1976)

$$2{,}000\ lb/day \div 1440\ min/day \div 0.0764\ lb/ft^3 \div 4.5 = 4.0\ scfm\ TCE\ vapor$$

Based on a typical gas flow rate of 300 scfm, the maximum TCE concentration would be 4.0 scfm ÷ 300 scfm x 1,000,000 ppmv = 13,300 ppmv. The TCE vapor concentration can also be rendered as

$$\frac{2000\frac{lb}{day}\times 453{,}592\frac{mg}{lb}}{300scfm\times 1440\frac{min}{day}\times 28.32\frac{l}{ft^3}} = 74.2\frac{mg}{l}$$

Percentage of Recovered TCE Mass that is Dissolved in Condensate Water

The environment of the condenser is a good application for Henry's Law. Based on a typical condenser temperature of 25°C (77°F), the dimensionless Henry's Law constant for TCE is 0.4169 (Howe et al. 1987). Based on a typical vapor flow rate of 300 scfm and a typical condensate production rate of 3.6 gpm (Table C.1), the percentage of TCE mass in the water dissolved phase leaving the condenser is

$$\frac{3.6gpm\ x\ 3.785\frac{l}{gal}}{3.6gpm\ x\ 3.785\frac{l}{gal}+0.4169\times 300scfm\times 28.32\frac{l}{ft^3}}\ x\ 100\% = 0.38\%$$

APPENDIX D

EQUIPMENT SPECIFICATIONS

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SPH PCU Specifications

The following are the specifications of the SPH Power Control Unit (PCU).

1. The SPH PCU shall have six electrical outputs that are 60" out of phase with each other.

2. The electrical outputs shall be remotely adjustable in voltage over the minimum range from 200 to 600 V. The PCU shall be capable of selecting and provide any voltage within this range to an accuracy of ±5%.

3. The PCU shall have a minimum power rating of 950 kilowatts (kW) at a duty cycle of 100% over the voltage range from 400 volts to 600 V.

4. The PCU shall be capable of supplying at least 390 amperes of current per phase over the voltage range from **200** to 400 V.

5. The PCU shall have full rated capacity at an ambient temperature of at least 30°C. The PCU shall be capable of reduced power operation at ambient temperatures up to 45°C.

6. The PCU shall be designed to accept a three-phase electrical input with a voltage range of 12.4kV to 14.4kV at its input fused disconnect.

7. Electrical metering shall provide revenue-quality measurements of energy (kW-hours) and demand (average and peak kW), on the input.

8. Surge protection shall be provided on input lines.

9. The voltage and current of each electrical output shall be metered. A control system with remote access capability shall record and display measurements from all meters and alarms. The PCU shall include a UPS or other method that will allow remote restart after a power failure of up to 20 minutes duration.

10. All transformers shall have over-temperature alarms.

11. The electrical equipment shall be protected from weather by being assembled following National Electrical Manufacturers Association (NEMA) 3R construction methods. Ventilation shall be designed to keep dust and wind-blown rain from entering the enclosure.

12. Heaters shall be provided to dry high voltage electrical windings following idle periods.

13. A contactor shall be provided to allow remote starting and stopping of output current.

14. **A** 100 ampere, 480 V, three-phase output with over-current protection shall be provided for auxiliary VR system loads.

15. The PCU shall be mounted on a street-legal semi-trailer.

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Steam Condenser Specifications

The following are the specifications of the SPH condenser.

The condenser shall be designed for the following inlet conditions: a) steam flow of 600 scfm; b) air flow of 300 scfm; c) temperature of up to 100°C; d) vacuum of up to 15 in. Hg; e) liquid water at up to 5 gpm; and f) chlorinated solvent vapors at up to 3% by weight of the inlet gas flow.

The condenser shall be designed to produce the following outlet conditions: a) air flow of up to 300 scfm at 100% relative humidity; b) temperature less than 5°C (9°F) above ambient or less than 10°C (50°F), whichever is greater; c) the differential pressure across the condenser shall be less than 2 in. Hg; and d) the discharge stream will be 99% free of water droplets greater than 10 micron.

3. The inlet connection shall be an 8-in. flange. The outlet connection shall be a 6-in. flange.

4. Liquid water in the inlet stream may contain dissolved minerals or silt. **A** vapor-liquid separator with demister element shall be provided upstream of the heat exchanger to remove liquid water that contains these potentially-fouling materials. This vapor-liquid separator shall be rated for a flow of 2000 actual cubic ft per minute (acfm).

5. The heat exchanger shall be of a type that offers low pressure drop on the vapor side. The heat exchanger shall be a plate-and-frame type that can be cleaned relatively easily to remove fouling materials. **A** plate-and-frame heat exchanger also will allow radionuclide scanning of internal surfaces upon project completion. The heat exchanger plates will be constructed of stainless steel and will have an exchange surface area of at least 300 ft^2. Any gaskets used in the heat exchanger must be capable of resisting water-dissolved TCE at concentrations of up to 200 mg/l.

6. **A** vapor-liquid separator shall be installed at the outlet of the heat exchanger to remove condensed water from the air/vapor stream. The vapor-liquid separator shall include a demister element that is 99% effective at removing water droplets greater than 10 micron.

7. An automatic water pumping system shall be installed to remove condensate and entrained liquid water from the two vapor-liquid separators.

8. The condenser shall include recycle loop piping, a recycle pump, and a cooling tower with sufficient capacity to meet the outlet conditions of specification 2. The recycle loop shall include a thermostat to shut off the cooling tower fan if the heat exchanger inlet temperature drops below 5°C (41°F). The cooling tower fan shall be 10 hp and shall be capable of a flow of at least 16,000 scfm.

9. The cooling tower will be mounted on a separate skid from the heat exchanger and the vapor-liquid separators. The heat exchanger skid will be enclosed and heated for freeze protection.

10. The condenser shall include the following instrumentation. Temperature gages: for vapor inlet and outlet, for recycle flow at heat exchanger inlet and outlet. Vacuum gages: for vapor inlet and outlet. Pressure gages: for recycle flow at heat exchanger inlet and outlet, for condensate pump discharge. Water totalizer: at condensate pump discharge.

11. The condenser shall include the following alarms: high discharge temperature adjustable through a minimum range of 35-60°C (95-140°F), high condensate level, high and low recycle water level.

12. The condenser shall be skid-mounted on two separte skids and shall be easily transportable with a width of 96 inches or less. The condenser shall be capable of placement on rough surfaces.

13. All exposed electrical enclosures will meet the requirements of NEMA 3R or better. All exposed motors shall be totally enclosed, fan cooled (TEFC).

14. All components shall be powered from a single disconnect that accepts 480 volt, three phase power.

15. Control wiring shall be 120 V. A 20-amp ground fault interrupt-protected convenience outlet shall be provided.

16. The control circuitry of the condenser shall be designed to automatically restart when an alarm condition clears or when a power failure is corrected.

17. The condenser shall not exceed a noise level of 80 decibels, A-weighted scale (dBA) at a distance of 1 m.

Vacuum Recovery Blower Specifications

The following are the specifications of the vacuum recovery blower.

1. The blower shall be of the rotary lobe type.

2. The vacuum blower will be capable of applying an absolute pressure ratio of 2:1 between the outlet and inlet. This will allow the blower to exert an inlet vacuum of up to 14.5 in. Hg.

3. The blower will be capable of pumping 450 inlet acfm at 10 in. Hg (300 scfm). To meet this specification, the minimum motor size shall be 20 horsepower.

4. The blower shall include an inlet bleed valve with filter/silencer to allow operator control of applied vacuum. The blower shall include a vacuum relief valve that is set to open in excess of 15 in. Hg.

5. The motor shall include either an electronic variable speed drive or a pulley and sheave drive that allows the adjustment of blower rotational speed.

6. The blower shall include an inlet vacuum gage and an outlet temperature gage.

7. The blower shall have an outlet silencer that is capable of reducing sound pressure levels by at least 20 dBA.

8. All exposed electrical enclosures will meet the requirements of NEMA 3R. All exposed motors shall be TEFC.

9. The blower shall provide a shutdown alarm.

10. The control circuitry of the blower shall be designed to automatically restart when an alarm condition clears or when a power failure is corrected.

11. The blower shall have flanged inlet and outlet connections.

12. The blower shall be skid-mounted and easily transportable. The blower shall be capable of placement on rough and uneven surfaces.

13. The blower shall have a noise quieting enclosure that reduces the sound pressure level to less than 80 dBA at a distance of 1 m.

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VR Blower Discharge Heat Exchanger Specifications

The following are the specifications of the VR blower discharge heat exchanger:

1. The heat exchanger shall be designed for the following inlet conditions: a) air flow of 300 scfm; b) temperature of up to 150°C (300°F); and c) chlorinated solvent vapors at up to 9% by weight of the inlet gas flow.

2. The heat exchanger shall be designed **to** reduce the discharge air temperature to 20°C above ambient or to 20°C, whichever is greater.

3. The heat exchanger will have a differential pressure of less than 10 in. H_2O.

4. The condenser shall be water cooled and will share the recycle flow of the condenser.

5. The heat exchanger will be plate-and-frame type to allow easy cleaning and to allow radionuclide scanning. The plates will be of stainless steel construction.

6. No alarms, meters, or electrical components are required.

7. The heat exchanger shall be skid-mounted and easily transportable. The heat exchanger shall be capable of placement on rough and uneven surfaces.

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Dilution Blower Specifications

The following are the specifications of the dilution blower.

1. The dilution blower shall be of the centrifugal type.

2. The dilution blower will be capable of applying a differential pressure of 10 in. H_2O column between the inlet and the outlet at a flow of up to 2,200 scfm.

3. The minimum motor size shall be 10 horsepower.

4. The electrical enclosure will meet the requirements of NEMA 3R. The motors shall be of TEFC construction.

5. The control circuitry of the blower shall be designed to automatically re-start when a power failure is corrected (maintained switch).

6. The blower shall have 8-in. flanged inlet and outlet connections.

7. The blower shall be skid-mounted and easily transportable. The blower shall be capable of placement on rough and uneven surfaces.

8. The blower shall not exceed 80 dBA at a distance of 1 m.

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Granular Activated Carbon Specifications

The following are the specifications of the **GAC** adsorbers.

1. The activated carbon in the adsorbers shall have the following specifications:
   a. Type: reactivated coconut shell (preferred) or reactivated coal-based
   b. Mesh size: 4 x 10 sieve
   c. Iodine number: 1050 minimum
   d. Butane number: **2**1.6 minimum
   e. Hardness number: 97% minimum
   f. Moisture: **3%** maximum
   g. Bulk density: 0.45-0.55 g/ml
   h. Total ash: 6% maximum

2. The differential pressure drop at 1,000 scfm shall be less than 1 in H_2O column.

3. The vessel interior shall be lined with epoxy resin.

4. The vessel type shall be roll-off bin. The roll-off bin shall be capable of placement on rough and uneven surfaces.

5. The vessels shall have a pressure rating in excess of **6** in. H_2O column.

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On-Line Photoacoustic Monitoring Specifications

The following are the specifications of the on-line monitor to detect vapors emitted from the vapor treatment system stack.

1. Detector – Photoacoustic infra-red spectroscopy analyzer for 5 vapor analytes plus water vapor according to ISO Standard 8158

2. Battery - Rechargeable, external, field replaceable Nickel Metal Hydride or lithium ion battery pack.

3. Display - Large Liquid Crystal Display, manual, darkness and alarm activated

4. Range, Resolution & Response time - (calibration gas)

Range	**Resolution**	**Response time (t90)**
0-50,000 ppm	0.05 ppm	< 40 sec for all 6 analytes

5. Measurement Accuracy: 5 decades range
   ± **2** ppm or 10% of reading < 2,000 ppm
   ± 20% of reading > 2,000 ppm

6. Photoacoustic Detector

7. Calibration - Two point field calibration of zero and standard reference gas for analytes: TCE, cis-dichloroethene, trans-DCE, vinyl chloride, chloroform and carbon tetrachloride

8. Direct readout - Instantaneous, average, short-term exposure limit (STEL) and peak value

9. Intrinsic Safety - Underwriters Laboratory Class 1, Division I, Group A,B,C,D (US & Canada)

10. Alarm Setting - Separate preset alarm limit for high, low, STEL and time-weighted average

11. Operating Mode - Survey or Hygiene, user selectable

12. Audible Alarm

13. Visual Alarm

14. Alarm Mode - Latching or automatic reset

15. Analog Output/Digital output RS-232 and IEEE 488 - Calibrated output, user selectable full-scale range

16. Sampling Pump - Low Flow Alarm

17. Temperature - 0" to 40°C (32" to 113°F)

18. Humidity - 0 % to 95 % relative humidity (non-condensing)

19. Complete with portable Intel Pentium III (or better) portable computer with DVD and CD RD drives, modem, all required software, filters, calibration gases, and startup kit for one year of operation, field maintenance and calibration for the analytes above.

20. Multipoint sampler for up to **6** points for use with above, complete with all required tubing, connectors and appliances.

21. Above suitable equivalents are Innova models 1312 plus 1303 and suitable portable computer as specified complete with noted accessories.

A second model 1312 will also be used **as** a backup and area monitor for the Health and Safety Survey instrument in the work area.

Multi-port Groundwater Monitoring Wells Specifications

The following are the specifications of the groundwater monitoring wells and the multi-port sampling system.

Groundwater Monitoring Wells

1. Concrete – compressive strength concrete, 2,500 psi with 5% air entrainment.

2. Cement Grout – Portland Cement Type I in accordance with ASTM C150.

3. Grout – Grout shall be a low or neutral pH mix. Acceptable mixes are Aqua-Grout/Benseal, PureGold Grout, or a Contractor Subcontract technical Representative (STR)-approved equal. High-density bentonite slurry will be a mixture of powdered bentonite and water. The bentonite will be mixed in a batch plant with paddle vanes and/or recirculating pump, such that lumps are minimized. The slurry will have a minimum of 30% solids by weight. Bentonite slurry will be placed with a side discharge tremie pipe.

4. Bentonite Pellet Seal – Bentonite will be free-flowing, high-swelling, sodium-based, Wyoming-type bentonite. The bentonite will be free of any additives and/or polymers.

5. Filter Sand Pack – Filter pack material will have 100% by weight passing a No. 4 U.S. standard sieve and no more than 5% by weight passing a No. 50 U.S. standard sieve. Sand will be clean quartz of rounded or subrounded particles.

6. Well casings – Well casings will consist of 4-in., Schedule 40 Type 316 stainless steel flush joint well casings. The well casings will be in 2 ft, 4 ft, 5 ft, or 10 ft length options, dependent upon the specified design. The well casing will not extend above 1 ft bgs in order to accommodate the manifold of the sampling system.

7. Well screens – Well screens will consist of 2-ft by 4-in. Schedule 40 Type 316 stainless steel flush joint 0.010-inch slotted screens. Each of the wells will contain seven screened intervals.

8. Surface Vault – Surface completion of each groundwater monitoring well will be flush mounted inside a 12-in. by 12-in. by 25-in. deep vault. *An* acceptable vault is the "PC" Style (Stackable) Service Box Assemblies manufactured by Quazite® Composolite, or a Contractor STR-approved equal. The vault will require a 4 ¾ -in. diameter hole centered in the base of the unit and a heavy-duty lid with gaskets. The unit also will have penta-head tamper resistant bolts.

9. Installation – The installation of the monitoring wells will require a drill rig capable of producing a boring with a 2-in. free annulus (i.e., exclusive of the auger flights) between the well and the hole. For example, if hollow stem augers are chosen as the drilling method, 8 ¼ in. ID augers are required to install 4-in. monitoring wells.

Multi-port Sampling System

1. System – A Solinst™ Multi-port sampling system will be installed inside each of the groundwater monitoring wells to the total depth of the well. The sampling system will rest on the bottom of the well to offset the weight of the system (i.e., the system will not hang in this installation).

2. Support Structure – The Solinst™ sampling system support structure will be constructed of 316 Schedule 10 stainless steel well casing with Schedule 80 stainless steel coupling ends.

3. Packers – The packer bladders will be constructed primarily of Viton.

4. Tubing – All tubing will be constructed of Teflon.

5. Manifold – The manifold at the top of the well will be constructed of stainless steel and will seal the top of the well casing. The manifold will be equipped with a pressure gauge and a pressure release valve.

6. Temperature – All materials will be able to withstand temperatures of 150°C.

All well materials required for each Multi-port Groundwater Monitoring Well are summarized as follows.

Well Components			Sampling System Structure			Sampling System Tubing			Well Annulus	
Length (ft)	Material	Ft bgs	Length (ft)	Material	Ft bgs	Length (ft)	Material	Ft bgs[b]	Material	Ft bgs
2	vault	0-2	0.5	manifold	0.5-1				concrctc	0-3
35	casing	1-36	32	casing	1-32				grout[c]	3-30
			3	packer	32-35				seal[d]	30-32
			2	casing	35-37				sand	32-42
2	screcn	36-38	0.5	port	37-37.5	52	Teflon[a]	+15-37		
22	casing	38-60	1	casing	37.5-38.5					
			3	packer	38.5-41.5					
			15	casing	41.5-56.5				seal[d]	42-51
			3	packer	56.5-59.5				sand	51-89
			1	casing	59.5-60.5					
2	screcn	60-62	0.5	port	60.5-61	75.5	Teflon[a]	+15-60.5		
4	casing	62-66	1	casing	61-62					
			3	packer	62-65					
			2	casing	65-67					
2	screen	66-68	0.5	port	67-67.5	82	Teflon[a]	+15-67		
4	casing	68-72	1	casing	67.5-68.5					
			3	packer	68.5-71.5					
			1	casing	71.5-72.5					
2	screen	72-74	0.5	port	72.5-73	87.5	Teflon[a]	+15-72.5		
6	casing	74-80	3	casing	73-76					
			3	packer	76-79					
			2	casing	79-81					
2	screen	80-82	0.5	port	81-81.5	96	Teflon[a]	+15-81		
4	casing	82-86	1	casing	81.5-82.5					
			3	packer	82.5-85.5					
			1	casing	85.5-86.5					
2	screen	86-88	0.5	port	86.5-87	101.5	Teflon[a]	+15-86.5		
18	casing	88-106	3	casing	87-90				seal[d]	89-98
			3	packer	90-93					
			10	casing	93-103				sand	98-110
			3	packer	103-106					
			1	riser	106-107					
2	screen	106-108	3.5	port	107-107.5	122	Teflon[a]	+15-107		
2	casing	108-110	2.5	riser	107.5-110					
0.3	endcap	110-110.3	3.3	baseplug	110-110.3					

[a] Teflon - two Teflon lines will be connected to each sampling port located inside the Solinst™ sampling system.
[b] ft bgs - the Teflon lines used to collect the sample will extend 15 ft beyond the top of the manifold.
[c] grout - cement grout.
[d] seal - bentonite pellet seal.

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