PNNL-16105

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Technology Survey to Support Revision to the Remedial Investigation/ Feasibility Study Work Plan for the 200-SW-2 Operable Unit at the U.S. Department of Energy's Hanford Site

M. J. Truex
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September 2007

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Summary

A survey of technologies was conducted to provide information for a Data Quality Objectives process being conducted to support revision of the *Remedial Investigation/Feasibility Study Work Plan for the 200-SW-2 Operable Unit*.[1] The technology survey considered remediation and characterization technologies. This effort was conducted to address, in part, comments on the previous version of the Remedial Investigation/Feasibility Study Work Plan for the 200-SW-2 Operable Unit as documented in *200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix, and Supporting Documentation*.[2] By providing a thorough survey of remediation and characterization options, this report is intended to enable the subsequent work plan revision processes to consider the full range of potential alternatives for planning of the Remedial Investigation/Feasibility Study activities.

[1] *200-SW-1 Nonradioactive Landfills and Dumps Group Operable Unit and 200-SW-2 Radioactive Landfills and Dumps Group Operable Unit Remedial Investigation/Feasibility Study Work Plan*. DOE/RL-2004-60, Draft A, U.S. Department of Energy, Richland Operations Office, Richland, Washington.
[2] *200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix, and Supporting Documentation, Final Product*. Correspondence Control No. 0064527, Washington State Department of Ecology and U.S. Department of Energy, Richland Operations Office, Richland, Washington, April 18, 2005.

Acknowledgements

The following table identifies characterization experts that reviewed or provided input to the technology survey.

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1.0 Introduction

1.1 Background

The 200-SW-2 Operable Unit (OU) primarily includes constructed/excavated waste disposal areas (landfills) where a variety of waste types have been disposed since the mid-1940s. Contaminants of potential concern include a wide range of radionuclides, transuranic radionuclides, heavy metals, and organic compounds that were disposed in a variety of physical forms (DOE 2004). Some of the radioactive waste was disposed to subsurface waste containers (e.g., caissons). Records also indicate some disposal of small volumes of containerized liquid waste typically stabilized with sorbent materials. At some 200-SW-2 waste sites, surface water ponding and infiltration have raised concern about potential impact to the waste materials and contaminant distribution.

Overall management of activities related to the 200-SW-2 OU is described in the *200 Areas Remedial/Investigation Feasibility Study Implementation Plan—Environmental Restoration Program* (DOE 1998; hereafter referred to as the “Implementation Plan”). As part of the Remedial Investigation/ Feasibility Study (RI/FS) process, a draft work plan (Draft A) that describes planned RI/FS activities was previously published by DOE (DOE 2004). Subsequently, a series of workshops were convened to discuss the RI/FS Work Plan. The outcomes of those workshops were published in a document entitled *200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix and Supporting Documentation* (Ecology and DOE 2005). That document, usually referred to as the “Collaborative Workshop Report,” provides a description of activities and considerations for revising the RI/FS Work Plan.

1.2 Purpose and Objectives

Technology surveys for remediation approach and characterization technologies relevant to the 200-SW-2 OU were conducted and documented herein to support revision to the RI/FS Work Plan and to address, in part, the comments in the Collaborative Workshop Report. The intent of this technology survey effort is to provide information that will support the RI/FS Work Plan revision process.

1.3 Report Organization

Section 2 of this report describes the methodology for the technology survey. The results of the survey for remediation approaches and associated likely response scenarios are presented in Sections 3 and 4, respectively. The results of the survey for characterization technology are presented in Section 5, and references used in the report are cited in Section 6. Finally, Appendix A includes a description of how the technology survey addresses specific items identified in the Collaborative Workshop Report.

2.0 Technology Survey Methodology

The intent of the technology surveys was to provide information suitable for use in the RI/FS Work Plan revision process. As such, technologies were not screened and retained or rejected. However, information for remediation technologies was gathered to update the description of potential remediation technologies and remediation alternatives identified in the Implementation Plan and support the technology basis for likely response scenarios (as discussed in the Collaborative Workshop Report) that can be considered in the RI/FS Work Plan revision process. Information was also gathered that will be relevant to assessing the suitability of characterization technologies for specific characterization activities. The methodology for gathering and presenting this information is presented below.

2.1 Remediation Technologies

The survey for remediation technologies was based on updating the remediation technology and remediation alternative information described in the Implementation Plan. This update was conducted in the context of providing information to support the remediation alternatives identified in the Implementation Plan and the likely response scenarios presented in the Collaborative Workshop Report. The update also considered ongoing relevant activities for the Hanford 618-10 and 618-11 burial grounds (identified as an action in the Collaborative Workshop Report). The initial listing of remediation technologies in the Implementation Plan was augmented with updated information where available for each technology. New technologies and associated descriptions were also added to the listing. Information for each technology was gathered and assessed with respect to the maturity of the technology and the ability to effectively evaluate the technology in terms of its effectiveness, the ability to implement it, and its cost for the 200-SW-2 OU. Based on this technology maturity evaluation, the need for treatability investigation for each technology is discussed (identified as an action in the Collaborative Workshop Report).

Using the updated technology information, a listing of likely response scenarios for remediation is presented in Section 4. This listing is a compilation of likely response scenarios identified in the Implementation Plan (denoted as remediation alternatives) and the Collaborative Workshop Report. Relevant technologies that support each likely response scenario are defined.

2.2 Characterization Technologies

The survey of characterization technologies was conducted using a broad range of information sources to identify technologies targeted at eight categories of characterization goals relevant to characterization of the 200-SW-2 landfills and the vadose zones beneath the landfills. The technologies identified were then crosschecked against the technology information in the previous 200-SW-2 RI/FS Work Plan (DOE 2004). Categories of characterization goals included in the technology survey were:

- Distribution of Debris and Physical Boundaries of Landfill Trenches (non-intrusive and intrusive)
- Distribution of Heavy Metals/Inorganic Compounds (non-intrusive and intrusive)
- Distribution of Organic Compounds (non-intrusive and intrusive)
- Lateral Distribution of Radionuclides (non-intrusive and intrusive)
- Vertical Distribution of Radionuclides (intrusive only)

- Identification of Transuranic Radionuclides (non-intrusive and intrusive)
- Enabling Technologies: Analytical
- Enabling Technologies: Subsurface Access.

The characterization technology survey considered ongoing, relevant activities for the Hanford 618-10 and 618-11 burial grounds and information from other Hanford projects and DOE sites (identified as an action in the Collaborative Workshop Report). Information presented for each technology includes a discussion of the advantages, disadvantages, limitations, uncertainties, state of development (maturity), and relative cost. Based on this information, the need for treatability investigation is discussed as appropriate (identified as an action in the Collaborative Workshop Report).

3.0 Remediation Technology Survey

Table 3.1 lists general response actions and associated technology type and remediation technologies that were considered in the remediation technology survey. This table lists technologies that were included in Table D-1 of the Implementation Plan, identifies where updated technology information is available, and includes new technologies that were not identified in the Implementation Plan. The first four columns of the table are based on Table D-1 of the Implementation Plan, updated as appropriate with new information, and use the same column headings as in the Implementation Plan except that remediation technology has been used instead of the process option heading that was used in the Implementation Plan. The fifth column is specific to the technology survey and describes the applicability of each technology to the 200-SW-2 OU. Remediation technologies that are applicable only for specialized applications (e.g., *ex situ* treatment of soil contaminated with organic contaminants) are noted.

Some technologies in the survey would likely be applied in conjunction with other technologies. However, development of technology groupings was not part of the scope for the survey.

Table 3.1. Potential Remediation Technologies for the 200-SW-2 OU

General Response Action	Technology Type	Remediation Technology	Contaminants Treated	200-SW-2 Applicability
No Action	No Action	No Action	NA	Yes
Institutional Controls	Land Use Restrictions	Deed Restrictions	NA	Yes
	Access Controls	Signs/Fences	NA	Yes
		Entry Control	NA	Yes
	Monitoring	Monitoring	NA	Yes
Containment	Surface Barriers	Arid Climate Engineered Cap	I, M, R, O	Yes
		Asphalt, Concrete, or Cement Type Cap	I, M, R, O	Yes
		RCRA Cap	I, M, R, O	Yes[(a)]
	Subsurface Barriers	Slurry Walls	I, M, R, O	Yes
		Grout Curtains	I, M, R, O	Yes
		Cryogenic Walls	I, M, R, O	No, unless < 20 years
		Sheet Pile	I, M, R, O	Yes
	Soil Stabilization	Membranes/Sealants/Wind Breaks/Wetting Agents	I, M, R, O	Yes
Removal	Excavation	Conventional	I, M, R, O, T	Yes
		Remote Processes	I, M, R, O, T	Yes
		Stabilization and Retrieval	I, M, R, O, T	Yes
		Soil Vacuum	I, M, R, O	Yes
Disposal	Landfill Disposal	Onsite Landfill	I, M, R, O	Yes
		Offsite Landfill/Repository	I, M, O, R (mixed with T), T	Yes

Table 3.1. (contd.)

General Response Action	Technology Type	Remediation Technology	Contaminants Treated	200-SW-2 Applicability
Ex Situ Treatment (assumes excavation)	Thermal Treatment	Calcination	I, O	Soil, Yes Debris, No
		Thermal Desorption	O	Soil, Yes Debris, No
		Incineration	O	Soil, Yes Debris, No
		Pyrolysis	O	Soil, Yes Debris, No
		Steam Reforming	O	Soil, Yes Debris, No
		Vitrification	I, M, R, O	Yes
		In-Container Vitrification	I, M, R, O	Yes
	Physical/Chemical Treatment	Chemical Leaching	I, M, R, O	Soil, Yes Debris, No
		Dehalonization	O	Soil, Yes Debris, No
		Vapor Extraction	O	Yes
		Soil Washing	I, M, R, O	Soil, Yes Debris, No
		Mechanical Separation	I, M, R, O	Yes
		Solvent Extraction	O	Soil, Yes Debris, No
		Chemical Reduction/Oxidation	I, M, O	Soil, Yes Debris, No
		Solidification/ Stabilization	I, M, R, O	Yes
		Automated segregation based on radioactivity	I, M, R, O, T	Soil, Yes Debris, No
	Biological Treatment	Composting	O	Soil, Yes Debris, No
		Biological Treatment	O	Soil, Yes Debris, No
		Landfarming	O	Soil, Yes Debris, No
		Slurry Phase Bio Treatment	O	Soil, Yes Debris, No
		Phytoremediation	M, R, O	Soil, Yes Debris, No

Table 3.1. (contd.)

General Response Action	Technology Type	Remediation Technology	Contaminants Treated	200-SW-2 Applicability
In Situ Treatment	Thermal Treatment	Vitrification	I, M, R, O	Yes
		Thermally Enhanced SVE	O	Soil, Yes Debris, No
	Chemical/Physical Treatment	Soil Flushing	I, M, R, O	Soil, Yes Debris, No
		Vapor Extraction	O	Soil, Yes Debris, No
		Grout Injection	I, M, R, O	Yes
		Soil Mixing	I, M, R, O	Soil, Yes Debris, No
		Vapor Extraction	O	Soil, Yes Debris, No
		Supersaturated Grouts	I, M, R, O	Soil, Yes Debris, No
		Soil Desiccation	I, M, R, O	Soil, Yes Debris, No
		Electrokinetics	I, M, R	Soil, Yes Debris, No
		Reactive gases (H_2S)	I, M, R, O	Soil, Yes Debris, No
		Nanoparticles	I, M, R, O	Soil, Yes Debris, No
	Biological Treatment	Biodegradation	O	Soil, Yes Debris, No
		Bioventing	O	Soil, Yes Debris, No
		Phytoremediation	M, R, O	Soil, Yes Debris, No
	Natural Attenuation	Monitored Natural Attenuation	I, M, R, O	Yes

Notes:
Process options that are *italicized* are additions to the original listing in Table D-1 of the Implementation Plan (page D-29).
(a) Conventional RCRA caps utilize a clay layer that is prone to desiccation and cracking in semi-arid and arid climates; modified versions of the RCRA caps have been developed and tested for semi-arid and arid site applications.
I = Other inorganics contaminants applicability
M = Heavy metals contaminants applicability
NA = Not applicable
[yellow] = Added technology
R = Radionuclide contaminants applicability
T = Transuranic radionuclides applicability
O = Organic contaminants applicability
[orange] = Specialized application only

Tables 3.2 through 3.8 provide additional information about remediation technologies that are generally applicable to the 200-SW-2 OU landfills. Figure 3.1 illustrates these technologies in relation to the general response actions and technology types listed in Table 3.1. Remediation technologies associated with the no action, institutional controls, and disposal general response actions and natural attenuation are not included in Tables 3.2 through 3.7. However, remediation alternatives incorporating these options are viable for consideration as potential remedial alternatives in the feasibility study for the 200-SW-2 OU. While *ex situ* technologies for treating contaminated media are included, treatment remediation technologies for contaminants already extracted from the media are not specifically included. Table 3.9 contains a listing of technologies that are potentially applicable for specialized applications in the 200-SW-2 OU (e.g., *ex situ* treatment of soil contaminated with organic contaminants).

Table 3.2. Containment Technologies

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Arid Climate Engineered Cap (Hanford Barrier) Hanford Barrier: Multiple-layer (9) surface barrier engineered to prevent water infiltration; plant, animal, and human intrusion; and wind or water erosion for a period of 1,000 years. The Hanford Barrier has a combined layer thickness of 4.5 m (14.7 ft). Previous full-scale tests in the 200 Area have demonstrated effective performance under ambient and extreme climatic conditions (1,000-year precipitation events). Evapotranspiration Barrier: Barrier designs that include evapotranspiration layers have been designed and tested for use in arid climates. This type of barrier has been proposed for the 216-U-8 and 216-U-12 sites at Hanford.	Tested and deployable. Full-scale Hanford Barrier Prototype constructed on the 216-B-57 crib in 200 East Area. Large field-scale testing of Hanford Barrier, ET Barriers, and RCRA Barriers conducted at Hill Air Force Base (Hanford Barrier Program) and Sandia National Laboratory (Alternative Landfill Cover Demo Project).	Effectiveness, ability to implement, and cost all are fully developed.	DOE (1998) DOE (1996)
Asphalt, Concrete, Cement-Type Cap Single-layer cover composed of asphalt or concrete constructed to form a surface barrier between a landfill or buried waste and the surface environment.	Mature technology. May not be durable over periods greater than 100 years in the Hanford climate. Mono-layer polyurea temporary cap planned for demonstration over the T Tank Farm in 200 West Area during FY 2007.	DOE-RL (1996) study suggests questionable effectiveness of monolayer caps. Ability and cost are known.	DOE (1998) DOE (1996) Additional information available on FRTR Version 4.0
RCRA Barrier A multilayered landfill cap consisting of an upper (topsoil) layer, a drainage layer, and a low permeability layer. A site specific Modified RCRA Subtitle C Barrier has been designed for use at Hanford. This specific design is composed of eight layers of durable material with a combined thickness of 1.7 m (5.5 ft). This particular design is intended to provide long-term containment and hydrologic protection for 500 years in the arid Hanford environment. A Modified RCRA Subtitle D Barrier also has been designed for a 100-year protection period.	Mature technology. Tested and deployable.	Effectiveness, ability to implement, and cost are all fully developed.	DOE (1998) DOE (1996) Additional information available on FRTR Version 4.0

Table 3.2. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Slurry Walls Slurry walls are vertical subsurface barriers constructed with a mixture of soil, bentonite and/or cement, and water placed in an excavated trench (some techniques allow in situ mixing of slurry materials and soil as the wall is excavated). Other slurry compositions can be used, such as pozzolan/bentonite, attapulgite, organically modified bentonite, or slurry/geomembrane composite if greater structural strength is required or if chemical incompatibilities exist. Slurry walls are generally placed at depths up to 30 m (100 ft) and are generally 0.6 to 1.2 m (2 to 4 ft) in thickness. Slurry walls can be deployed in conjunction with surface caps for vadose zone containment but are usually deployed to control contaminant transport within shallow groundwater. Slurry wall compositions can also incorporate additives such as calcium hydroxyapatite to reduce the mobility of Tc-99 and other mobile radioactive contaminants.	Mature	Site-specific effectiveness is not fully known. Ability to implement and cost factors are available.	DOE (1998) Additional information available on FRTR Version 4.0
Grout Curtains Grout curtains or walls are formed by injecting a cement grout, under pressure, into the soil directly or with drilling (jet-grouting) at regularly spaced intervals to for a continuous vertical low permeable barrier. New innovative materials may limit contaminant mobility through chemical reaction.	Mature	Site-specific effectiveness is not fully known. Ability to implement and cost factors are available.	DOE (1998) Additional information available on FRTR Version 4.0

Table 3.2. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Cryogenic Walls Frozen soil barrier technology consists of a series of subsurface heat transfer devices, known as thermoprobes, which are installed around a contaminant source and function to freeze the soil pore water. The barrier is maintained for a finite period of time until remediation or removal of the contaminants is complete. The thermoprobes are installed with drilling techniques. Aboveground refrigeration units and interconnecting piping are installed and operated. Insulation and a waterproof membrane are installed at grade to prevent heat gain from the surface and minimize infiltration. Frozen soil barriers offer advantages by being "self-healing" and allowing immobilization within the frozen matrix or containment. However, unlike the grout or cement barriers, frozen barriers do require electric power for the life of the barrier. Therefore, use of these barriers is best restricted to durations of 20 years or less. Demonstration projects have been limited to shallow depths (10 m) and small areas (less than 0.15 acre).	Developmental	Effectiveness not known; concerns over fate/transport of contaminants immobilized in frozen matrix when electrical power ceases and walls are allowed to melt. Ability to implement and cost have been demonstrated but not applied for remediation.	DOE (1999)
Sheet Pile Sheet piling consist of a series of panels with interlocking connections, driven into the ground with impact or vibratory hammers to form a vertical barrier. Sheets can be made of steel, vinyl, plastic, recast concrete, or fiberglass. Large subsurface obstacles such as boulders limit installation. Liquid leakage through joints may be a problem. Depths to 23 m (75 ft) below ground surface may be attained. Large cobles in Hanford sediment may preclude installation.	Mature	Effectiveness not known. Ability to implement and cost factors are known. Previous Hanford Site testing in the 100 Areas had poor results.	EPA (1998) http://www.sheetpile.com/

Table 3.2. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Soil Stabilization Technologies There are numerous surface-applied polymers that can be categorized as short-term fugitive dust control agents to moderate-term surface soil binders (<10 years). These polymers stabilize the soil to differing degrees in terms of physically enclosing or chemically binding a surface layer or discrete volume of soil with associated contaminants. Climatic weathering affects the long-term stability of the binding agent. Organic contaminants are generally not immobilized over longer periods. Several types of stabilizing processes may be considered: mixing with molten bitumen and extrusion; emulsified asphalt mixing; modified sulfur cement mixing; polyethylene extrusion; pozzolan/Portland cement incorporation; soluble phosphate immobilization.	Developing to mature for soil stabilization.	Effectiveness is not fully known. Ability to implement and cost factors are known. Treatability investigation required.	FRTR Version 4.0; *Caltrans Storm Water Quality Handbooks-Construction Site Best Management Practices Manual*

Table 3.3. Removal Technologies

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Conventional Excavation Excavation of buried waste with conventional earthmoving equipment is conducted with backhoes and front-end loaders. Clamshell bucket cranes may be used to remove larger waste debris. Uncontaminated cover material may be stockpiled. Selection of excavation equipment is based on worker safety, production rates, and quantity of overburden. Materials may be roughly characterized and sorted for appropriate follow-up treatment or disposal. Hazardous or radioactive material is either treated (see *ex situ* treatment technologies) or transported to a regulatory-compliant landfill or repository depending on the contaminants.	Mature	Effectiveness, ability to implement, and cost are all fully developed. Has been used at the Hanford Site.	DOE (1998)
Discrete Excavation Excavation of discrete zones within a landfill can be accomplished by isolating the zones with a caisson or sheet pile driven into the trench and then excavation within the isolated area. This technique eliminates the need for side slope, but introduces potential problems and uncertainties with driving the caisson or sheet pile into a waste trench. Shored excavation is routinely used to excavate deep basements. Examples may be seen in most large cities, including Seattle and Bellevue in Washington State; and Vancouver, BC in Canada.	Mature in other industries, not demonstrated for waste trenches.	Effectiveness, ability to implement, and cost are generally known, but would need to be adapted to landfill application.	Shoring Engineers (http://www.shoringengineers.com/) Book: A. Macnab, *Earth Retention Systems Handbook*, McGraw-Hill

Table 3.3. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Remote Processes Where access or safety conditions preclude conventional equipment, robotic or remote-extended reach equipment may be employed to remove subsurface waste. At the Hanford site, remote excavation has been successfully implemented for the F and H fuel storage basins. There are numerous remotely-controlled technologies from other industries and demolition operations that could be applied for trench excavation. Brokk is the dominant turn-key supplier of remote controlled excavators of multiple sizes. However, Bobcat, Caterpillar, and Case equipment have been made remote controlled by National Instruments and several university engineering departments.	Mature	Effectiveness, ability to implement, and cost are all fully developed. Has been used at the Hanford Site.	Brokk excavators (http://www.brokk.com/) Technology fact sheet for the 105-F Fuel Storage Basin
Stabilization and Retrieval This hybrid approach entails application of a chemical binding agent (see *ex situ* solidification /stabilization) during the process of excavation and removing the bound soil or debris mass in encapsulated or bound form. The retrieved material is then treated or disposed. This excavation may facilitate fugitive dust control and minimize release of contaminants to the environment. Potentially, *in situ* vitrification can also be used to stabilize soil and waste and the monolith excavated for disposal at another location.	Developmental/ demonstrated	Effectiveness, ability to implement, and cost are not fully developed. Treatability testing available from 618-10/11 efforts.	Hanford 618-10/11 project
Intact removal of waste containment structures Use of large-scale equipment to encapsulate and remove large intact waste containers. Testing of this approach has been funded through DOE EM-21 technology program in support of remediation design for the 618-10/11 burial grounds at Hanford.	Developmental	Ability to implement not fully known. Effectiveness and cost generally available. Treatability testing from 618-10/11.	Hanford 618-10/11 project

Table 3.3. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Soil Vacuum High vacuum can be employed for soil excavation as has been successfully demonstrated through use of the Guzzler soil vacuum in the 300 Area. Alternately, a wand with a supersonic air stream is delivered through a nozzle under high pressure to break up soil and move soil particles. A secondary air vacuum withdraws loose soil from the excavation to a collection vessel. Suction depths as great as 60 feet below the vacuum equipment have been excavated using Vacmaster equipment. Nominal excavation depths between 35 to 40 feet are routinely obtained using this technology. Actual depths will depend on soil properties. Soil vacuum processes facilitate removal of waste objects with minimal damage.	Mature, use with hazardous and radioactive materials has been demonstrated with the Guzzler unit. Also used for utility line excavation (e.g., "potholing").	Effectiveness, implementability, and cost are all fully developed. Has been used at the Hanford Site.	Guzzler Mfg., Guzzler technology deployment fact sheet (Washington Closure Hanford Technology Application) Soil vacuum manufactures: http://www.vacmasters.com/

Table 3.4. *Ex Situ* Thermal Treatment Technologies (Assumes Prior Excavation)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Vitrification Vitrification, or molten glass, utilizes heat up to 1200°C to melt wastes and form glass or other crystalline solids. The high temperature destroys organic contaminants with minimal byproducts. Inorganic contaminants, including radionuclides, are incorporated in a glass structure that is relatively strong, durable, and resistant to leaching. Process is energy intensive.	Mature	Effectiveness, ability to implement, and cost factors generally known.	DOE (1998) Additional information available on FRTR Version 4.0
In-Container Vitrification Also described as bulk vitrification or GeoMelt process. The process mixes silica-rich contaminated soil with sand and insulation in a large steel box. Two large electrodes heat the mixture to over 1300°C to form, when cooled, a large brick of glass, resembling, but more durable than obsidian. Inorganic contaminants, including radionuclides, are immobilized in the solid; organic contaminants are destroyed by the thermal process. The entire container with glass and electrodes can be disposed in a landfill. Off gases are collected and treated by filtration, scrubbing and thermal treatment. The technology was investigated to immobilize mixed low-activity tank waste at the Hanford Site, and as an option for drummed uranium waste at the 618-4 burial ground.	Demonstrated	Implementability, effectiveness, and cost factors generally known.	CH2M HILL Newsletter: http://www.hanfordcleanup.info/ May 2005 http://www.geomelt.com/ Petersen et al. (2002)

Table 3.5. *Ex Situ* Physical/Chemical Treatment Technologies (Assumes Prior Excavation)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Chemical Leaching Chemical extraction or leaching does not destroy wastes, but is a method of separating hazardous contaminants from soils, sediments, and sludges. The volume of waste requiring subsequent processing is thereby reduced. This technology uses an extracting chemical other than water. The extracting chemical may be a ligand, acid, or solution having a high affinity for the contaminant.	Mature	Effectiveness is not fully known. Ability to implement and cost factors are known.	DOE (1998) Additional information available on FRTR Version 4.0
Soil Washing Contaminants sorbed onto fine soil particles are separated from bulk soil in an aqueous-based system on the basis of particle size. The wash water may be augmented with a basic leaching agent, surfactant, pH adjustment, or chelating agent to help remove organics or heavy metals. This is a media transfer technology: wash water is subsequently treated. Complex waste mixtures (e.g., metals with organics) make formulating washing fluid difficult.	Mature	Effectiveness is not fully known. Implementability and cost factors are known.	DOE (1998) Additional information available in EPA (1997)
Mechanical Separation Physical separation processes are applied to remove and concentrate contaminated concentrates from soil or sediment. Gravity separation is a solid/liquid process, which relies on density differences between phases. Sieving uses different size sieves and screens to concentrate contaminants into smaller volumes using the tendency that most contaminants tend to bind preferentially to soil fines. Magnetic separation is used to extract slightly magnetic radioactive particles (U, Pu) from soil.	Mature, except magnetic separation is developmental.	Effectiveness, ability to implement, and cost are all fully developed.	DOE (1998) Additional information available on FRTR Version 4.0

Table 3.5. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Solidification/Stabilization Contaminants are physically bound or enclosed within a stabilized mass (solidification) or chemical reactions are induced between the stabilizing agent and contaminants to reduce their mobility (stabilization). Multiple processes that employ this technology include bituminization, emulsified asphalt, modified sulfur cement, polyethylene extrusion, pozzolan/Portland cement, sulfide-forming compounds, and soluble phosphates. The target contaminant group is inorganics, including radionuclides. Most solidification/ stabilization processes have limited effectiveness with organic contaminants.	Mature	Effectiveness, ability to implement, and cost are generally known.	DOE (1998) Additional information available on FRTR Version 4.0
Automated Segregation based on Radioactivity Systems have been developed that convey soil past radioactivity sensors. Soil can be segregated based on a set threshold radioactivity.	Demonstrated	Effectiveness, ability to implement, and cost are generally known.	Segmented Gate System (http://www.eberlineservices.com/sgs.htm)

Table 3.6. *In Situ* Thermal Treatment Technologies

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Vitrification Electric current through electrodes in soil melts soil/sediment at extremely high temperatures (1600 to 2000°C) and thereby immobilize most inorganics and destroy organic pollutants by pyrolysis. Inorganic contaminants are incorporated within a vitrified glass and crystalline mass. Off gases may require collection and treatment. Radionuclides and heavy metals are retained within the molten soil. Certain wastes are incompatible. Site-specific treatability investigation is required. Energy cost is high.	Mature	Effectiveness, ability to implement, and cost are generally known.	DOE (1998) http://www.geomelt.com/ Additional information available on FRTR Version 4.0

Table 3.7. *In Situ* Chemical/Physical Treatment Technologies

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Soil Flushing Water or water containing an additive to enhance contaminant solubility is applied to soil. Contaminants are leached into the groundwater, which is then extracted and treated. The target contaminant groups are inorganic materials and radionuclides. Low permeability or heterogeneous soils are difficult to treat. Flushing solutions can reduce effective soil porosity. Potential of washing contaminants beyond the capture zone and introduction of surfactants to the subsurface are areas of concern.	Mature	Effectiveness is not fully known. Ability to implement and cost factors are known.	DOE (1998) Additional information available on FRTR Version 4.0
Grout Injection A cement or binding agent is injected into the subsurface to physically bind or enclose or chemically react with contaminants to reduce mobility. Borehole drilling systems and injector head systems are used to apply the solidification/stabilization agent. Grout injection is effective in reducing mobility of inorganic and radionuclide contaminants where contacted. Not applicable for organic materials. Some applications result in significant volume increases. Certain wastes are incompatible with grout. Confirmatory sampling and application verification difficult. Large debris or stone may inhibit effective application.	Mature. Relevant demonstrations have been conducted at Hanford Site and INL.	Effectiveness is not fully known. Ability to implement and cost factors are known.	DOE (1998) Additional information available on FRTR Version 4.0
Soil Mixing A cement or binding agent is mixed into subsurface soil to physically bind or enclose or chemically react with contaminants to reduce mobility. Auger/caisson systems are used to apply the solidification/stabilization agent. Grout application is effective in reducing mobility of inorganic and radionuclide contaminants where mixing occurs. Not applicable for organic materials. Some applications result in significant volume increases. Certain wastes are incompatible with grout. Confirmatory sampling and application verification difficult. Large debris or cobbles may inhibit effective application.	Mature	Effectiveness is not fully known. Ability to implement and cost factors are known.	DOE (1998) Additional information available on FRTR Version 4.0

Table 3.7. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Supersaturated Grouts Based on grout injection or soil mixing application methodology, grout composed of supersaturated solutions of slightly soluble sulfates or carbonates are used. Such mixtures are formulated with precipitation inhibitors that temporarily allow grout transport into the formation before crystallization occurs to stabilize the contaminant. The result is a gypsum or barium sulfate mineral with very favorable immobilization properties.	Developmental	Effectiveness is not fully known. Ability to implement and cost factors are generally known.	Gerald Ziegenbalg, Technical University Bergakademie Freiberg
Soil Desiccation Drying vadose soils by air injection to completely remove soil moisture removes a transport mechanism for contaminants to move deeper. Multiple wells are used to inject dry air into the subsurface and extract moist air. This method can remove VOCs in a manner similar to soil vapor extraction techniques.	Developmental	Effectiveness and ability to implement are not fully known. Cost factors are generally known.	Geomatrix (2005)
Electrokinetics This technology relies upon application of low-intensity direct current through soil between ceramic electrodes that are divided into a cathode array and an anode array. The current promotes desorption and removal of metals and polar organic contaminants. Targeted contaminants are heavy metals, anions, and polar organics. Electrokinetics is more applicable in low permeability soils that are typically saturated or partially saturated clays and silty-clays. Not effective in dry soils (moisture $<10\%$).	Developmental	Effectiveness, ability to implement, and cost are not fully developed.	FRTR Version 4.0A
Reactive gases (H_2S) Injection of a reactive gas into the subsurface can induce redox reactions with inorganic contaminants and immobilize or decrease the water solubility of the contaminant. Pilot testing of H_2S injection in vadose zone soils have demonstrated 70% reduction of hexavalent chromium to levels below cleanup criteria.	Developmental	Effectiveness is not fully known. Ability to implement and cost factors are known.	PNNL-12121

Table 3.7. (contd)

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Nanoparticles Injection of nanoscale (10-100 nm) particles of a reactive agent (i.e., iron) has been shown to facilitate, in saturated soils, the remediation of chlorinated organic contaminants. This technology may be applicable to vadose soils if application is assisted with gas-phase vacuum or pressure application techniques. This technology is unproven.	Experimental	Effectiveness, ability to implement, and cost are not fully developed.	Conceptual for vadose zone applications

Table 3.8. Natural Attenuation

Technology	Maturity	Status of Effectiveness, Ability to Implement, Cost Information, and Treatability Investigation Needs	Reference
Monitored Natural Attenuation Monitored Natural attenuation is implemented following an Office of Solid Waste and Emergency Response Directive (9200.4-17P). Protocols providing guidance for implementation of MNA for hydrocarbons and chlorinated solvents available from the EPA. Protocols for metals and radionuclides are being developed.	Mature	Effectiveness, ability to implement, and cost are generally known.	DOE (1998) EPA OSWER Directive 9200.4-17P (EPA 1999)

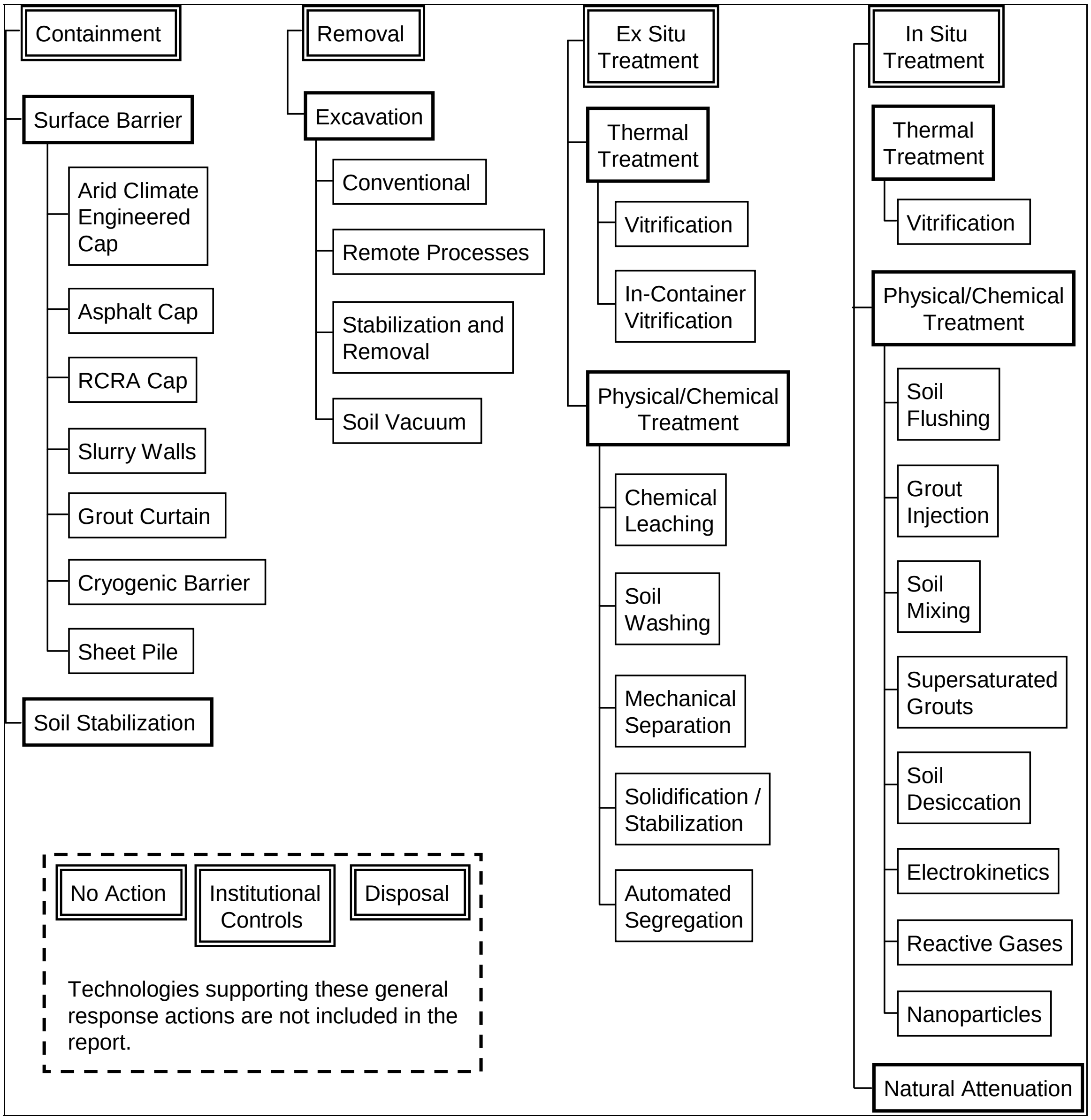

Figure 3.1. Organization of Remediation Technologies Included in Tables 3.2 through 3.7. Remediation technologies for specialized application only are not included in the figure, but are listed in Table 3.8.

Table 3.9. Technologies for Specialized Applications

Technology	Comment
Calcination	*Ex situ* treatment of organic wastes by kiln or furnace.
Thermal Desorption	*Ex situ* volatilization treatment of organic wastes by heating.
Incineration	*Ex situ* combustion of organic wastes at high temperature.
Pyrolysis	*Ex situ* thermal decomposition of organic wastes in the absence of oxygen.
Steam Reforming	*Ex situ* thermal treatment of organic wastes using superheated steam.
Dehalonization	*Ex situ* chemical treatment of halogenated organic waste by decomposition using sodium bicarbonate or alkaline polyethylene glycol.
Vapor Extraction	*Ex situ* volatile chemical removal by induced air flow.
Solvent Extraction	*Ex situ* removal of organic contaminant by contacting waste with organic solvent.
Chemical Reduction/Oxidation	*Ex situ* chemical treatment of waste with chemical oxidizer to immobilize contaminant.
Composting	*Ex situ* biological treatment of organic contaminant with addition of bulking agents.
Biological Treatment	*Ex situ* treatment of organic contaminant using microorganisms, air moisture, and nutrients within a control volume.
Landfarming	*Ex situ* biological treatment of organic contaminant by spreading over soil, adding nutrients, moisture and tilling.
Slurry Phase Bio Treatment	*Ex situ* biological treatment of organic contaminant as a water/solid mixture within a reactor vessel.
Phytoremediation	*Ex situ* biological treatment in an engineered area using plants.
Vapor Extraction	*In situ* physical treatment by application of vacuum to induce volatilization and removal of volatile organic compounds from soil.
Biodegradation	*In situ* biological treatment of organic contaminants by managing and stimulating microbial activity.
Bioventing	*In situ* biological treatment of organic contaminants by inducing air flow to subsurface to promote microbial activity.
Phytoremediation	*In situ* biological treatment of shallow depth soils by cultivating plants to remove, transfer, stabilize, and destroy contaminants.

4.0 Likely Response Scenarios and Supporting Remediation Technologies

The purpose for listing likely response scenarios in this report is to provide information that can be used to guide selection of characterization targets and approaches for the revised RI/FS Work Plan. These likely response scenarios are a starting point for considering potential remediation alternatives. They are defined as a reasonable compilation of the remediation alternatives and likely response scenarios previously identified in the Implementation Plan and the Collaborative Workshop Report with consideration of the updated technology information gathered as part of the technology survey. Formal development and consideration of remediation alternatives for the 200-SW-2 OU is planned as part of subsequent feasibility study efforts.

The following remediation alternatives relevant to the 200-SW-2 OU are included in the Implementation Plan.

- No action.
- Institutional controls.
- Engineered surface barriers with or without vertical barriers. Three conceptual surface barrier designs from DOE-RL (1996) provide a range of protective levels. Feasible vertical barriers include slurry walls and grout curtains. Dynamic compaction is also provided as a foundation improvement technique for surface barriers when needed.
- Excavation and disposal with or without ex situ treatment. Feasible technologies for organic compounds include thermal processing, vapor extraction, and stabilization. Feasible technologies for radionuclides include soil washing, mechanical separation, vitrification, and stabilization. Options for both onsite and offsite disposal are provided.
- Excavation, ex situ treatment, and geologic disposal of soil meeting the definition of TRU waste.
- In situ grouting or stabilization of soil.
- In situ vitrification of soil.
- In situ vapor extraction of VOCs (limited applicability).
- Monitored Natural Attenuation (applicability primarily to the vadose zone beneath the waste sites).

The Collaborative Workshop Report identifies likely response scenarios relevant to the 200-SW-2 OU as follows.

- Excavation, treatment (as necessary), and disposal of waste from within individual landfills.
- Excavation, treatment (as necessary), and disposal of waste from within portions of individual landfills.
- Capping of individual landfills.
- In situ treatment (e.g., vitrification/grouting) of portions of individual landfill.
- Some combination of the above.

Table 4.1 presents the composite listing of likely response scenarios for the 200-SW-2 OU, the potential supporting technologies (described in Tables 3.2 through 3.7), and an indication of whether treatability investigation may be required based on review of the information available and the author's technical judgment. Potential supporting technologies were not evaluated or prioritized for inclusion in Table 4.1. Technologies from Table 3.8 are not included at this level of likely response scenario assessment. The likely response scenarios are categorized as applicable 1) to within a landfill or 2) to the vadose zone beneath a landfill. The no-action alternative, institutional controls, and disposal general response actions are not included in this listing. The composite listing in Table 4.1 is a summary of the likely response scenarios that were selected as useful for consideration in the RI/FS work plan revision. *In situ* contaminant extraction techniques were not considered for application within a landfill because they are not intended for use on debris. Subsequent assessment of likely response scenarios through development of remedial alternatives may include further classification and evaluation into more specific approaches that will be suitable for feasibility evaluation.

Table 4.1. Summary of Likely Response Scenarios and Associated Technologies for Consideration in the 200-SW-2 RI/FS Work Plan Revision

Likely Response Scenario	Supporting Technologies	Treatability Needed?[(a)]
Applicable Within a Landfill		
Surface Barrier	Arid climate engineered cap	No
	Asphalt, concrete, cement-type cap	Yes (E)
	RCRA cap	No
	Slurry walls	No
	Grout curtains	No
	Dynamic compaction[(b)]	No
RTD for all or portions of an individual landfill	Conventional	No
	Remote processes	No
	Stabilization and retrieval	Yes (E, I, C)
	Soil vacuum	No
	Vitrification	No
	In-container vitrification	No
	Soil washing	No
	Mechanical separation	No
	Solidification/stabilization	No
	Automated segregation based on radioactivity	No
In Situ stabilization for all or portions of a landfill	Vitrification	No
	Grout injection	Yes (E)
	Soil mixing	Yes (E)
Applicable in Vadose Zone Beneath a Landfill		
In Situ stabilization	Grout injection	Yes (E)
	Supersaturated grouts	Yes (E)
	Soil desiccation	Yes (E)
	Reactive gases	Yes (E)
	Nanoparticles	Yes (E, I, C)
Contaminant extraction	Soil flushing	Yes (E)
	Electrokinetics	Yes (E)
Natural attenuation	Monitored Natural Attenuation	No

(a) Indicates additional information may be needed to support feasibility assessment in the area of effectiveness (E), ability to implement (I), or cost (C). See Tables 3.2 through 3.7 for additional detail on technology and developmental status. Some technologies not listed as requiring treatability investigation may still need site-specific design information as part of remedial design efforts. Additional comments and considerations prior to near-term treatability investigation are listed in the text below.

(b) Dynamic compaction is an established geotechnical foundation technology. Formal treatability investigation is not warranted. However, soil density testing and geophysical testing during construction can be used to verify compaction during implementation.

Treatability Need Comments and Considerations

The following comments and considerations are presented to support treatability investigation planning. The 200-SW-2 Project RI process will be conducted in a phased manner due to the complexity of the waste in 200 Area landfills and the lack of detailed waste disposal records. Similarly, pre-ROD treatability investigations are proposed in a phased manner as information about the nature and extent of contamination becomes known through the phased RI process. A phased approach to treatability investigations will be useful to ensure investments in technologies focused on site remediation based on the known nature and extent of contamination. Post-ROD treatability investigations may also be required to collect site-specific information in support of the remedial design and remedial action.

Asphalt, concrete, cement-type barriers: DOE/RL studies have questioned the suitability of mono-layer caps in arid environments; may not be durable over periods of more than 100 years. Therefore, mono-layer caps are more of an interim rather than long-term solution. 200-SW-2 investment in treatability investigations for mono-layer caps is not recommended at this time. Information about the performance of mono-layer caps can be obtained through the demonstration of a polyurea/polyurethane cap planned at T Tank Farm during FY 2007.

RCRA Cap: Treatability investigations of conventional RCRA caps in arid environments are not recommended. Alternatives to RCRA caps investigated at Hanford, Sandia National Laboratory, Idaho National Laboratory and elsewhere focused on the compacted clay component in the conventional RCRA cap that is susceptible to failure due to desiccation cracking. Testing has resulted in the Modified RCRA C and D barrier designs for arid sites and other designs that rely on evaporation and plant transpiration (ET barriers) to control near-surface water balance and recharge. Caps constructed over biodegradable or collapsible waste typically require some form of waste compaction/consolidation to minimize future subsidence events and potential impacts on cover integrity and performance.

Stabilization and Retrieval: 200-SW-2 investment in treatability investigations for stabilization and retrieval are not recommended at this time. Relevant information can be obtained through leveraging of the treatability investigations to be performed in support of retrieval, treatment, and disposal at the 618-10 and 618-11 burial grounds. Information about the cost of TRU solid waste retrieval currently underway through the M-91 Project at Hanford and at INL can also be considered.

In Situ Grout Injection/Soil Mixing: A technique has been demonstrated at Hanford and applied at INL involving dynamic compaction and grout injection. This process induces liquefaction in soil/waste matrix resulting in good mixing and effective waste stabilization. Additional assessments for in situ grouting/soil mixing should be deferred until after review of the potential for use of the dynamic compaction/grouting technique at 200-SW-2.

All In Situ Stabilization/Extraction Technologies in Vadose Zone Beneath Landfills: Treatability investigations should be deferred until after completion of remedial investigations to determine the nature and extent of vadose zone contamination. Wastes were mostly dry, with very little free liquids disposed. Although, four landfills flooded in the past due to rapid snow melt. The remedial investigation should provide information about the nature and extent of contamination, if any, as a result of these episodic events. Treatability investigations could be conducted post-ROD (if one of these techniques is selected in the ROD) in support of remedial design.

5.0 Characterization Technology Survey

Characterization technology information was collected and compiled into separate tables for each characterization goal identified as relevant to characterization of the 200-SW-2 landfills and vadose zone beneath the landfills. Categories of characterization goals and the corresponding table containing the technology information are listed in Table 5.1. Figure 5.1 depicts the potential types of characterization technology applications. Tables 5.2 through 5.17 list characterization technology information. In these tables, relative cost is identified as high, medium, or low for the geophysical techniques based on the information presented by Murray et al. (2005).

Table 5.1. Organization of Characterization Technology Information

Category	Application	Table Number
Distribution of debris and identification of landfill trench boundaries	Non-intrusive	5.2
	Intrusive	5.3
Distribution of heavy metals/inorganic compounds	Non-intrusive	5.4
	Intrusive	5.5
Distribution of organic compounds	Non-intrusive	5.6
	Intrusive	5.7
Lateral distribution of radionuclides	Non-intrusive	5.8
	Intrusive	5.9
Vertical distribution of radionuclides	Intrusive	5.10
Identification of transuranic radionuclides	Non-intrusive	5.11
	Intrusive	5.12
Enabling technologies	Analytical – Radionuclides	5.13
	Analytical – TRU	5.14
	Analytical – Heavy Metals	5.15
	Analytical – Organics	5.16
	Subsurface Access	5.17

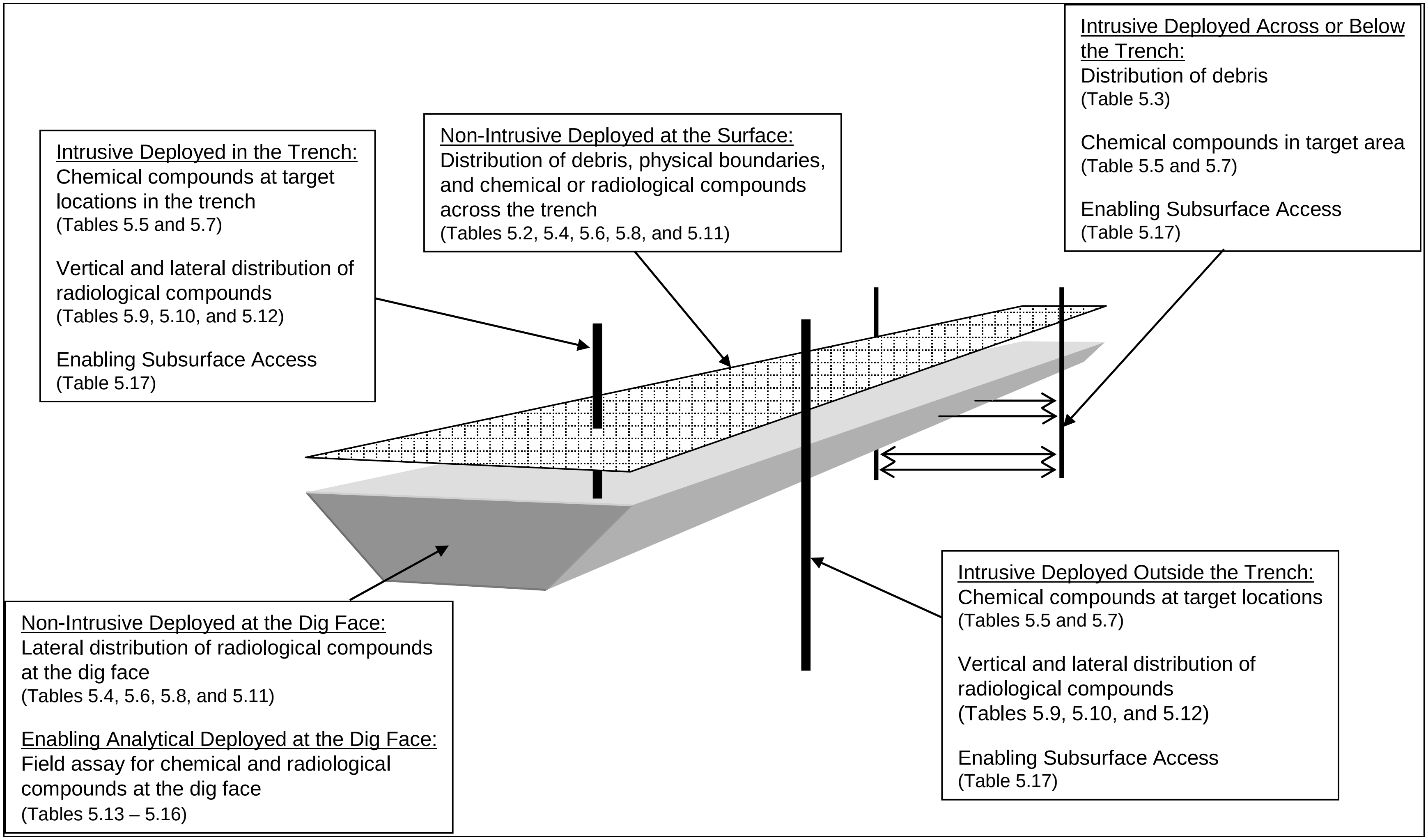

Figure 5.1. Potential Applications for Characterization Technologies Considered in the Technology Survey for the 200-SW-2 Operable Unit

Table 5.2. Distribution of Debris and Identification of Landfill Trench Boundaries: Non-Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex resistivity (CR) [spectral induced polarization (SIP)]	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. CR (sometimes referred to as spectral induced polarization [IP] or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electromagnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (10s of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – DC resistivity – Three-dimensional resistivity imaging (e.g., high resolution resistivity [HRR])	Three-dimensional electrical resistivity imaging (e.g., HRR) is similar to electrical profiling, but uses more advanced modeling/reduction software to process the resistivity data to produce three-dimensional or pseudo- three-dimensional images. Useful for stratigraphy/lithology, geologic structure, and moisture. Steel casing of well/borehole used for intrusive version.	Depth: ~ 60 m. Resolution: sub-meter scale. Need resistivity structure of the stratigraphy. Sensitive to signal interference from power transmission lines. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages. IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally the resistivity decreases as the measurement frequency increases. IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA, (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.		
Electrical – Spontaneous/Self Potential (SP)	Various electrical potentials occur around dissimilar materials in native ground or within the subsurface altered by human actions. Self potential techniques (also called spontaneous potential) measure the electrical potentials between a base electrode and a roving electrode placed in a grid or along a profile line. Interpretation can range from simple qualitative plots of the self-potentials, to complex computer modeling to resolve subtle interactions between temperature, electrochemical reactions, and earth geometry. Useful for metallic constituents.	Requires the installation of one fixed electrode, and an electrode that is moved on a grid over the site of interest. Electrical signals and/or conductors (e.g., metal well casings, underground storage tanks, etc.) can complicate interpretation. Can be slow. Cables must be dragged after the operator. Commercial technology; limited availability; medium cost.	Murray et al. (2005) (PNNL-15305)
Electromagnetic (EM) – Electromagnetic Radiography (EMR)	Variant of ground penetrating radar (GPR) technology that may enable identification and quantification of chemical contaminants (e.g., DNAPLs, organic contaminant plumes).	Best used for chemical contaminants that are unlike the chemicals in the surrounding matrix. Currently limited to depths of 50 ft. Technology is at the field testing stage.	Detection Sciences, Inc., Dan Stanfill III, (978) 369-7999, detsci@tiac.net Dr. Aka Finci, Mission Research Corporation, Albuquerque, NM, (505) 768-7739 Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Frequency domain EM (FDEM) – EM Induction and EM Metal Detectors	Induces subsurface currents and magnetic fields using either two or three rigidly connected coils, usually closely spaced. Primarily used for electromagnetic metal detectors, where the inclusion of a third coil can help distinguish between deep and shallow metallic objects. EM metal detectors have an advantage over magnetometers because they are sensitive to all metals, not just ferrous metals.	Both ferrous and nonferrous metals may be detected. The surface area of the target is more important that its mass. Surveys are rapid and detailed and inexpensive. Depth of investigation is very limited with most instruments. Metallic litter and urban noise can severely disrupt metal detection at some sites.	Murray et al. (2005) (PNNL-15305)

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Frequency domain EM (FDEM) – Horizontal Loop EM (HLEM)	HLEM uses two coils with large separation distances and is primarily used in mining applications for identification of deep conductive metal deposits. The technique provides greater depth penetration, but with low resolution and can only detect relatively large differences in conductivity.	Primarily used in mining applications for deep conductive deposits, does not appear to provide advantages over other EM methods for work at the Hanford Site.	Murray et al. (2005) (PNNL-15305)
Electromagnetic (EM) – Frequency domain EM (FDEM) – Magneto-tellurics (controlled source [CSAMT])	Controlled source AMT (CSAMT) measures the subsurface electric and magnetic fields resulting from input of high frequency, non-polarized, artificially transmitted electromagnetic waves.	Primarily used to detect deep conductive materials.	Murray et al. (2005) (PNNL-15305)
Electromagnetic (EM) – Frequency domain EM (FDEM) – Magneto-tellurics (Natural [AMT])	Natural or audio magneto-tellurics (AMT) determines the subsurface electrical resistivity distribution by measuring time-dependent variations of the earth's subsurface electromagnetic fields resulting from natural variation in the earth's electrical field (i.e., distant lightning). Primarily used to detect deep conductive materials.	Primarily used to detect deep conductive materials, especially metallic deposits, which is not of interest at the Hanford Site. Energy source is naturally occurring thunderstorms. This technique now mostly supplanted by controlled source AMT (CSAMT), especially for shallow applications.	Murray et al. (2005) (PNNL-15305)
Electromagnetic (EM) – Frequency domain EM (FDEM) – Terrain Conductivity (TC)	Terrain conductivity EM systems allow a rapid determination of the average conductivity of the ground because they do not require electrical contact with the ground as is required with DC resistivity techniques. However, the technique provides limited vertical resolution of differences in conductivity and usually is supplemented with a limited number of DC resistivity or TDEM soundings. Measures secondary (induced) magnetic field strength of soil matrix and buried objects. Limited utility for mapping layers with different conductivity (e.g., aquifer/aquitard discrimination or conductive inorganic plumes).	Proven technology, readily available. Can detect fill areas, metal objects. Aboveground metal objects or subsurface conductivity plumes produce interference. Vertical resolution fair. Maximum penetration depth about 30 m (related to coil spacing of instrument). Need to survey using instrument with several coil spacings and loop orientations to get useful vertical sounding data. Presence of high resistivity soils leads to greater noise. Metals may obscure boundary interfaces. Often used as a preliminary survey tool, followed by other EM or resistivity sounding methods. Commercial technology; widely available; low cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-4.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Frequency domain EM (FDEM) – Very Low Frequency (VLF EM)	Inductive technique that relies on very low frequency horizontal EM signals from remote military transmitters as an electrical source. Localized conductors, such as water-filled fractures, cause angular disturbances in this signal which are measured with the VLF-EM instrument. Primarily used for mapping water-bearing fractures or faults in hard bedrock.	New technology for this application. Is dependent on signal reception from U.S. Navy transmitter sites; signal subject to fade-outs; orientation of targets to signal azimuth can affect the response. Primarily used for mapping water-bearing fractures or faults in hard bedrock, which are not major issues at the Hanford Site. Could possibly be used at the Site to identify faults or fractures that allow communication between the unconfined and confined aquifers. Use of this technology is increasing in environmental applications.	Murray et al. (2005) (PNNL-15305) GEM Systems (905) 764-8008 http://www.gemsys.on.ca/ Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Holographic	GPR with advanced digital signal-processing features.	Provides three-dimensional image of target area and is subject to interference from utility lines, piping, and other artifacts. Equipment availability and cost are issues. Good resolution (including vertical resolution). Requires additional data collection and data processing than standard GPR, which increases the cost. Commercial technology; limited availability; medium to high cost.	Terraplus USA: (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Surface	Uses high frequency pulsed electromagnetic waves (generally 10 to 1000 MHz) to acquire subsurface information. Energy is propagated downward into the ground and is reflected back to the surface from boundaries at which there are electrical property contrasts (e.g., from objects or density variations). Uses include identifying DNAPL, LNAPL, hydrocarbons, and conductive inorganic plumes.	Good resolution (including approximately 0.5 m vertical resolution) on both metallic and non-metallic targets. Subject to interference from utility lines, piping, and other artifacts. Proven technology; readily available. Shallow penetration (usually less than 10 m), resolution tens to hundreds of centimeters dependent on geometry, frequency. Three-dimensional imaging requires closely spaced lines (<1 m) and more data processing. Borehole data optional for interpretation and inversion. Large amounts of clay can prevent radar wave penetration; metallic objects can make interpretation difficult; contaminant mapping requires homogeneous subsurface geology and/or prior knowledge of subsurface geology. Cross-well radar, surface and cross-well seismic, VSP, resistivity surveys, and tracer tests are all complementary. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov/ http://costperformance.org/monitoring/#38 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Time Domain EM (TDEM)	TDEM uses two coils, a transmitter, and a receiver coil. The transmitter current, while periodic, is a modified symmetrical square wave. After every second-quarter period the transmitter current is abruptly reduced to zero for one quarter period, whereupon it flows in the opposite direction. The process of abruptly reducing the transmitter current to zero induces a short-duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire. However, because of finite ground resistivity, the amplitude of the current starts to decay immediately. This decaying current similarly induces a voltage pulse that causes more current to flow, but now at a larger distance from the transmitter loop and also at greater depth. This deeper current flow also decays because of the finite resistivity of the ground, inducing even deeper current flow. The amplitude of the current flow as a function of time is measured by measuring its decaying magnetic field using the small multi-turn receiver coil usually located at the center of the transmitter loop. By measuring the voltage in the receiver coil as a function of time measurement is made of the current flow and, thus, also of the electrical resistivity of the earth at successively greater depths. This process forms the basis of central loop resistivity sounding in the time domain. Useful for stratigraphy, aquifer-aquitard delineation, and conductive inorganic plumes. Technology includes the EM61 time domain metal detector.	Proven technology, readily available. Detects metallic targets. Metals may obscure boundary interfaces. Depth of penetration varies with transmitter type, can be several hundred meters, but resolution decreases with depth. Pre-acquisition modeling recommended for design, esp. for resolution of thin layers. Data quality affected by lightning storms, power lines, or nearby metal structures. Better resolution of vertical and horizontal changes in subsurface conductivity than possible with traditional direct current resistivity methods. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-4.pdf http://www.geonics.com/index.html

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Time Domain Reflectometry (TDR)	Measures travel time of electromagnetic wave in coaxial transmission using soil as dielectric	Good penetration and vertical resolution. Susceptible to interference from power lines, nearby metal objects. Very low soil conductivity may decrease effectiveness. Some use for environmental applications.	Yu X and VP Drnevich. 2004. "Soil Water Content and Dry Density by Time Domain Reflectometry." *J. Geotech. Geoenviron. Eng.*, 130(9):922-934. Jones SB, JM Wraith, and D Or. 2002. "Time Domain Reflectometry Measurement Principles and Applications." *Hydrol. Process.*, 16(1):141-153. http://www.cprl.ars.usda.gov/wmru/pdfs/DekkerEvettTDR.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)
Infrared Monitor (IR)	An infrared monitor is a device used to monitor the heat signature of an object and thereby detect buried objects in soil. Thermal anomalies around waste sites are typically associated with buried objects or disturbed soil. Sites as large as 50 acres may be analyzed in one day, yielding estimates of waste pit and trench boundaries and locations of buried objects. Used with other noninvasive geophysical methods, the technique can gather extensive characterization data on a site before drilling and sampling activities begin.	Effectiveness will depend on depth of waste/debris and the nature of the contaminants and co-disposed material.	http://web.em.doe.gov/tie/newtechn.html Weil GJ and RJ Graf. 1994. "Nondestructive Remote Sensing of Hazardous Waste Sites." *Proc. SPIE* 2217:117-126. Havlena JA and RG Knowlton. 1993. "Evaluation of Infrared Thermographic Imaging for Environmental Applications." In *Proc. of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*. San Diego, California. Vol. 1, pp. 129-143.

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Potential Field – Gravity (traditional or microgravity)	The intensity of the force of gravity resulting from a buried mass difference (concentration or void) is superimposed on the larger force of gravity from the total mass of the earth. By very precise measurement of gravity and by careful correction for variations in the larger component due to the whole earth, a gravity survey can sometimes detect natural or manmade voids, variations in the depth to bedrock, and geologic structures of engineering interest. Precise and small-scale studies used for environmental and engineering processes are often referred to as microgravity studies. Not sensitive to changes in sediment properties, stratigraphy, or contaminant distribution.	Not sensitive to changes in sediment properties, stratigraphy, or contaminant distribution. May have limited utility at Hanford Site for mapping depth to basalt, but several sources of noise make this unlikely.	Murray et al. (2005) (PNNL-15305)
Potential Field – Total Magnetic Field	Many rocks and minerals are weakly magnetic or are magnetized by induction in the Earth's field, and cause spatial variations or "anomalies" in the Earth's magnetic field. Man-made objects containing iron or steel (e.g., steel drums) are often highly magnetized and locally can cause large anomalies. Magnetic methods are generally used to map the location and size of ferrous objects.	Proven technology and readily available. Detects ferro-metallic targets or other magnetic-anomaly-producing disturbances. Vertical resolution fair. This technology is commonly used for environmental applications.	EPA (1997a) (EPA/510/B-97/001: http://www.epa.gov/OUST/pubs/esa-ch3.pdf) Petersen et al. (2001) (BHI-01484, Rev. 1)
Seismic – Seismic Reflection – Amplitude Versus Offset (AVO)	Surface reflection methods use surface deployed sources and arrays of geophones; they record the seismic energy reflected from subsurface boundaries. The amount of energy reflected at a boundary depends on the densities and seismic velocities of the materials above and below the boundary. Advanced recording and processing techniques can be used to generate three-dimensional images of stratigraphy as well as both sediment and fluid properties. Useful for stratigraphy, depth to bedrock, buried channels, porosity, permeability, and DNAPL.	Resolution tens to hundreds of centimeters dependent on geometry, frequency. Pre-acquisition modeling required; need large numbers of geophones and complex acquisition equipment. Need subsurface samples for calibration. AVO modeling needed for design of seismic acquisition parameters. Works to depths greater than 125.2 m; acquisition of both P-wave and S-wave can be useful for measuring physical properties. Three-dimensional imaging requires closely spaced lines (~1 m) and more data processing. Large amounts of surface noise are major interference. Can be very sensitive to poor weather. Seismic refraction and reflection provide complementary depth coverage. Stratigraphy: commercial; widely available; high cost. Contamination: emerging; at the research stage; high cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-3.pdf

Table 5.2. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Seismic – Seismic Refraction	Seismic refraction uses surface deployed sources and geophones to record the first arrivals of seismic waves that have been refracted at a subsurface boundary. The technique can be used to map the depth to a subsurface reflector and the velocity within the subsurface layers above and below that reflector. Useful for stratigraphy, depth to bedrock, and sediment properties.	Depths less than 30.5 m; resolution tens to hundreds of centimeters dependent on geometry, frequency. Increase in seismic velocity with depth. Cannot be used in areas where seismic velocity decreases with depth. Seismic refraction and reflection provide complementary depth coverage. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-3.pdf

Table 5.3. Distribution of Debris and Identification of Landfill Trench Boundaries: Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex Resistivity (CR) (Spectral Induced Polarization [SIP])	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. CR (sometimes referred to as spectral IP or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electro-magnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – DC Resistivity – Three-Dimensional Resistivity Imaging (e.g., High-Resolution Resistivity [HRR])	Three-dimensional electrical resistivity imaging (e.g., high resolution resistivity) is similar to electrical profiling, but uses more advanced modeling/reduction software to process the resistivity data to produce three-dimensional or pseudo-three-dimensional images. Useful for stratigraphy/lithology, geologic structure, and moisture. Steel casing of well/borehole used for intrusive version.	Depth ~60 m. Resolution – sub-meter scale. Need resistivity structure of the stratigraphy. Sensitive to signal interference from power transmission lines. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov
Electrical – DC Resistivity – Electrical Impedance Tomography	Electrical impedance tomography is similar to electrical resistivity tomography (ERT) but uses the magnitude and phase of the measured electrical impedance (which under direct current conditions corresponds to resistance). Useful for stratigraphy/lithology, geologic structure, moisture, and conductive plumes.	Relatively poor resolution. Requires the installation of a series of electrodes in at least two boreholes. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. The presence or use of steel cased boreholes adds complication and reduces resolution. Emerging technology at the research stage; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov
Electrical – DC Resistivity – Electrical Resistance (Resistivity) Tomography (ERT)	ERT uses multiple electrically isolated electrodes place in vertical arrays in a cross-borehole geometry, to produce relatively high-quality, high-resolution images. Useful for stratigraphy/lithology, geologic structure, moisture, and conductive plumes.	Resolution – sub-meter scale. Requires the installation of a series of electrodes in at least two boreholes. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov http://costperformance.org/monitoring/

Table 5.3. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Equipotential and Mise-à-la-Masse methods	Equipotential or Mise-à-la-Masse techniques measure the electrical potentials between electrodes (and/or a conductive body in contact with that electrode). When good or poor conductors are imbedded in a homogeneous medium between the electrodes, a distortion of the electrical field occurs. The shape of the equipotential lines typically mimic to some degree, the footprint of the conductive body. Useful for stratigraphy/lithology, geologic structure, moisture, conductive plumes, and organic contaminants.	Good for leak detection Requires the installation of electrodes in favorable locations (e.g., in conductive body, beneath known LNAPL). Electrical signals and/or conductors (e.g., metal well casings, underground storage tanks, etc.) can complicate interpretation. Thin contaminant plumes or very old plumes can be difficult to interpret. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305)
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages. IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally, the resistivity decreases as the measurement frequency increases. IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA, (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.3. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.		
Electrical – Spontaneous/ Self Potential (SP)	Various electrical potentials occur around dissimilar materials in native ground or within the subsurface altered by human actions. Self potential techniques (also called spontaneous potential) measure the electrical potentials between a base electrode and a roving electrode placed in a grid or along a profile line. Interpretation can range from simple qualitative plots of the self-potentials, to complex computer modeling to resolve subtle interactions between temperature, electrochemical reactions and earth geometry. Useful for metallic constituents.	Requires the installation of one fixed electrode, and an electrode that is moved on a grid over the site of interest. Electrical signals and/or conductors (e.g., metal well casings, underground storage tanks, etc.) can complicate interpretation. Can be slow. Cables must be dragged after the operator. Commercial technology; limited availability; medium cost.	Murray et al. (2005) (PNNL-15305)
Electromagneti c (EM) – Cross Borehole Electromagneti c Imaging	EM Imaging is based on the radio imaging method. This continuous wave form technique measures the strength and timing (amplitude and phase) relationship of a transmitted waveform (15 million cycles per second) as the signal travels from borehole-to-borehole or borehole-to-surface. The imaging system consists of a transmitter and receiver, 2 in. in diameter and 6 to 12 ft in length. The transmitter and receiver are placed in separate boreholes and lowered by fiber optic cables, or the transmitter is placed in one borehole and the receiver on the ground surface. The tomographic data is collected in a series of ray path fans (a set of received signals that look like a fan). This is similar to medical tomographic imaging, which shows a two- or three-dimensional image of a body structure constructed by computer from a series of flat cross-sectional images made along a certain axis. The transmitter and receiver are lowered to a station location and a measurement is made. The receiver is moved to the next location (approximately 2.5 to 5 ft apart) and another measurement is made. The receiver is	Cross Borehole Electromagnetic Imaging optimizes sampling, fills in gaps between boreholes, distinguishes between water soluble and organic contamination, minimizes drilling and sampling requirements, and does not require radioactive sources.	http://www.sandia.gov/Subsurface/factshts/ert/cbem.pdf

Table 5.3. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	again moved, and the measurements are made repeatedly until the ray path fan is completed. Transmitter and receiver calibrations are taken at each station (calibration Electromagnetic Imaging System values are used to normalize the data). The resolution (smallest object imaged) is 1/20 of the distance between the transmitter and the receiver. The distribution of electrical conductivity between boreholes can be reconstructed from the repeated and overlapping measurements of amplitude and phase between boreholes. These properties are sensitive to changes in moisture content, permeability, and water chemistry.		
Electromagnetic (EM) – Frequency domain EM (FDEM) – Electrical Offset Logging (EOL)	EOLS is an EM method intended to allow three-dimensional mapping of subsurface electrical conductivity. The method uses a source loop placed at a number of stations on the surface. For each surface station, the resulting electromagnetic field is surveyed using a large number of measurements in a nearby borehole, which must be cased with PVC and not steel. Essentially, uses electromagnetic TC methods in boreholes.	Better resolution than surface TC measurements. Requires cone penetrometer or drilled borehole. Installation of boreholes increases cost over surface techniques, but may provide enhanced vertical resolution. Poor results when technique was applied at the Hanford Site in the 618-4 burial grounds.	Murray et al. (2005) (PNNL-15305) GEHM Environmental (660) 882-3485 http://www.gehm.com/
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Cross-Borehole Radar Tomography	A borehole-deployed radar method using multiple shot and receiver locations in pairs of boreholes, which samples the subsurface over a large array of possible ray paths. Data recorded is direct arrival information rather than reflection data. Tomographic inversion of the amplitude and arrival data can provide detailed estimates of the subsurface properties between the boreholes.	High resolution; can profile specific targets. Requires cone penetrometer truck and small-diameter borehole. Can also work using drilled holes. Well spacing restricted (usually less than 20 m), resolution tens to hundreds of centimeters dependent on geometry, frequency. Metallic casings cannot be used. Need good coupling between casing (e.g., PVC) and subsurface. Often deployed with cross-borehole seismic. Installation of boreholes increases cost over surface techniques, but may give enhanced vertical resolution. Equipment cost and availability are possible issues. Commercial technology; limited availability; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.3. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Seismic – Cross-Borehole Seismic Tomography	Cross-borehole seismic tomography is similar to cross-borehole radar. The method uses multiple source and receiver locations in pairs of boreholes, which samples the subsurface over a large array of possible ray paths. Data recorded is direct arrival information rather than reflection data. Tomographic inversion of the amplitude and arrival data can provide detailed estimates of the subsurface properties between the boreholes. Useful for stratigraphy, geologic heterogeneity, porosity, and permeability.	Well spacing restricted to distances less than 20 to 30 m. Resolution of tens to hundreds of centimeters, dependent on geometry, frequency. Boreholes required. Requires good coupling between boreholes and subsurface; steel-cased boreholes okay. Cross-well radar, surface and cross-well seismic, VSP, resistivity surveys, and tracer tests are all complementary. Emerging technology; deployed; high cost.	Murray et al. (2005) (PNNL-15305)
Seismic – Surface Vertical Seismic Profile (VSP) Tomography	Surface VSP involves the use of a surface seismic source and a string of geophones deployed in a nearby borehole. Primary use of the method is to provide better estimates of vertical variations in seismic velocity with depth. Recent studies suggest integrated use of surface VSP data with surface reflection seismic and cross-borehole tomography. Useful for stratigraphy, geologic heterogeneity, porosity, and permeability.	Used primarily for identification of shallow velocity field at depths less than 20 m. Boreholes required. Requires good coupling between boreholes and subsurface; steel-cased boreholes acceptable. Joint inversion of VSP data performed with surface reflection and/or cross-borehole seismic tomographic data. Emerging technology in the research stage; high cost.	Murray et al. (2005) (PNNL-15305)
Subsurface Access – Direct Push – Geologic and Environmental Probe System (GEOPS)	Multiple-use, low-cost, subsurface probing system. Probe casing is installed to the desired depth using direct push or sonic drill rigs. Once placed in a zone of interest, the probe casing accepts any of several instrument inserts, including lysimeter, tensiometer, and vapor port probes for the unsaturated zone and water sampling and water level measurement of groundwater in the saturated zone. The casing can accept other types of sensors and also provides access for geophysical surveys (e.g., neutron/spectral logging). Metal or clear-wall may be used, the latter of which allows repeated video logging through the walls. Sampling and logging occur at the bottom tip by placing inserts into GEOPS tubing for single or repeated measurements.	Instrument inserts are fully retrievable, allowing use of the appropriate instrument(s) and fast probe change-out/installation. The GEOPS system allows multiple uses, shortens installation schedules, and eliminates generation of secondary waste. Does not require backfill, so the observations are more representative of the formation.	http://www.inl.gov/scienceandtechnology/factsheets/d/geops.pdf Holdren KJ, DL Anderson, BH Becker, NL Hampton, LD Koeppen, SO Magnuson, and AJ Sondrup. 2006. *Remedial Investigation and Baseline Risk Assessment for Operable Unit 7 13/14*. DOE/ID-11241, Idaho National Laboratory, Idaho Falls, Idaho.

Table 5.4. Distribution of Heavy Metals (soil): Non-Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex Resistivity (CR) [Spectral Induced Polarization (SIP)]	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the Earth at low frequencies. CR (sometimes referred to as spectral IP or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electromagnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – DC Resistivity – Three-Dimensional Resistivity Imaging (e.g., High Resolution Resistivity [HRR])	Three dimensional electrical resistivity imaging (e.g., high resolution resistivity) is similar to electrical profiling, but uses more advanced modeling/reduction software to process the resistivity data to produce three-dimensional or pseudo- three-dimensional images. Useful for stratigraphy/lithology, geologic structure, and moisture. Steel casing of well/borehole used for intrusive version.	Depth ~ 60 m. Resolution – sub-meter scale. Need resistivity structure of the stratigraphy. Sensitive to signal interference from power transmission lines. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov
Electrical – Direct Current Resistivity – Traditional Wenner and Schlumberger arrays (Soundings)	Traditional direct current resistivity techniques use surface based (horizontal) arrays of electrodes to apply the current to the ground and to measure the earth voltage. The most commonly used electrode arrangements include the Wenner, Schlumberger, and dipole-dipole arrays. These techniques can be used for both vertical electrical soundings (VES) to determine the depth to geoelectrical horizons, or for electrical profiling to map lateral changes and identify near-vertical features. Useful for moisture and conductive plumes.	Depth - 10s to 100s of meters, resolution - meter scale. Resistivity profile (e.g., soil conductivity samples, CPT-resistivity tip) is required. Interferences may come from conductive materials (e.g., pipelines, etc.) at surface/near surface or electrical powerlines. Direct current resistivity is governed by volume distributions of electrical parameters and therefore is relatively insensitive to small changes contributed by the presence of contaminants. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://www.hydrogeophysics.com http://vadose.pnl.gov

Table 5.4. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages. IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally the resistivity decreases as the measurement frequency increases. IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA, (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.4. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Electromagnetic Radiography (EMR)	Variant of ground penetrating radar (GPR) technology that may enable identification and quantification of chemical contaminants (e.g., DNAPLs, organic contaminant plumes).	Best used for chemical contaminants that are unlike the chemicals in the surrounding matrix. Currently limited to depths of 50 ft. Technology is at the field testing stage.	Detection Sciences, Inc., Dan Stanfill III, 978-369-7999, detsci@tiac.net Dr. Aka Finci, Mission Research Corporation, Albuquerque, NM, 505-768-7739 Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Frequency domain EM (FDEM) – Terrain Conductivity (TC)	Terrain conductivity EM systems allow a rapid determination of the average conductivity of the ground because they do not require electrical contact with the ground as is required with direct current resistivity techniques. However, the technique provides limited vertical resolution of differences in conductivity and usually is supplemented with a limited number of direct current resistivity or TDEM soundings. Measures secondary (induced) magnetic field strength of soil matrix and buried objects. Limited utility for mapping layers with different conductivity (e.g., aquifer/aquitard discrimination or conductive inorganic plumes).	Proven technology, readily available. Can detect fill areas, metal objects. Aboveground metal objects or subsurface conductivity plumes produce interference. Vertical resolution fair. Maximum penetration depth about 30 m (related to coil spacing of instrument). Need to survey using instrument with several coil spacings and loop orientations to get useful vertical sounding data. Presence of high resistivity soils leads to greater noise. Metals may obscure boundary interfaces. Often used as a preliminary survey tool, followed by other EM or resistivity sounding methods. Commercial technology; widely available; low cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-4.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Surface	Uses high frequency pulsed electromagnetic waves (generally 10 to 1000 MHz) to acquire subsurface information. Energy is propagated downward into the ground and is reflected back to the surface from boundaries at which there are electrical property contrasts (e.g., from objects or density variations). Uses include identifying DNAPL, LNAPL, hydrocarbons, conductive inorganic plumes.	Good resolution (including approximately 0.5 m vertical resolution) on both metallic and non-metallic targets. Subject to interference from utility lines, piping, and other artifacts. Proven technology; readily available. Shallow penetration (usually less than 10 m), resolution tens to hundreds of centimeters dependent on geometry, frequency. Three-dimensional imaging requires closely spaced lines (<1 m) and more data processing. Borehole data optional for interpretation and inversion. Large amounts of clay can prevent radar wave penetration; metallic objects can make interpretation difficult; contaminant mapping requires homogeneous subsurface geology and/or prior knowledge of subsurface geology. Cross-well radar, surface and cross-well seismic, VSP, resistivity surveys, and tracer tests are all complementary. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov/ http://costperformance.org/monitoring/#38 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.4. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electromagnetic (EM) – Time Domain EM (TDEM)	TDEM uses two coils, a transmitter, and a receiver coil. The transmitter current, while periodic, is a modified symmetrical square wave. After every second-quarter period the transmitter current is abruptly reduced to zero for one quarter period, whereupon it flows in the opposite direction. The process of abruptly reducing the transmitter current to zero induces a short-duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire. However, because of finite ground resistivity, the amplitude of the current starts to decay immediately. This decaying current similarly induces a voltage pulse that causes more current to flow, but now at a larger distance from the transmitter loop and also at greater depth. This deeper current flow also decays due to finite resistivity of the ground, inducing even deeper current flow and so on. The amplitude of the current flow as a function of time is measured by measuring its decaying magnetic field using the small multi-turn receiver coil usually located at the center of the transmitter loop. By measuring the voltage in the receiver coil as a function of time measurement is made of the current flow and, thus, also of the electrical resistivity of the earth at successively greater depths. This process forms the basis of central loop resistivity sounding in the time domain. Useful for stratigraphy, aquifer-aquitard delineation, and conductive inorganic plumes. Technology includes the EM61 time domain metal detector.	Proven technology, readily available. Detects metallic targets. Metals may obscure boundary interfaces. Depth of penetration varies with transmitter type, can be several hundred meters, but resolution decreases with depth. Pre-acquisition modeling recommended for design, esp. for resolution of thin layers. Data quality affected by lightning storms, power lines, or nearby metal structures. Better resolution of vertical and horizontal changes in subsurface conductivity than possible with traditional DC resistivity methods. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/publications/eng-manuals/em1110-1-1802/c-4.pdf http://www.geonics.com/index.html

Table 5.5. Distribution of Heavy Metals (soil): Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex Resistivity (CR) [Spectral Induced Polarization (SIP)]	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the Earth at low frequencies. CR (sometimes referred to as spectral IP or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electro-magnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – Direct Current Resistivity – Three-Dimensional Resistivity Imaging (e.g., High Resolution Resistivity [HRR])	Three-dimensional electrical resistivity imaging (e.g. high resolution resistivity) is similar to electrical profiling, but uses more advanced modeling/reduction software to process the resistivity data to produce three-dimensional or pseudo-three-dimensional images. Useful for stratigraphy/ lithology, geologic structure, and moisture. Steel casing of well/borehole used for intrusive version.	Depth ~60 m. Resolution – sub-meter scale. Need resistivity structure of the stratigraphy. Sensitive to signal interference from power transmission lines. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov
Electrical – Direct Current Resistivity – Electrical Impedance Tomography	Electrical impedance tomography is similar to ERT but uses the magnitude and phase of the measured electrical impedance (which under direct current conditions corresponds to resistance). Useful for stratigraphy/lithology, geologic structure, moisture, and conductive plumes.	Relatively poor resolution. Requires the installation of a series of electrodes in at least two boreholes. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. The presence or use of steel cased boreholes adds complication and reduces resolution. Emerging technology at the research stage; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov
Electrical – Direct Current Resistivity – Electrical Resistance (Resistivity) Tomography (ERT)	Electrical resistivity tomography (ERT) uses multiple electrically isolated electrodes place in vertical arrays in a cross-borehole geometry, to produce relatively high-quality, high-resolution images. Useful for stratigraphy/lithology, geologic structure, moisture, and conductive plumes.	Resolution – sub-meter scale. Requires the installation of a series of electrodes in at least two boreholes. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. The presence or use of steel cased boreholes adds complication and reduces resolution. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov http://costperformance.org/monitoring/

Table 5.5. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Direct Current Resistivity – Traditional Wenner and Schlumberger arrays (Soundings)	Traditional direct current resistivity techniques use surface based (horizontal) arrays of electrodes to apply the current to the ground and to measure the earth voltage. The most commonly used electrode arrangements include the Wenner, Schlumberger, and dipole-dipole arrays. These techniques can be used for both vertical electrical soundings (VES) to determine the depth to geoelectrical horizons, or for electrical profiling to map lateral changes and identify near-vertical features. Useful for moisture and conductive plumes.	Depth – tens to hundreds of meters. Resolution - meter scale. Resistivity profile (e.g. soil conductivity samples, CPT-resistivity tip) is required. Interferences may come from conductive materials (e.g., pipelines, etc.) at surface/near surface or electrical powerlines. Direct current resistivity is governed by volume distributions of electrical parameters and therefore is relatively insensitive to small changes contributed by the presence of contaminants. Commercial technology; widely available; medium cost.	Murray et al. (2005) (PNNL-15305) http://www.hydrogeophysics.com http://vadose.pnl.gov
Electrical – Equipotential and Mise-à-la-Masse methods	Equipotential or Mise-à-la-Masse techniques measure the electrical potentials between electrodes (and/or a conductive body in contact with that electrode). When good or poor conductors are imbedded in a homo-geneous medium between the electrodes, a distortion of the electrical field occurs. The shape of the equi-potential lines typically mimic to some degree, the footprint of the conductive body. Useful for stratigraphy/lithology, geologic structure, moisture, conductive plumes, and organic contaminants.	Good for leak detection Requires the installation of electrodes in favorable locations (e.g., in conductive body, beneath known LNAPL). Electrical signals and/or conductors (e.g., metal well casings, underground storage tanks, etc.) can complicate interpretation. Thin contaminant plumes or very old plumes can be difficult to interpret. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305)
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages. IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (10s of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.5. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally the resistivity decreases as the measurement frequency increases. IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.		
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Cross-Borehole Radar Tomography	A borehole-deployed radar method using multiple shot and receiver locations in pairs of boreholes, which samples the subsurface over a large array of possible ray paths. Data recorded is direct arrival information rather than reflection data. Tomographic inversion of the amplitude and arrival data can provide detailed estimates of the subsurface properties between the boreholes.	High resolution; can profile specific targets. Requires cone penetrometer truck and small-diameter borehole. Can also work using drilled holes. Well spacing restricted (usually less than 20 m); resolution tens to hundreds of centimeters dependent on geometry, frequency. Metallic casings cannot be used. Need good coupling between casing (e.g., PVC) and subsurface. Often deployed with cross-borehole seismic. Installation of boreholes increases cost over surface techniques, but may give enhanced vertical resolution. Equipment cost and availability are possible issues. Commercial technology; limited availability; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.5. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Sample Collection – Discrete Sampling	Area or object of interest is sampled and the sample is analyzed (with either onsite or offsite facilities/ instruments)	Accurate. Requires physical contact with waste or possible contamination. Transport issues involved if offsite facilities used. This technology is proven and is the baseline predominant method at the Hanford Site. Environmental controls during sampling increase costs.	PNNL (Elwood Lepel, [509] 376-3390), 222-S Laboratory Petersen et al. (2001) (BHI-01484, Rev. 1)
Subsurface Access – Direct Push – Geologic and Environmental Probe System (GEOPS)	Multiple-use, low-cost, subsurface probing system. Probe casing is installed to the desired depth using direct push or sonic drill rigs. Once placed in a zone of interest, the probe casing accepts any of several instrument inserts, including lysimeter, tensiometer, and vapor port probes for the unsaturated zone and water sampling and water level measurement of groundwater in the saturated zone. The casing can accept other types of sensors and also provides access for geophysical surveys (e.g., neutron/spectral logging). Metal or clear-wall may be used, the latter of which allows repeated video logging through the walls. Sampling and logging occur at the bottom tip by placing inserts into GEOPS tubing for single or repeated measurements.	Instrument inserts are fully retrievable, allowing use of the appropriate instrument(s) and fast probe change-out/installation. The GEOPS system allows multiple uses, shortens installation schedules, and eliminates generation of secondary waste. Does not require backfill, so the observations are more representative of the formation.	http://www.inl.gov/sciencean dtechnology/factsheets/d/geo ps.pdf Holdren KJ, DL Anderson, BH Becker, NL Hampton, LD Koeppen, SO Magnuson, and AJ Sondrup. 2006. *Remedial Investigation and Baseline Risk Assessment for Operable Unit 7 13/14*. DOE/ID-11241, Idaho National Laboratory, Idaho Falls, Idaho.
Subsurface Access – Direct Push – Site Characterization and Analysis Penetrometer System (SCAPS)	Mobile, 20-ton platform (hydraulic cone penetrometer truck) and a suite of cost-effective sensing and sampling technologies that rapidly detect, discriminate, and quantify a wide variety of contaminants. SCAPS technologies detect contaminants in both soil and groundwater *in situ* while simultaneously determining subsurface geophysical characteristics. LIBS, XRF, and spectral gamma probe are examples of the instrumentation that can be used with SCAPS.	Demonstration of this technology indicated that it produces screening level data. The technology can provide rapid assessment of the distribution of fluorescent material in the subsurface. The technology may be sensitive to matrix heterogeneity, based on the very small volume sampled.	http://www.erdc.usace.army. mil/pls/erdcpub/WWW_WE LCOME.NAVIGATION_PA GE?tmp_next_page=49777 http://www.cluin.org/downlo ad/toolkit/thirdednew/scaps9 9073.pdf EPA. 1995. *Site Characterization Analysis Penetrometer System (SCAPS): Innovative Technology Evaluation Report*. EPA/540/R-95/520, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research

Table 5.5. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
			Laboratory, Cincinnati, Ohio. Available at: http://www.epa.gov/ORD/SITE/reports/540r95520/540r95520.pdf DOE. 1999. *Innovative Directional and Position Specific Sampling Technique (POLO)*. DOE/EM-0434, Innovative Technology Summary Report 316, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr316.pdf

Table 5.6. Distribution of Organic Contamination (soil): Non-Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex Resistivity (CR) [Spectral Induced Polarization (SIP)]	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the Earth at low frequencies. CR (sometimes referred to as spectral IP or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electro-magnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages. IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally the resistivity decreases as the measurement frequency increases.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (10s of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Terraplus USA (303) 799-4140 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.6. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.		
Electromagnetic (EM) – Electromagnetic Radiography (EMR)	Variant of ground penetrating radar (GPR) technology that may enable identification and quantification of chemical contaminants (e.g., DNAPLs, organic contaminant plumes).	Best used for chemical contaminants that are unlike the chemicals in the surrounding matrix. Currently limited to depths of 50 ft. Technology is at the field testing stage.	Detection Sciences, Inc., Dan Stanfill III, 978-369-7999, detsci@tiac.net Dr. Aka Finci, Mission Research Corporation, Albuquerque, NM, 505-768-7739 Petersen et al. (2001) (BHI-01484, Rev. 1)
Electromagnetic (EM) – Ground Penetrating Radar (GPR) – Surface	Uses high frequency pulsed electromagnetic waves (generally 10 to 1000 MHz) to acquire subsurface information. Energy is propagated downward into the ground and is reflected back to the surface from boundaries at which there are electrical property contrasts (e.g., from objects or density variations). Uses include identifying DNAPL, LNAPL, hydrocarbons, and conductive inorganic plumes.	Good resolution (including approximately 0.5 m vertical resolution) on both metallic and non-metallic targets. Subject to interference from utility lines, piping, and other artifacts. Proven technology; readily available. Shallow penetration (usually less than 10 m), resolution tens to hundreds of cm dependent on geometry, frequency. Three-dimensional imaging requires closely spaced lines (<1 m) and more data processing. Borehole data optional for interpretation and inversion. Large amounts of clay can prevent radar wave penetration; metallic objects can make interpretation difficult; contaminant mapping requires homogeneous subsurface geology and/or prior knowledge of subsurface geology. Cross-well radar, surface and cross-well	Murray et al. (2005) (PNNL-15305) http://vadose.pnl.gov/ http://costperformance.org/monitoring/#38 Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.6. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
		seismic, VSP, resistivity surveys, and tracer tests are all complementary. Commercial technology; widely available; medium cost.	
Seismic – Seismic Reflection – Amplitude Versus Offset (AVO)	Surface reflection methods use surface deployed sources and arrays of geophones; they record the seismic energy reflected from subsurface boundaries. The amount of energy reflected at a boundary depends on the densities and seismic velocities of the materials above and below the boundary. Advanced recording and processing techniques can be used to generate 3-D images of stratigraphy as well as both sediment and fluid properties. Useful for stratigraphy, depth to bedrock, buried channels, porosity, permeability, and DNAPL.	Resolution tens to hundreds of centimeters dependent on geometry, frequency. Pre-acquisition modeling required; need large numbers of geophones and complex acquisition equipment. Need subsurface samples for calibration. AVO modeling needed for design of seismic acquisition parameters. Works to depths greater than 125.2 m; acquisition of both P-wave and S-wave can be useful for measuring physical properties. Three-dimensional imaging requires closely-spaced lines (~1 m) and more data processing. Large amounts of surface noise are major interference. Can be very sensitive to poor weather. Seismic refraction and reflection provide complementary depth coverage. Stratigraphy: Commercial – widely available; High Cost Contamination: Emerging – research; High Cost	Murray et al. (2005) (PNNL-15305) http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-1-1802/c-3.pdf http://www.clu-in.org/conf/tio/geophysical_121201/chp_3.pdf
Soil Gas Sampling – EMFLUX®	The EMFLUX® system is a passive soil gas sampling technology designed for use in shallow deployment to identify and quantify a broad range of VOCs and semivolatile organic compounds (SVOC), including halogenated compounds, petroleum hydrocarbons, polynuclear aromatic hydrocarbons, and other compounds present at depths to more than 200 ft. The EMFLUX® cartridge consists of 100 mg of sorbent sealed in a fine-mesh screen, which is placed in a glass vial; the vial and cartridge make up the EMFLUX® field collector. This assembly is inserted into the soil, but only the cartridge is thermally desorbed and analyzed in the laboratory. The EMFLUX® field collector is installed by creating a 3 to 4-in.-deep pilot hole using a manual hammer and a stake, and inserting the sampler manually. The sampler is then covered to reduce the potential for sorption of airborne contaminants.	Can be used to define relative concentration contours, but not actual subsurface concentrations. Applicable mainly for VOCs/SVOCs. Effectiveness depends upon subsurface lithology (permeability, adsorptive capacity, depth of contamination, preferential paths for gas flow, etc.). Can be non-intrusive (set on the ground surface). Better effectiveness for (minimally) intrusive installation, which requires pushing a 0.5 to 0.75-in. diameter hole into the ground with the adsorbent cartridge either near the ground surface or actually in the subsurface. This technology is commonly used for environmental applications.	Tetra Tech EM, Inc. 1998. *Innovative Technology Verification Report: Soil Gas Sampling Technology, Quadrel Services, Inc. EMFLUX Soil Gas System*. EPA/600/R-98/096, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Las Vegas, Nevada. Available at: http://www.epa.gov/ORD/SITE/reports/600r98096/600r98096.pdf

Table 5.6. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
			Beacon Environmental Services, 800-878-5510, http://www.beacon-usa.com/whybeacon.htm Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.7. Distribution of Organic Contamination (soil): Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Electrical – Complex Resistivity (CR) [Spectral Induced Polarization (SIP)]	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the Earth at low frequencies. CR (sometimes referred to as spectral IP or SIP) is essentially a multi-frequency version of IP where chargeability is estimated by recording the phase difference between transmitted current and measured voltages. Its primary advantage is that it helps to discriminate between certain types of polarizable materials, such as pyrite, chalcopyrite, graphite, clay, and other forms of alteration, and can provide sufficient information to enable the removal of electromagnetic coupling effects. CR is often used in areas where coupling effects distort the results from a conventional IP survey.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (tens of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials is uncertain. Emerging technology; deployed; medium to high cost.	Murray et al. (2005) (PNNL-15305) Guillen and Hertzog (2004) Petersen et al. (2001) (BHI-01484, Rev. 1)
Electrical – Equipotential and Mise-à-la-Masse methods	Equipotential or Mise-à-la-Masse techniques measure the electrical potentials between electrodes (and/or a conductive body in contact with that electrode). When good or poor conductors are imbedded in a homogeneous medium between the electrodes, a distortion of the electrical field occurs. The shape of the equipotential lines typically mimic to some degree, the footprint of the conductive body. Useful for stratigraphy/lithology, geologic structure, moisture, conductive plumes, and organic contaminants.	Good for leak detection Requires the installation of electrodes in favorable locations (e.g., in conductive body, beneath known LNAPL). Electrical signals and/or conductors (e.g., metal well casings, underground storage tanks, etc.) can complicate interpretation. Thin contaminant plumes or very old plumes can be difficult to interpret. Commercial technology; widely available; medium to high cost.	Murray et al. (2005) (PNNL-15305) http://www.clu-in.org/programs/21m2/spotlight/080304.pdf
Electrical – Induced Polarization (IP)	Uses electrodes with time-varying currents and voltages to map the variation of electrical chargeability (dielectric constant) in the earth at low frequencies. IP is observed when a steady current through two electrodes in the earth is shut off; the voltage does not return to zero instantaneously, but decays slowly, indicating that charge has been stored in the rocks. This effect can be measured in either the time domain by observing the rate of decay of voltage or in the frequency domain by measuring phase shifts between sinusoidal currents and voltages.	Evaluation of data dependent on baseline characteristics; minerals in soil may cause interference. Meter scale resolution, but depth somewhat limited (10s of meters). Spacing and depth considerations are important. Low sensitivity to organic contamination. Cross-hole uses electrodes placed in boreholes on the order of about 20 m apart. Electrical signals associated with other electrical geophysical methods, generators, utilities, etc. Most promising for detecting clay-organic reactions. Applicability to other contaminants and geologic materials	Murray et al. (2005) (PNNL-15305) Terraplus USA (303) 799-4140, www.terraplus.com Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	IP is a measure of a delayed voltage response in earth materials. The IP effect is caused by a current-induced electron transfer reaction between electrolyte ions and metallic-luster minerals. IP is a low frequency measurement of the electrical energy storage capacity of the earth. By passing an induced current into the ground and measuring the change in voltage with respect to time, or changes in phase at a given frequency with respect to a reference phase, the IP effect can be determined. To produce an IP effect, fluid-filled pores must be present, because the rock matrix is basically an insulator. The IP effect becomes evident when these pore spaces are in contact with metallic-luster minerals, graphite, clays or other alteration products. IP effects make the apparent resistivity of the host rock change with frequency—generally the resistivity decreases as the measurement frequency increases. IP work is performed in the time or frequency domain. In the time domain, the polarization effect is determined by measuring the rate of decay of the voltage after the current has been turned off. This involves determining of the area beneath the decay curve between two time intervals, a parameter known as chargeability. For the standard "Newmont" chargeability, the area beneath the decay curve from 0.45 to 1.1 sec is used. In the old frequency domain measurements, the ratio of the resistivity at two frequencies was obtained, yielding the percent frequency effect (PFE). This technique is noise-prone and is very seldom used. The standard frequency domain measurement used today is based on the measured phase shift between the transmitted signal and the received signal.	is uncertain. Emerging technology; deployed; medium to high cost.	
NAPL Characterization – Laser-Induced Fluorescence (LIF) Probe	Sensor for delineating contaminants that fluoresce. Although DNAPLs do not fluoresce at standard excitation wavelengths, organic matter (e.g., oils) that are usually found with solvents (DNAPLs) do fluoresce, and their fluorescence is used to infer the presence of DNAPLs. LIF systems, available from commercial and government cone penetrometer drilling operators, are best for source zone	Indirect evidence based on fluorescence of commingled materials (naturally occurring organics, multi-ring fuel compounds, etc.). Rapid measurement in real time. Depth discreet signals. Can be coupled with lithologic sensors for correlation. Good screening method with high resolution. Can use several off-the-shelf energy sources. Limited by lithology. False negatives and positives possible.	http://www.p2pays.org/ref/14/13973.htm http://clu-in.org/download/char/GWMR_Fall_109-123.pdf

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	characterization since they are sensitive to only very high DNAPL concentrations.	Commingled fluorophores required. Semi-quantitative, so requires confirmation samples. Not yet fully mature. Pressure or heat front may force droplets away from window.	
NAPL Characterization – Membrane Interface Probe System (MIPS)	Quick, depth-discrete detection and quantification of high concentration, dissolved volatile organic compounds (VOCs). Deployed with a cone penetrometer, MIPS incorporates a heated, semipermeable membrane into the cone penetrometer tip. VOCs diffuse through the membrane into a carrier gas, which circulates through tubing to analytical instruments at the surface. Once the MIPS probe is retracted, the hole can be grouted through the cone penetrometer rod itself. Although MIPS's detection limit is not as low as that with baseline drilling, sampling, and laboratory analysis, it offers significant time and cost savings when data quality objectives can be met.	When operating with a noncontinuous configuration, user required to determine appropriate depths while "on the fly," which can be difficult in zones of "ganglia." Bulk fluids cannot travel across membrane. Semi-quantitative. Clogging can occur. Limited by lithology. Heat front or pressure front may inhibit membrane contact with contaminant.	http://www.p2pays.org/ref/14/13973.htm GeoProbe Systems http://clu-in.org/download/char/GWMR_Fall_109-123.pdf
NAPL Characterization – Partitioning Interwell Tracer Test (PITT)	Technology is based on differing transport properties (partitioning) of several tracers. A forced flow field is established to transport tracers through a specific volume of aquifer investigated. A suite of tracers is introduced to the subsurface within a target DNAPL zone and recovered from a different location, typically using injection and recovery wells. At least one of the tracers is nonreactive (e.g., nonpartitioning and nonabsorbing) with respect to the DNAPL organic liquid, while the other tracers partition, to various levels, into the organic liquid. The organic liquids detain the partitioning tracers and retard their migration, thereby leading to differential recovery times corresponding to the strength of partitioning and amount of DNAPL encountered.	Widely deployed in the oil filed business; limited use in the environmental business; requires an atypically high level of expertise to be successful. Tracer migration may follow different pathway than DNAPL. Split flow paths and meandering can lead to inaccurate measurements. In organic rich soils, may have partitioning into organics other than DNAPL. Inadequate tracer detection limits may lead to underestimation of NAPL saturations, especially in low permeability layers. Tracers may not partition out of solution in low permeability soils that inhibit ground water flow. Porous-media heterogeneity and variable DNAPL saturation can decrease accuracy. An inferential volume integrating estimate.	http://clu-in.org/download/char/GWMR_Fall_109-123.pdf

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
NAPL Characterization – Precision Injection/ Extraction (PIX) Probe	Delivers small amounts of alcohol to the subsurface to solubilize any DNAPL present. The two-step process consists of an injection/extraction of water followed by an injection/extraction of alcohol and a tracer. The presence of a DNAPL source is indicated by a dramatic increase in DNAPL concentration in the extraction from the second step, which contains any DNAPL source freed from pore spaces by the alcohol. The tracer verifies that all injected fluids have been removed.	Produces direct evidence of NAPL. Difficult to ensure direct contact between co-solvent and DNAPL. Density differences between co-solvent and DNAPL could pose challenges. Best-guess approach for sampling location/depth. Requires relatively long sampling times (approximately two hours or more per sample).	http://www.p2pays.org/ref/14/13973.htm http://clu-in.org/download/char/GWMR_Fall_109-123.pdf
NAPL Characterization – Radon Flux Rates	Radon-222 is a naturally occurring, chemically inert radioactive gas resulting from the decay of uranium-238 and is often present as a dissolved gas in subsurface fluids. Radon-222 has a strong preferential affinity to organic fluids versus water. By observing a relative deficit in the aqueous radon-222 concentration, one can surmise that partitioning into a NAPL phase has occurred. The radon-222 concentration within a NAPL-contaminated zone decreases compared to a background value as the NAPL saturation increases. As residual NAPL saturation increases, radon-222 concentration in the ground water adjacent to the NAPL will greatly decrease relative to the background radon-222 concentrations.	Logistically difficult. Lack of reliable sampling methodology. Specialized sampling and analytical procedures required. Site-specific NAPL to water radon-222 partition coefficients difficult to obtain. Best-guess approach for sampling location/depth. Areas displaying highly variable background radon concentrating may prove challenging. Geologic factors may lead to low correlation between radon concentration and NAPL presence.	http://clu-in.org/download/char/GWMR_Fall_109-123.pdf
NAPL Characterization – Ribbon NAPL Sampler (RNS)	The sampler consists of a dye-impregnated ribbon inside a reusable inflatable liner. When deployed into an existing borehole, the sampler is turned inside out and inflated so that the ribbon maintains contact with the borehole walls. The sampler indicates the presence of NAPLs by turning red at those depths along the borehole length where NAPLs reside. The sampler is easily deployed into open boreholes. Using the sampler to characterize in collapsing sediments or the saturated zone requires a more complex installation accomplished with a cone penetrometer or other drilling techniques.	Ribbon NAPL sampler; DOE developed; functions via hydrophobic ribbon deployed within a FLUTe membrane system; tested at Savannah River Laboratory and PNNL. Direct evidence. Can be deployed using CPT. Good screening method with good resolution. Qualitative. Requires confirmation sampling. May be difficult to apply in consolidated materials.	http://www.p2pays.org/ref/14/13973.htm Flexible Liner Underground Technologies (FLUTe), Ltd. of Santa Fe, New Mexico http://clu-in.org/download/char/GWMR_Fall_109-123.pdf

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Sample Collection – Discrete Sampling	Area or object of interest is sampled and the sample is analyzed (with either onsite or offsite facilities/ instruments)	Accurate. Requires physical contact with waste or possible contamination. Transport issues involved if offsite facilities used. This technology is commonly used for environmental applications. Environmental controls during sampling increase costs.	PNNL (Elwood Lepel, 509-376-3390), 222S Laboratory Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – Active Sample Collection and Analysis	Involves installing a probe (i.e., direct push point) into the ground, withdrawing several inches, and then pumping soil gases from the subsurface into a sample container (e.g., evacuated canister, tube, vial glass bulb, gas sample bag, syringe) or through a sorbent medium. Typically, active soil gas systems require the removal of several hundreds of milliliters of soil gas during line purging and sample collection, which may lead to the lack of correlation between these measurements and collected soil samples. Newer "micro-purge" systems may be suitable for collecting very small quantities of gas (several milliliters). Thermally assisted vapor extraction may be an enhancement useful for volatizing heavy organics that may go otherwise unnoticed.	Most effective for detecting compounds with low molecular weights, high vapor pressures, and low aqueous solubilities. Degradation processes (e.g., oxidation or reduction) can eliminate or transform contaminants in the soil atmosphere. The susceptibility of a contaminant to degradation is influenced by such factors as soil moisture content, pH, redox potential, and the presence of microorganisms that can degrade the compound. Other site-specific characteristics affecting results are soil type, air-filled porosity, depth to the source, barriers to vapor transport, and hydrogeology.	http://www.epa.gov/etv/pdfs/testplan/01_tp_soilgastech.pdf Wolfe WJ and SD Williams. 2002. "Soil Gas Screening for Chlorinated Solvents at Three Contaminated Karst Sites in Tennessee." *Ground Water Monitoring and Remediation*, 22(4):91-99. http://www.dtsc.ca.gov/LawsRegsPolicies/Policies/SiteCleanup/upload/SMBR_ADV_activesoilgasinvst.pdf
Soil Gas Sampling – EMFLUX®	The EMFLUX® system is a passive soil gas sampling technology designed for use in shallow deployment to identify and quantify a broad range of VOCs and semivolatile organic compounds (SVOC), including halogenated compounds, petroleum hydrocarbons, polynuclear aromatic hydrocarbons, and other compounds present at depths to more than 200 ft. The EMFLUX® cartridge consists of 100 mg of sorbent sealed in a fine-mesh screen, which is placed in a glass vial; the vial and cartridge make up the EMFLUX® field collector. This assembly is inserted into the soil, but only the cartridge is thermally desorbed and analyzed in the laboratory. The EMFLUX® field collector is installed by creating a 3 to 4-in. deep pilot hole using a manual hammer and a stake, and inserting the sampler manually. The sampler is then covered to reduce the potential for sorption of airborne contaminants.	Can be used to define relative concentration contours, but not actual subsurface concentrations. Applicable mainly for VOCs/SVOCs. Effectiveness depends upon subsurface lithology (permeability, adsorptive capacity, depth of contamination, preferential paths for gas flow, etc.). Can be non-intrusive (set on the ground surface). Better effectiveness for (minimally) intrusive installation, which requires pushing a 0.5 to 0.75-in. diameter hole into the ground with the adsorbent cartridge either near the ground surface or actually in the subsurface. This technology is commonly used for environmental applications.	Tetra Tech EM, Inc. 1998. *Innovative Technology Verification Report: Soil Gas Sampling Technology, Quadrel Services, Inc. EMFLUX Soil Gas System*. EPA/600/R-98/096, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Las Vegas, Nevada. Available at: http://www.epa.gov/ORD/SITE/reports/600r98096/600r98096.pdf Beacon Environmental Services, (800) 878-5510

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
			http://www.beacon-usa.com/whybeacon.htm Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – GORE™ Module	Patented passive diffusion sampler (formerly known as the GORE-SORBER® Module) for sampling air, soil gas, and water. The module is constructed of a GORE-TEX® membrane tube, a chemically-inert, waterproof, yet vapor-permeable membrane, which houses engineered sorbents. Target compounds present in air or soil gas, migrate unimpeded through the tube to the sorbents. When placed in water, dissolved compounds partition to vapor across the membrane and are captured by the sorbent.	Field screening technique that provides an estimate of the actual concentration of contaminants in soil gas. Installation is straightforward and quick. The modules must be left in place for a specified amount of time (e.g., a 10 day time was used in the EPA demonstration). May have problems at higher contaminant concentrations because of sorbent saturation.	http://www.gore.com/en_xx/products/geochemical/environmental/index.html http://www.gore.com/en_xx/products/geochemical/environmental/surveys_environmental_modules.html Tetra Tech EM, Inc. 1998. *Innovative Technology Verification Report: Soil Gas Sampling Technology, W. L. Gore & Associates, Inc. GORE-SORBER Screening Survey*. EPA/600/R-98/095, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Las Vegas, Nevada. Available at: http://www.epa.gov/ORD/SITE/reports/600r98095/600r98095.pdf
Subsurface Access – Direct Push – Geologic and Environmental Probe System (GEOPS)	Multiple-use, low-cost, subsurface probing system. Probe casing is installed to the desired depth using direct push or sonic drill rigs. Once placed in a zone of interest, the probe casing accepts any of several instrument inserts, including lysimeter, tensiometer, and vapor port probes for the unsaturated zone and water sampling and water level measurement of groundwater in the saturated zone. The casing can accept other types of sensors and also provides access for geophysical surveys (e.g., neutron/spectral	Instrument inserts are fully retrievable, allowing use of the appropriate instrument(s) and fast probe change-out/installation. The GEOPS system allows multiple uses, shortens installation schedules, and eliminates generation of secondary waste. Does not require backfill, so the observations are more representative of the formation.	http://www.inl.gov/scienceandtechnology/factsheets/d/geops.pdf Holdren KJ, DL Anderson, BH Becker, NL Hampton, LD Koeppen, SO Magnuson, and AJ Sondrup. 2006. *Remedial Investigation and Baseline Risk Assessment for*

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	logging). Metal or clear-wall may be used, the latter of which allows repeated video logging through the walls. Sampling and logging occur at the bottom tip by placing inserts into GEOPS tubing for single or repeated measurements.		*Operable Unit 7 13/14*. DOE/ID-11241, Idaho National Laboratory, Idaho Falls, Idaho.
Subsurface Access – Direct Push – Rapid Optical Screening Tool (ROST™)	ROST™ is a laser-induced fluorescence sensor deployed by Cone Penetration Testing (CPT) equipment that characterizes stratigraphy and petroleum hydrocarbons in soils. This process is accomplished continuously, in real-time and without collecting samples.	Demonstration of this technology indicated that it produces screening level data. The technology can provide rapid assessment of the distribution of fluorescent material in the subsurface. The technology may be sensitive to matrix heterogeneity, based on the very small volume sampled.	http://www.geo.fugro.com/services/Geosciences/ROST.asp EPA. 1995. *Rapid Optical ScreenTool (ROST): Innovative Technology Evaluation Report*. EPA/540/R-95/519, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. Available at: http://www.epa.gov/ORD/SITE/reports/540r95519/540r95519.pdf
Subsurface Access – Direct Push – Site Characterization and Analysis Penetrometer System (SCAPS)	Mobile, 20-ton platform (hydraulic cone penetrometer truck) and a suite of cost-effective sensing and sampling technologies that rapidly detect, discriminate, and quantify a wide variety of contaminants. SCAPS technologies detect contaminants in both soil and groundwater *in situ* while simultaneously determining subsurface geophysical characteristics. LIBS, XRF, and spectral gamma probe are examples of the instrumentation that can be used with SCAPS.	Demonstration of this technology indicated that it produces screening level data. The technology can provide rapid assessment of the distribution of fluorescent material in the subsurface. The technology may be sensitive to matrix heterogeneity, based on the very small volume sampled.	http://www.erdc.usace.army.mil/pls/erdcpub/WWW_WELCOME.NAVIGATION_PAGE?tmp_next_page=49777 http://www.cluin.org/download/toolkit/thirdednew/scaps99073.pdf EPA. 1995. *Site Characterization Analysis Penetrometer System (SCAPS): Innovative Technology Evaluation Report*. EPA/540/R-95/520, U.S. Environmental Protection Agency, Office of

Table 5.7. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
			Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. Available at: http://www.epa.gov/ORD/SITE/reports/540r95520/540r95520.pdf DOE. 1999. *Innovative Directional and Position Specific Sampling Technique (POLO)*. DOE/EM-0434, Innovative Technology Summary Report 316, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr316.pdf

Table 5.8. Lateral Distribution of Radioactivity: Non-Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Global Positioning Radiometric Scanner	Utilizes a detection system, a portable computer, a differential global positioning system (d-gps), and a four-wheel drive vehicle. Once the survey data has been collected, a software program called GeoSoft generates a graphical representation of the radiological contamination extent.	Measurements are collected at a height of 3 ft and an optimal speed of 5 mph. This technology is only applicable to gamma-emitting radionuclides. Weather and soil conditions could affect the measurements and the decontamination requirements. Benefits expected from using GPRS include reduced labor hours associated with performing the survey, increased number of survey data points, real time, *in situ* radiological measurements, and more accurate and reproducible survey results.	DOE. 2001. *Global Positioning Radiometric Scanner System*. DOE/EM-0541, Innovative Technology Summary Report 2954, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr2954.pdf http://costperformance.org/monitoring/pdf/gprs_2.pdf
In Situ Object Counting System (ISOCS)	Uses a cryogenically cooled high purity germanium crystal as the detector for high resolution and high efficiency. This gamma-ray spectroscopy system identifies radioactive isotopes and provides real-time assays of the radioactive contents of containers, surfaces, and samples. The system provides traditional spectra of counts as a function of gamma energy, which are then converted to radionuclide concentration using a proprietary software system. The entire system is mounted on a portable cart, which allows rotation of the detector about a horizontal axis. The ISOCS does not produce an image.	May detect surface expression of buried source, but unlikely to detect radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft. Has been deployed at F&H reactor fuel storage basins for identification of fuel elements. Some use for environmental applications.	Canberra (www.canberra.com) http://www.canberra.com/Products/709.asp Petersen et al. (2001) (BHI-01484, Rev. 1)
Large Area Plastic Scintillation (LAPS) Detector	The LAPS detector is composed of a 1.5-in.-thick by 3-in.-wide by 33-in.-long plastic scintillator detector that has been designed to detect greater than 300 kiloelectron volt (keV) beta particles and greater than 40 keV gamma photons. The HHD 440A hand-held detector provides high voltage to the detector, data display, and data communication to a laptop computer. A Motorola Global Positioning System (GPS) provides automatic measurement and recording of positional data for the mobile unit. The laptop computer serves as a data logger for both the detector count rate and the GPS positional data. A fixed-base Motorola GPS operates simultaneously with the mobile	This technology has been successfully demonstrated under the ESTCP program, including sites at Kirtland AFB and at Sandia National Laboratory.	DoD. 2000. *ESTCP Cost and Performance Report: In-Situ Radiation Detection Demonstration*. CU-9915, U.S. Department of Defense, Environmental Security Technology Certification Program, Arlington, Virginia.

Table 5.8. (contd)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	unit. GPS data collected from the base unit provides time-referenced correction factors for post-processing of field survey data having 1-m positional accuracy. A strap-type mounting device facilitates mounting the detector on a variety of survey platforms (e.g., 4x4 vehicle, all terrain vehicle, backpacks, etc.). Survey speeds are dictated by the terrain and the equipment used to transport the detector. Under ideal conditions up to 25 acres per day can be surveyed. Nominally between 12 and 25 acres is routinely surveyed. Uses existing, proven radiation survey technology (from IT Corporation, now Shaw Environmental) and a computer model providing radionuclide specific calibration factors (from Sandia National Laboratory).		
Mobile Surface Contamination Monitor (MSCM)	Consists of large area plastic scintillation detectors interfaced with a National Nuclear System-10 controller recording background reference detector counts per second. The MSCM-II collects data points (e.g., radiological information and physical coordinates from the on-board GPS receiver) once per second for acquisition by the on-board computer system.	Has been deployed at the Hanford Site in the past. It is unclear who currently is the custodian of this technology, which was originally developed by Westinghouse Hanford Company.	http://www.osti.gov/energycitations/servlets/purl/10161431-Smu2JI/native/10161431.pdf
Neutron Detection – Directional Neutron Detector	Collimates neutrons for detection of a source in a targeted area.	May detect surface expression of buried source, but unlikely to detect transuranic radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft. Is in the testing stage for environmental applications.	PNNL (David Stromswold, [509] 372-2626) Peurrung AJ, DC Stromswold, RR Hansen, PL Reeder, and DS Barnett. 1999. *Long-Range Neutron Detection*. PNNL-13044, Pacific Northwest National Laboratory, Richland, Washington. http://www.lanl.gov/orgs/p/pdfs/pr/PR94.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.9. Lateral Distribution of Radioactivity: Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Sample Collection – Discrete Sampling	Area or object of interest is sampled and the sample is analyzed (with either onsite or offsite facilities/instruments).	Accurate. Requires physical contact with waste or possible contamination. Transport issues involved if offsite facilities used. This technology is commonly used for environmental applications. Environmental controls during sampling increase costs.	PNNL (Elwood Lepel, [509] 376-3390), 222S Laboratory Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – Helium-3 Soil Gas Probes	Soil gas probes measure helium-3 (first daughter product of tritium decay) to determine tritium concentration/location.	Used to characterize tritium in groundwater or vadose zone; probes need to be installed 5 to 15 ft. into the soil. Some use for environmental applications.	PNNL (Evan Dresel, [509] 376-8341) Olsen KB, PE Dresel, and JC Evans. 2001. *Measurement of Helium-3/Helium-4 Ratios in Soil Gas at the 618-11 Burial Ground*. PNNL-13675, Pacific Northwest National Laboratory, Richland, Washington. Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – Xenon Gas Analysis	Xenon is produced as a fission product in nuclear reactors and through spontaneous fission of some transuranic isotopes. Xenon, an inert rare gas, will be released from buried transuranic waste. Xenon isotopes in soil gas can be analyzed to detect transuranic waste in the subsurface. Two complementary methods for xenon isotope measurements exist, radiometric analysis of short-lived radio-xenon isotopes and mass spectrometry for detection of stable xenon isotopes. The radio-xenon analysis has the greatest sensitivity due to lower background concentrations than exist for the stable isotopes. However, stable isotope ratios may be used to distinguish irradiated fuel sources from pure spontaneous fission sources.	The greatest unknown in the evaluation is the release rate of xenon from the waste forms. This will be dependant on the type of waste and container integrity. The radio-xenon isotopes will be most affected by slow release rates because of their short half lives.	PNNL (Evan Dresel, [509] 376-8341) Dresel PE and SR Waichler. 2004. *Evaluation of Xenon Gas Detection as a Means for Identifying Buried Transuranic Waste at the Radioactive Waste Management Complex, Idaho National Environmental and Engineering Laboratory*. PNNL-14617, Pacific Northwest National Laboratory, Richland, Washington.
Soil Gas Sampling – Track-Etch	Deploys passive film-strip based detectors (TrackEtch cups) in shallow holes in surface soil. After a suitable interval, film strips are retrieved and assessed for radiation exposure, typically assumed to be from radon gas in natural environments. Data are contoured for location of highest rad count. Can be coupled with more aggressive active soil gas techniques.	Generally applied to natural elements in adequate equilibrium such that alpha-emitting soil gas (radon) levels are abundant enough to produce a usable signal. Generally, anthropogenic wastes are not in equilibrium and alpha particles do not travel through solids adequately for even slightly remote detection. However some decay paths produce adequate gaseous alpha emitters, and in those isolated instances this method would be applicable. For example, some Hanford Site tank waste formulations have high radon signatures.	Sorey ML, CD Farrar, and HA Wollenberg. 1984. Workshop on hydrologic and geochemical monitoring in the Long Valley Caldera: proceedings. LBL-20020, Lawrence Berkeley Laboratory, Berkeley, California. http://www.radonlab.net/tracketch.htm

Table 5.10. Vertical Distribution of Radioactivity: Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Borehole Logging	Geophysical tool deployed in borehole created by drilling or cone penetrometer; gamma ray, or neutron detector. Gross Gamma Ray, Spectral Gamma Ray, Neutron/Moisture, Temperature.	Good vertical resolution. Requires cone penetrometer borehole or drilled borehole. Identifies potential transuranic waste by increased neutron radiation or energy-characteristic gamma rays. Active methods to induce fission and measure resulting neutrons are available but expensive. Common Use for This Application. Cost of access within landfill increases costs.	Last and Horton (2000) (PNNL-13149) EPA/625/R-92/007 (Tables 7-6, 7-7, and 7-8) Waste Management Hanford (James Meisner, 509-372-1120) NucSafe, others Petersen et al. (2001) (BHI-01484, Rev. 1)
Neutron Detection – Active	Active neutron detectors usually use central anode wire tubes filled with boron triflouride or helium-3, with a voltage potential across the tube. An impinging neutron produces a nuclear reaction product of a lithium nucleus and an alpha particle (in the case of a boron triflouride tube) or a tritium nucleus and a proton (for a helium-3 tube). These detectors can be operated in a pulse or a current mode (depending on counting rate).	Because the required nuclear reaction is much more probable with slow neutrons, high-energy neutrons need to be moderated (using graphite, for example) to be reliably detectable. These detectors may suffer from interference from high levels of gamma radiation.	Petersen et al. (2001) (BHI-01484, Rev. 1) Weaver JA, MJ Joyce, AJ Peyton, J Roskell, and MJ Armishaw. 2001. "Unique Broad-Spectrum Neutron Sensing Instrument." *Review of Scientific Instruments* 72(4):2043-2047. http://www.fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00326408.pdf (Neutron Detectors, Crane and Baker)
Neutron Detection – Detector for Passive Neutrons	Neutron flux can be used to measure transuranic radionuclides because the neutron production in sediment is caused by the alpha-neutron reaction that occurs when transuranic radionuclides emit alpha radiation in the presence of oxygen-rich soil. While any gamma-emitting radionuclide will affect the detected gamma activity, only transuranic radionuclides through the alpha-neutron reaction produce a neutron response. Thus, the neutron flux can then be correlated with the presence and activity of transuranic radionuclides in the subsurface.	The gamma radiation spectrum is also measured using a small diameter gamma probe to provide additional information for determining the presence and activity of transuranic radionuclides. Has been deployed at the Hanford Site previously.	Tommasino L. 2004. "Advanced Passive Detectors for Neutron Dosimetry and Spectrometry." *Radiation Protection Dosimetry* 110(1-4):183-186.

Table 5.10. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Neutron Detection – Induced-Fission Detector	Induced-fission detectors use a neutron source to induce fission in the materials under survey and measure the resulting neutron flux. This type of device is deployed on geophysical tool strings.	Because these detectors emit radiation, they require trained personnel and controlled conditions to operate.	Petersen et al. (2001) (BHI-01484, Rev. 1) http://www.canberra.com/pdf/Literature/Neutron%20Det%20and%20Counting%20SF.pdf
Neutron Detection – Passive Detector of Neutrons	Technique to passively measure neutron flux. Pieces of copper metal are placed next to the item to be surveyed or in an access borehole for a specified period of time. Neutrons impinging on the copper metal activate the copper. The activated copper is removed and analyzed in the laboratory to determine the neutron flux from the surveyed area.	Can measure neutron flux in the presence of high gamma background. The technique requires laboratory assay of the copper, real-time results are not possible. Some use for environmental applications.	PNNL (David Stromswold, [509] 372-2626) Petersen et al. (2001) (BHI-01484, Rev. 1)
Sample Collection – Discrete Sampling	Area or object of interest is sampled and the sample is analyzed (with either onsite or offsite facilities/instruments)	Accurate. Requires physical contact with waste or possible contamination. Transport issues involved if offsite facilities used. This technology is commonly used for environmental applications. Environmental controls during sampling increase costs.	PNNL (Elwood Lepel, [509] 376-3390), 222S Laboratory Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – Xenon Gas Analysis	Xenon is produced as a fission product in nuclear reactors and through spontaneous fission of some transuranic isotopes. Xenon, an inert rare gas, will be released from buried transuranic waste. Xenon isotopes in soil gas can be analyzed to detect transuranic waste in the subsurface. Two complementary methods for xenon isotope measurements exist, radiometric analysis of short-lived radio-xenon isotopes and mass spectrometry for detection of stable xenon isotopes. The radio-xenon analysis has the greatest sensitivity because of lower background concentrations than exist for the stable isotopes. However, stable isotope ratios may be used to distinguish irradiated fuel sources from pure spontaneous fission sources.	The greatest unknown in the evaluation is the release rate of xenon from the waste forms. This will be dependant on the type of waste and container integrity. The radio-xenon isotopes will be most affected by slow release rates due to their short half lives.	PNNL (Evan Dresel, [509] 376-8341) Dresel PE and SR Waichler. 2004. *Evaluation of Xenon Gas Detection as a Means for Identifying Buried Transuranic Waste at the Radioactive Waste Management Complex, Idaho National Environmental and Engineering Laboratory*. PNNL-14617, Pacific Northwest National Laboratory, Richland, Washington.

Table 5.10. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Subsurface Access – Direct Push – Geologic and Environmental Probe System (GEOPS)	Multiple-use, low-cost, subsurface probing system. Probe casing is installed to the desired depth using direct push or sonic drill rigs. Once placed in a zone of interest, the probe casing accepts any of several instrument inserts, including lysimeter, tensiometer, and vapor port probes for the unsaturated zone and water sampling and water level measurement of groundwater in the saturated zone. The casing can accept other types of sensors and also provides access for geophysical surveys (e.g., neutron/spectral logging). Metal or clear-wall may be used, the latter of which allows repeated video logging through the walls. Sampling and logging occur at the bottom tip by placing inserts into GEOPS tubing for single or repeated measurements.	Instrument inserts are fully retrievable, allowing use of the appropriate instrument(s) and fast probe change-out/installation. The GEOPS system allows multiple uses, shortens installation schedules, and eliminates generation of secondary waste. Does not require backfill, so the observations are more representative of the formation.	http://www.inl.gov/scienceandtechnology/factsheets/d/geops.pdf Holdren KJ, DL Anderson, BH Becker, NL Hampton, LD Koeppen, SO Magnuson, and AJ Sondrup. 2006. *Remedial Investigation and Baseline Risk Assessment for Operable Unit 7 13/14*. DOE/ID-11241, Idaho National Laboratory, Idaho Falls, Idaho.
Subsurface Access – Direct Push – Site Characterization and Analysis Penetrometer System (SCAPS)	Mobile, 20-ton platform (hydraulic cone penetrometer truck) and a suite of cost-effective sensing and sampling technologies that rapidly detect, discriminate, and quantify a wide variety of contaminants. SCAPS technologies detect contaminants in both soil and groundwater *in situ* while simultaneously determining subsurface geophysical characteristics. LIBS, XRF, and spectral gamma probe are examples of the instrumentation that can be used with SCAPS.	Demonstration of this technology indicated that it produces screening level data. The technology can provide rapid assessment of the distribution of fluorescent material in the subsurface. The technology may be sensitive to matrix heterogeneity, based on the very small volume sampled.	http://www.erdc.usace.army.mil/pls/erdcpub/WWW_WELCOME.NAVIGATION_PAGE?tmp_next_page=49777 http://www.cluin.org/download/toolkit/thirdednew/scaps99073.pdf EPA. 1995. *Site Characterization Analysis Penetrometer System (SCAPS): Innovative Technology Evaluation Report*. EPA/540/R-95/520, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. Available at: http://www.epa.gov/ORD/SITE/reports/540r95520/540r95520.pdf DOE. 1999. *Innovative Directional and Position Specific Sampling Technique (POLO)*. DOE/EM-0434, Innovative Technology Summary Report

Table 5.10. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
			316, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr316.pdf
TRUPRO	Concrete/metal sampling and profiling tool. Technology has four major components: 1) a drill with a specialized cutting and sampling head, 2) drill bits, 3) a sample collection unit, and 4) a vacuum pump. The equipment in conjunction with portable radiometric instruments produces a profile of radiological or chemical contamination through the material being studied. The drill head is used under hammer action to penetrate hard surfaces. This causes the bulk material to be pulverized as the drill travels through the radioactive media, efficiently transmitting a representative sample of bulk material to the sampling unit.	Targeted at concrete or other solid materials (versus soil). However, may be suitable for assaying monolithic materials (e.g., drums) that have been previously identified.	http://www.nmnuclear.com/products1.htm

Table 5.11. Identification of Transuranic Radionuclides: Non-Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
In Situ Object Counting System (ISOCS)	Uses a cryogenically cooled high purity germanium crystal as the detector for high resolution and high efficiency. This gamma-ray spectroscopy system identifies radioactive isotopes and provides real-time assays of the radioactive contents of containers, surfaces, and samples. The system provides traditional spectra of counts as a function of gamma energy, which are then converted to radionuclide concentration using a proprietary software system. The entire system is mounted on a portable cart, which allows rotation of the detector about a horizontal axis. The ISOCS does not produce an image.	May detect surface expression of buried sources, but unlikely to detect radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft. Has been deployed at F&H reactor fuel storage basins for identification of fuel elements. Some use for environmental applications.	Canberra (www.canberra.com) http://www.canberra.com/Products/709.asp http://www.bhi-erc.com/opportunities/technology/documents/FY2001FactSheets/ISOCS.pdf http://www.bhi-erc.com/projects/s_m/cdi/pdfs/ISOCS_CDI_factsheet.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)
Neutron Detection – Directional Neutron Detector	Collimates neutrons for detection of a source in a targeted area.	May detect surface expression of buried source, but unlikely to detect transuranic radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft. Is in the testing stage for environmental applications.	PNNL (David Stromswold, 509-372-2626) Peurrung AJ, DC Stromswold, RR Hansen, PL Reeder, and DS Barnett. 1999. *Long-Range Neutron Detection*. PNNL-13044, Pacific Northwest National Laboratory, Richland, Washington. http://www.lanl.gov/orgs/p/pdfs/pr/PR94.pdf Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.12. Identification of Transuranic Radionuclides: Intrusive

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Borehole Logging	Geophysical tool deployed in borehole created by drilling or cone penetrometer; gamma-ray or neutron detector. Gross Gamma-Ray, Spectral Gamma-Ray, Neutron/Moisture, Temperature	Good vertical resolution. Requires cone penetrometer borehole or drilled borehole. Identifies potential transuranic waste by increased neutron radiation or energy-characteristic gamma rays. Active methods to induce fission and measure resulting neutrons are available but expensive. Common Use for This Application. Cost of access within landfill increases costs.	Last and Horton (2000) (PNNL-13149) EPA/625/R-92/007 (Tables 7-6, 7-7, and 7-8) Waste Management Hanford (James Meisner, 509-372-1120) NucSafe, others Petersen et al. (2001) (BHI-01484, Rev. 1)
Neutron Detection – Active	Active neutron detectors usually use central anode wire tubes filled with boron triflouride or helium-3, with a voltage potential across the tube. An impinging neutron produces a nuclear reaction product of a lithium nucleus and an alpha particle (in the case of a boron triflouride tube) or a tritium nucleus and a proton (for a helium-3 tube). These detectors can be operated in a pulse or a current mode (depending on counting rate).	Because the required nuclear reaction is much more probable with slow neutrons, high-energy neutrons need to be moderated (using graphite, for example) to be reliably detectable. These detectors may suffer from interference from high levels of gamma radiation.	Petersen et al. (2001) (BHI-01484, Rev. 1) Weaver JA, MJ Joyce, AJ Peyton, J Roskell, and MJ Armishaw. 2001. "Unique Broad-Spectrum Neutron Sensing Instrument." *Review of Scientific Instruments* 72(4):2043-2047. http://www.fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00326408.pdf (Neutron Detectors, Crane and Baker)
Neutron Detection – Detector for Passive Neutrons	Neutron flux can be used to measure transuranic radionuclides because the neutron production in sediment is caused by the alpha-neutron reaction that occurs when transuranic radionuclides emit alpha radiation in the presence of oxygen-rich soil. While any gamma-emitting radionuclide will affect the detected gamma activity, only transuranic radionuclides through the alpha-neutron reaction produce a neutron response. Thus, the neutron flux can then be correlated with the presence and activity of transuranic radionuclides in the subsurface.	The gamma radiation spectrum is also measured using a small diameter gamma probe to provide additional information for determining the presence and activity of transuranic radionuclides. Has been deployed at the Hanford Site previously.	Tommasino L. 2004. "Advanced Passive Detectors for Neutron Dosimetry and Spectrometry." *Radiation Protection Dosimetry* 110(1-4):183-186.
Neutron Detection – Induced-Fission Detector	Induced-fission detectors use a neutron source to induce fission in the materials under survey and measure the resulting neutron flux. This type of device is deployed on geophysical tool strings.	Because these detectors emit radiation, they require trained personnel and controlled conditions to operate.	Petersen et al. (2001) (BHI-01484, Rev. 1) http://www.canberra.com/pdf/Literature/Neutron%20Det%20and%20Counting%20SF.pdf

Table 5.12. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Neutron Detection – Passive Detector of Neutrons	Technique to passively measure neutron flux. Pieces of copper metal are placed next to the item to be surveyed or in an access borehole for a specified period of time. Neutrons impinging on the copper metal activate the copper. The activated copper is removed and analyzed in the laboratory to determine the neutron flux from the surveyed area.	Can measure neutron flux in the presence of high gamma background. The technique requires laboratory assay of the copper; real-time results are not possible. Some use for environmental applications.	PNNL (David Stromswold, 509-372-2626) Petersen et al. (2001) (BHI-01484, Rev. 1)
Sample Collection – Discrete Sampling	Area or object of interest is sampled and the sample is analyzed (with either onsite or offsite facilities/instruments)	Accurate. Requires physical contact with waste or possible contamination. Transport issues involved if offsite facilities used. This technology is commonly used for environmental applications. Environmental controls during sampling increase costs.	PNNL (Elwood Lepel, 509-376-3390), 222S Laboratory Petersen et al. (2001) (BHI-01484, Rev. 1)
Soil Gas Sampling – Xenon Gas Analysis	Xenon is produced as a fission product in nuclear reactors and through spontaneous fission of some transuranic isotopes. Xenon, an inert rare gas, will be released from buried transuranic waste. Xenon isotopes in soil gas can be analyzed to detect transuranic waste in the subsurface. Two complementary methods for xenon isotope measurements exist, radiometric analysis of short-lived radio-xenon isotopes and mass spectrometry for detection of stable xenon isotopes. The radio-xenon analysis has the greatest sensitivity because of lower background concentrations than exist for the stable isotopes. However, stable isotope ratios may be used to distinguish irradiated fuel sources from pure spontaneous fission sources.	The greatest unknown in the evaluation is the release rate of xenon from the waste forms. This will be dependant on the type of waste and container integrity. The radio-xenon isotopes will be most affected by slow release rates because of their short half lives.	PNNL (Evan Dresel, 509-376-8341) Dresel PE and SR Waichler. 2004. *Evaluation of Xenon Gas Detection as a Means for Identifying Buried Transuranic Waste at the Radioactive Waste Management Complex, Idaho National Environmental and Engineering Laboratory*. PNNL-14617, Pacific Northwest National Laboratory, Richland, Washington.
Subsurface Access – Direct Push – Geologic and Environmental Probe System (GEOPS)	Multiple-use, low-cost, subsurface probing system. Probe casing is installed to the desired depth using direct push or sonic drill rigs. Once placed in a zone of interest, the probe casing accepts any of several instrument inserts, including lysimeter, tensiometer, and vapor port probes for the unsaturated zone and water sampling and water level measurement of groundwater in the saturated zone. The casing can accept other types of sensors and also provides access for geophysical surveys (e.g., neutron/spectral logging). Metal or clear-wall may be used, the latter of which allows repeated video logging through the walls.	Instrument inserts are fully retrievable, allowing use of the appropriate instrument(s) and fast probe change-out/installation. The GEOPS system allows multiple uses, shortens installation schedules, and eliminates generation of secondary waste. Does not require backfill, so the observations are more representative of the formation.	http://www.inl.gov/scienceandtechnology/factsheets/d/geops.pdf Holdren KJ, DL Anderson, BH Becker, NL Hampton, LD Koeppen, SO Magnuson, and AJ Sondrup. 2006. *Remedial Investigation and Baseline Risk Assessment for Operable Unit 7 13/14*. DOE/ID-11241, Idaho National Laboratory, Idaho Falls, Idaho.

Table 5.12. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
	Sampling and logging occur at the bottom tip by placing inserts into GEOPS tubing for single or repeated measurements.		
Subsurface Access – Direct Push – Site Characterization and Analysis Penetrometer System (SCAPS)	Mobile, 20-ton platform (hydraulic cone penetrometer truck) and a suite of cost-effective sensing and sampling technologies that rapidly detect, discriminate, and quantify a wide variety of contaminants. SCAPS technologies detect contaminants in both soil and groundwater *in situ* while simultaneously determining subsurface geophysical characteristics. LIBS, XRF, and spectral gamma probe are examples of the instrumentation that can be used with SCAPS.	Demonstration of this technology indicated that it produces screening level data. The technology can provide rapid assessment of the distribution of fluorescent material in the subsurface. The technology may be sensitive to matrix heterogeneity, based on the very small volume sampled.	http://www.erdc.usace.army.mil/pls/erdcpub/WWW_WELCOME.NAVIGATION_PAGE?tmp_next_page=49777 http://www.cluin.org/download/toolkit/thirdednew/scaps99073.pdf EPA. 1995. *Site Characterization Analysis Penetrometer System (SCAPS): Innovative Technology Evaluation Report*. EPA/540/R-95/520, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, Ohio. Available at: http://www.epa.gov/ORD/SITE/reports/540r95520/540r95520.pdf DOE. 1999. *Innovative Directional and Position Specific Sampling Technique (POLO)*. DOE/EM-0434, Innovative Technology Summary Report 316, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr316.pdf

Table 5.12. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
TRUPRO	Concrete/metal sampling and profiling tool. Technology has four major components: a drill with a specialized cutting and sampling head, drill bits, a sample collection unit, and a vacuum pump. The equipment in conjunction with portable radiometric instruments produces a profile of radiological or chemical contamination through the material being studied. The drill head is used under hammer action to penetrate hard surfaces. This action pulverizes the bulk material as the drill travels through the radioactive media, efficiently transmitting a representative sample of bulk material to the sampling unit.	Targeted at concrete or other solid materials (versus soil). However, may be suitable for assaying monolithic materials (e.g., drums) that have been previously identified.	http://www.nmnuclear.com/products1.htm

Table 5.13. Enabling Technologies: Analytical – Radionuclides

Technology	General Description	Example Vendor/Reference Information
Analytical – Beta/gamma detection	Hand-held instruments for beta/gamma detection in discrete samples or surfaces.	http://www.cpeo.org/techtree/ttdescript/surfgrd.htm NRC, EPA, and DOE. 2000. "Description of Field Survey and Laboratory Analysis Equipment." In: *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*. NUREG-1575, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC. Appendix H. (Also numbered as EPA/402/R-97/016, Rev. 1 and DOE/EH-0624, Rev. 1.) Available at: http://www.epa.gov/radiation/marssim/obtain.htm.
Analytical – BetaScintTM Fiber-Optic Sensor	For detecting strontium-90 and uranium-238 in soil. Beta particles (electrons) emitted by radioactive soil contaminants excite electrons in plastic fiber doped with fluorescent compounds in the layers of the sensor. The plastic fibers give off light (scintillate) when the fluorescent molecules lose energy and return to their ground state. Scintillations in the plastic fibers are counted by photodetectors to determine beta radioactivity of the soil sample. BetaScint sample processing for this application is limited to drying and sieving soil samples to remove rocks and excessive organic matter. The BetaScint system is easy to operate, and does not create secondary wastes. The BetaScint sensor is commercially available and is optimized for obtaining measurements on contaminated soils, concrete, and other solid surfaces.	DOE. 1998. *BetaScint Fiber-Optic Sensor for Detecting Strontium-90 and Uranium-238 in Soil*. DOE/EM-0424, Innovative Technology Summary Report 70, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://costperformance.org/monitoring/pdf/itsr70.pdf
Analytical – Dig-Face Characterization System	Consists of multiple real-time sensors (geophysical, chemical, radiological, and physical) at the dig-face to provide characterization information during excavation.	DOE. 1999. *Dig Face Characterization*. DOE/EM-0498, Innovative Technology Summary Report 12, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://costperformance.org/monitoring/pdf/itsr12.pdf
Analytical – Field-Transportable Beta Counter-Spectrometer	PC-controlled, field-transportable beta counter-spectrometer that uses solid scintillation coincident counting and low-noise photomultiplier tubes to count element-selective filters and other solid media. The instrument can detect and measure technetium-99, strontium-90, and other beta emitters. Benefits are derived from field generated results (i.e., faster turnaround time) and the dry scintillation technique (i.e., reduction in secondary waste).	DOE. 1998. *Field Transportable Beta Spectrometer*. DOE/EM-0399, Innovative Technology Summary Report 1853, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/ost/pubs/itsrs/itsr1853.pdf
Analytical – Gamma camera	Gamma sensor and video image combined. Provides two-dimensional information on the position and relative strengths of gamma-ray radiation fields located from a few feet to several hundred feet from the observer. The system consists of a portable sensor head that contains both gamma ray and visual imaging systems and a portable computer for control. May detect surface expression of buried source, but unlikely to detect radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft.	DOE. 1998. *GammaCam Radiation Imaging System*. DOE/EM-0345, Innovative Technology Summary Report 1840, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/OST/pubs/itsrs/itsr1840.pdf EDO Corp. (http://www.edocorp.com/NuclearDetectionSystem.htm) BIL Solutions Ltd. (formerly BNFL Instruments) (http://www.bilsolutions.co.uk/) Petersen et al. (2001) (BHI-01484, Rev. 1)

Table 5.13. (contd)

Technology	General Description	Example Vendor/Reference Information
Analytical – Hand-Held Spectral Gamma	Hand-held instrument that can collect both gross gamma ray and spectral information. Provides real-time analysis of isotopes. May detect surface expression of buried source, but unlikely to detect radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft.	Washington Closure Hanford Technology Application
Analytical – High Purity Germanium (HPGe) Detectors	High-purity germanium (HPGe) detector for quantification of isotopes (e.g., uranium-238, radium-226, and thorium-232). Various configurations are available (e.g., a tripod-mounted HPGe detector for precision stationary measurements or a mobile cart). Gamma-ray spectra, acquired using high-resolution gamma-ray spectroscopy, are processed by data acquisition and analysis software. Benefits are derived from this being a field analysis technology (e.g., faster turnaround time, reduced excavation/secondary waste).	http://www.ead.anl.gov/project/dsp_fsdetail.cfm?id=87 Hagenauer R. 2000. "A Portable HPGe System for Measuring Contaminated Soils and Floors." In: *Proceedings for Spectrum 2000*, Chattanooga, Tennessee, September 24-28, 2000. Available at: http://www.ortec-online.com/papers/Isotopic-Spectrum_2000.pdf (ISO-Cart system)
Analytical – Large-Area Survey Monitor (LASM)	Designed to provide fast, accurate and efficient *in situ* measurement of plutonium in soil, debris, and buried containers for criticality control.	Boissiere PT, JL Lockhart, JM Steffes, J Santo, T Baumgartner, and PE Dresel. 2005. "Remote Systems for Hazardous Waste Site Remediation and Characterization." In: *Proceedings of Waste Management '05*, Tucson, Arizona, February 27-March 3, 2005. Available at: http://www.wmsym.org/abstracts/pdfs/5190.pdf
Analytical – Portable NaI Detector	Mobile sodium-iodine (NaI) detectors exist for large area surveys of uranium-238, radium-226, and thorium-232. Also used for cesium-137 counts. A very sensitive gamma detector. Gives best currently available energy resolution for gamma rays in a room temperature detector that is relatively inexpensive and available in a wide variety of sizes (according to NucSafe). Benefits are derived from this being a field analysis technology (e.g., faster turnaround time, reduced excavation/secondary waste).	http://www.ead.anl.gov/project/dsp_fsdetail.cfm?id=87 http://www.nucsafe.com/Technology/selecting_gamma_detector.htm
Analytical – Thermoluminescent Dosimeters	Consists of short (~ 1 cm) aluminum oxide rod that is physically and optically coupled to a conventional fiber optic channel. The sensor is placed in new or existing boreholes around radioactive waste sources such as waste tanks, trenches, and cribs. The fiber optic channels are sheathed in an inert material to prevent damage to the channel and to facilitate deployment in potentially hazardous environments. Aluminum oxide is an inert, structurally strong material that will not interact or be affected by hazardous materials that it may contact during deployment. A portable readout device, consisting of a light source, a photomultiplier tube, and associated electronics, will be used to measure radiation dose collected by the sensor. The measured dose is subsequently correlated to the type of radioactive contaminants and contamination levels in the soil by using appropriate calibration factors.	Durham JS, MS Akselrod, and SWS McKeever. 2001. "In Situ, Long-term Monitoring System for Radioactive Contaminants." In: *Proceedings of Industry Partnerships for Environmental Science & Technology*, Morgantown, West Virginia, October 30 - November 1, 2001. Available at: http://www.netl.doe.gov/publications/proceedings/01/indpartner/emp.06.pdf

Table 5.14. Enabling Technologies: Analytical – TRU

Technology	General Description	Example Vendor/Reference Information
Analytical – Beta/gamma detection	Hand-held instruments for beta/gamma detection in discrete samples or surfaces.	http://www.cpeo.org/techtree/ttdescript/surfgrd.htm NRC, EPA, and DOE. 2000. "Description of Field Survey and Laboratory Analysis Equipment." In: *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*. NUREG-1575, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC. Appendix H. (Also numbered as EPA/402/R-97/016, Rev. 1 and DOE/EH-0624, Rev. 1.) Available at: http://www.epa.gov/radiation/marssim/obtain.htm.
Analytical – Dig-Face Characterization System	Consists of multiple real-time sensors (geophysical, chemical, radiological, and physical) at the dig-face to provide characterization information during excavation.	DOE. 1999. *Dig Face Characterization*. DOE/EM-0498, Innovative Technology Summary Report 12, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://costperformance.org/monitoring/pdf/itsr12.pdf
Analytical – Hand-Held Spectral Gamma	Hand-held instrument that can collect both gross gamma ray and spectral information. Provides real-time analysis of isotopes. May detect surface expression of buried source, but unlikely to detect radiation through existing overburden. May work if overburden is decreased to 1 to 2 ft.	Washington Closure Hanford Technology Application
Analytical – High Purity Germanium (HPGe) Detectors	High-purity germanium (HPGe) detector for quantification of isotopes (e.g., uranium-238, radium-226, and thorium-232). Various configurations are available (e.g., a tripod-mounted HPGe detector for precision stationary measurements or a mobile cart). Gamma-ray spectra, acquired using high-resolution gamma-ray spectroscopy, are processed by data acquisition and analysis software. Benefits are derived from this being a field analysis technology (e.g., faster turnaround time, reduced excavation/secondary waste).	http://www.ead.anl.gov/project/dsp_fsdetail.cfm?id=87 Hagenauer R. 2000. "A Portable HPGe System for Measuring Contaminated Soils and Floors." In: *Proceedings for Spectrum 2000*, Chattanooga, Tennessee, September 24-28, 2000. Available at: http://www.ortec-online.com/papers/Isotopic-Spectrum_2000.pdf (ISO-Cart system)
Analytical – Large-Area Survey Monitor (LASM)	Designed to provide fast, accurate and efficient *in situ* measurement of plutonium in soil, debris, and buried containers for criticality control.	Boissiere PT, JL Lockhart, JM Steffes, J Santo, T Baumgartner, and PE Dresel. 2005. "Remote Systems for Hazardous Waste Site Remediation and Characterization." In: *Proceedings of Waste Management '05*, Tucson, Arizona, February 27-March 3, 2005. Available at: http://www.wmsym.org/abstracts/pdfs/5190.pdf
Analytical – Laser Ablation/Laser-Induced Fluorescence (LA-LIF)	Field portable instrument for measuring the isotopic composition of uranium compounds. May apply to other contaminant as well (e.g., sodium). Analysis of complex samples can be difficult due to spectral overlap of different luminescing compounds. Detection limits will vary between sites. Extensive experience required for proper system operation. Sensors limited to a maximum depth of 150 ft because of attenuation in optical fiber cord.	http://www.technet.pnl.gov/sensors/chemical/projects/es4lalif.stm

Table 5.15. Enabling Technologies: Analytical – Heavy Metals

Technology	General Description	Example Vendor/Reference Information
Analytical – Dig-Face Characterization System	Consists of multiple real-time sensors (geophysical, chemical, radiological, and physical) at the dig-face to provide characterization information during excavation.	DOE. 1999. *Dig Face Characterization*. DOE/EM-0498, Innovative Technology Summary Report 12, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://www.costperformance.org/monitoring/pdf/itsr12.pdf
Analytical – Fiber Optic Chemical Sensors	Fiber optic chemical sensors operate by transporting light that, either by wavelength or intensity, provides information about the analyte in the environment surrounding the sensor. Such sensors are typically used with analytical techniques such as laser-induced fluorescence or Raman spectroscopy. The analytes detected will depend on the analytical technique (light source) as well as the coatings/end-tip configuration. The technology may be used for organics (petroleum hydrocarbons, aromatics, PAHs, PCBs, chlorinated solvents), explosives, or metals.	Sims JL. 2002. *State-of-the-Science of Hazardous Waste Site Characterization Strategies and Technologies*. Utah State University, Utah Water Research Laboratory, Logan, Utah. Available at: http://www.engineering.usu.edu/uwrl/www/sims/hazwaste.pdf EPA. 2006. *Characterization Technology Vendor Summary*. Available at: http://www.cluin.org/vendor/vendorinfo/. http://www.nrl.navy.mil/techtransfer/pdfs/S01.pdf http://www.sentix.org/FocInfo.htm
Analytical – Immunoassay	Immunoassay is an innovative technology used to measure compound-specific reactions to individual compounds or classes of compounds. The reactions are used to detect and quantify contaminants. Field test kits using this method are available for the following compounds or groups of compounds: benzene, toluene, ethylbenzene, and xylene (BTEX), PCPs, PCBs, PAHs, pesticides, explosives, and metals. For some test kits you need to know the suspected contaminant levels as well as the target analyte.	http://www.envirotools.org/factsheets/Remediation/testtech.shtml#soilsamp DoD. 2000. *ESTCP Cost and Performance Report: Explosives Detecting Immunosensors*. CU-9713, U.S. Department of Defense, Environmental Security Technology Certification Program, Arlington, Virginia. Available at: http://www.estcp.org/documents/techdocs/199713.pdf EPA. 2000. *Environmental Technology Verification Report on Explosives Detection Technology, Research International, Inc., Fast 2000*. EPA/600/R-00/045, United States Environmental Protection Agency, Office of Research and Development, Washington, D.C. Available at: http://www.estcp.org/documents/techdocs/ETV_Report_RII.pdf http://costperformance.org/monitoring/pdf/elisa_2.pdf Rogers KR and CL Gerlach. 1996. "Environmental Biosensors: A Status Report." *Environ. Sci. Technol.*, 30(11):486A-491A. Available at: http://pubs.acs.org/hotartcl/est/96/nov/envir.html Rogers KR and CL Gerlach. 1999. "Update on Environmental Biosensors." *Environ. Sci. Technol*. 33(23):500A-506A. Available at: http://pubs.acs.org/cgi-bin/article.cgi/esthag-a/1999/33/i23/html/gerl.html
Analytical – Laser Ablation/Laser-Induced Fluorescence (LA-LIF)	Field portable instrument for measuring the isotopic composition of uranium compounds. May apply to other contaminant as well (e.g., sodium). Analysis of complex samples can be difficult due to spectral overlap of different luminesing compounds. Detection limits will vary between sites. Extensive experience required for proper system operation. Sensors limited to a maximum depth of 150 ft because of attenuation in optical fiber cord.	http://www.technet.pnl.gov/sensors/chemical/projects/es4lalif.stm

Table 5.15. (contd.)

Technology	General Description	Example Vendor/Reference Information
Analytical – Laser-Induced Breakdown Spectroscopy (LIBS)	Atomic emission spectroscopy that uses a highly energetic laser pulse as the excitation source. LIBS can analyze any matter regardless of its physical state, be it solid, liquid or gas. Even slurries, aerosols, gels, and more can be readily investigated. Because all elements emit light when excited to sufficiently high temperatures, LIBS can detect all elements, limited only by the power of the laser as well as the sensitivity and wavelength range of the spectrograph and detector. Operationally, LIBS is very similar to arc/spark emission spectroscopy.	Martin M, S Wullschleger, C Garten Jr., A Palumbo, B Evans, H O'Neill, and J Woodward. 2002. "Environmental and Biological Applications of Laser-Induced Breakdown Spectroscopy." In: *Proceedings of the Workshop on Advances in Laser Technology and Applications*, Redstone Arsenal, Alabama, August 21-22, 2002. Available at: http://www.ornl.gov/~webworks/cppr/y2001/pres/115067.pdf DeLucia Jr., FC, AC Samuels, RS Harmon, RA Walters, KL McNesby, A LaPointe, RJ Winkel, Jr., and AW Miziolek. 2005. "Laser-Induced Breakdown Spectroscopy (LIBS): A Promising Versatile Chemical Sensor Technology for Hazardous Material Detection." *IEEE Sensors J*., 5(4):681-689. Yueh F-Y, JP Singh, and H Zhang. 2000. "Laser-Induced Breakdown Spectroscopy, Elemental Analysis." In: *Encyclopedia of Analytical Chemistry: Applications, Theory, and Instrumentation*. RA Meyers, (Ed.). John Wiley & Sons, New York. pp. 2066-2087. http://www.oceanoptics.com/Products/libs.asp
Analytical – Raman Spectroscopy	Measurement of the wavelength and intensity of scattered light from molecules. When electromagnetic radiation passes through matter, most of the radiation continues in its original direction. However, a small fraction is scattered in other directions. Using Raman spectroscopy, the Raman probe detects many organic and inorganic chemicals in the media surrounding the probe. The probe uses laser light beamed through a sapphire window. When the light hits the sample, it causes molecules to vibrate in a distinctive way, creating a "fingerprint." The fingerprint is captured and transmitted via fiber optic cables to an analyzer, where it is compared to known signals. Can be used to provide direct evidence of NAPL. Data interpretation can be complex. Only a few analyte groups can be identified.	DOE. 1999. *Raman Probe*. DOE/EM-0442, Innovative Technology Summary Report 1544, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/ost/pubs/itsrs/itsr1544.pdf http://www.cpeo.org/techtree/ttdescript/ramprob.htm
Analytical – X-Ray Fluorescence – Field Portable Instrument	A x-ray fluorescence analyzer is a self-contained, field-portable instrument, consisting of an energy dispersive x-ray source, a detector, and a data processing system that detects and quantifies individual metals or groups of metals.	http://www.epa.gov/superfund/lead/products/xrffaqs.pdf http://costperformance.org/monitoring/pdf/xrf_2.pdf Clark S, W Menrath, M Chen, S Roda, and P Succop. 1999. "Use of a Field Portable X-Ray Fluorescence Analyzer to Determine the Concentration of Lead and Other Metals in Soil Samples." *Ann. Agric. Environ. Med*. 6(1):27-32. http://www.niton.com/martin.html http://www.niton.com/shef02.html

Table 5.16. Enabling Technologies: Analytical – Organics

Technology	General Description	Example Vendor/Reference Information
Analytical – Atomic Emission Spectroscopy	Fieldable, real-time monitor to determine vadose zone chlorinated hydrocarbon vapor concentrations.	http://www.technet.pnl.gov/sensors/chemical/projects/es4_halo.stm
Analytical – Colorimetric Detection Tubes/Test Kits	Colorimetric refers to chemical reaction-based indicators that are used to produce compound reactions to individual compounds, or classes of compounds. The reactions, such as visible color changes or other easily noted indications, are used to detect and quantify contaminants. Colorimetric kits can be used to analyze for organic and explosive contaminants.	http://www.envirotools.org/factsheets/Remediation/testtech.shtml#soilsamp http://www.drycleancoalition.org/download/Color_tec_2005.pdf EPA. 2006. *Characterization Technology Vendor Summary*. Available at: http://www.cluin.org/vendor/vendorinfo/ Thiboutot S, G Ampleman, and AD Hewitt. 2002. *Guide for Characterization of Sites Contaminated with Energetic Materials*. ERDC/CRREL TR-02-1, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi. Sims JL. 2002. *State-of-the-Science of Hazardous Waste Site Characterization Strategies and Technologies*. Utah State University, Utah Water Research Laboratory, Logan, Utah.
Analytical – Dig-Face Characterization System	Consists of multiple real-time sensors (geophysical, chemical, radiological, and physical) at the dig-face to provide characterization information during excavation.	DOE. 1999. *Dig Face Characterization*. DOE/EM-0498, Innovative Technology Summary Report 12, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://costperformance.org/monitoring/pdf/itsr12.pdf
Analytical – Fiber Optic Chemical Sensors	Fiber optic chemical sensors operate by transporting light that, either by wavelength or intensity, provides information about the analyte in the environment surrounding the sensor. Such sensors are typically used with analytical techniques such as laser-induced fluorescence or Raman spectroscopy. The analytes detected will depend on the analytical technique (light source) as well as the coatings/end-tip configuration. The technology may be used for organics (petroleum hydrocarbons, aromatics, PAHs, PCBs, chlorinated solvents), explosives, or metals.	Sims JL. 2002. *State-of-the-Science of Hazardous Waste Site Characterization Strategies and Technologies*. Utah State University, Utah Water Research Laboratory, Logan, Utah. Available at: http://www.engineering.usu.edu/uwrl/www/sims/hazwaste.pdf EPA. 2006. *Characterization Technology Vendor Summary*. Available at: http://www.cluin.org/vendor/vendorinfo/ http://www.nrl.navy.mil/techtransfer/pdfs/S01.pdf http://www.sentix.org/FocInfo.htm
Analytical – Fiber Optic Chemical Sensor – LLNL Device	This device works by placing a small amount of contaminated vapor in a small reaction chamber where it reacts quantitatively with a chemical reagent. The principle of detection is that the chemical reagent becomes increasingly opaque to specific wavelengths when reacted with specific chlorinated compounds. This light-absorbing sensor has demonstrated dramatically improved performances over previously reported fluorescence-based sensors. This sensor is easily controlled remotely by incorporating fused quartz optical fibers as a wave-guide to conduct light to and from a down-hole probe. The reaction chamber is small enough to fit in a cone penetrometer. The small amount of contaminated reagent (<50 µL/ measurement) is stored in the probe and removed when the reagent is replenished.	http://www.llnl.gov/sensor_technology/STR55.html Milanovich FP, SB Brown, BW Colston, Jr., PF Daley, and J Rossabi. 1993. "A New Fiber-Optic Sensor Technology for Rapid and Inexpensive Characterization of Soil Contamination." UCRL-JC-113731, Lawrence Livermore National Laboratory, Livermore, California.

Table 5.16. (contd.)

Technology	General Description	Example Vendor/Reference Information
Analytical – Flame Ionization Detector (FID)	A flame ionization detector (FID) measures the change of signal as analytes are ionized by a hydrogen-air flame. A FID can be used alone to give a total reading of ionized contaminants in parts per million (ppm). When used in this setting, the FID is a screening tool for soil contamination. It can give you a general idea whether soil is slightly or grossly impacted based on the total ppm reading. However, note that there is not a direct relationship between the contaminant levels identified with a FID and those obtained during laboratory analysis of the soil. In addition, when a FID is used alone, the contaminant is unknown because it can not identify the individual contaminants causing the ionization. Because a FID can detect phenols, phthalates, PAHs, VOCs, and petroleum hydrocarbons, the ppm reading could be any one of these individual contaminants or a combination of them. A FID can also be used in conjunction with a gas chromatograph to identify and quantify the individual constituents causing the soil contamination.	http://www.envirotools.org/factsheets/Remediation/testtech.shtml#soilscreen http://www.newmoa.org/cleanup/advisory/gc.htm http://www.ceainstr.com/pdf_datasheets/sleuth_Info.pdf
Analytical – Gas Chromatography (GC) or Gas Chromatography/Mass Spectrometry (GC/MS) – Portable	The GC/MS instrument separates chemical mixtures (the GC component) and identifies the components at a molecular level (the MS component). It is one of the most accurate tools for analyzing environmental samples. The GC works on the principle that a mixture will separate into individual substances when heated. The heated gases are carried through a column with an inert gas (such as helium). As the separated substances emerge from the column opening, they flow into the MS. Mass spectrometry identifies compounds by the mass of the analyte molecule. For VOCs.	http://www.cpeo.org/techtree/ttdescript/msgc.htm Einfeld W. 1998. *Environmental Technology Verification Report: Field-Portable Gas Chromatograph/Mass Spectrometer*. EPA/600/R-98/142, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Las Vegas, Nevada. Available at: http://costperformance.org/monitoring/pdf/hapsite_2.pdf http://www.fieldportable.com/gcmsapp.html http://www.syagen.com/field_portable_ms.asp http://www.newmoa.org/cleanup/advisory/gc.htm
Analytical – Immunoassay	Immunoassay is an innovative technology used to measure compound-specific reactions to individual compounds or classes of compounds. The reactions are used to detect and quantify contaminants. Field test kits using this method are available for the following compounds or groups of compounds: benzene, toluene, ethylbenzene, and xylene (BTEX), PCPs, PCBs, PAHs, pesticides, explosives, and metals. For some test kits you need to know the suspected contaminant levels as well as the target analyte.	http://www.envirotools.org/factsheets/Remediation/testtech.shtml#soilsamp DoD. 2000. *ESTCP Cost and Performance Report: Explosives Detecting Immunosensors*. CU-9713, U.S. Department of Defense, Environmental Security Technology Certification Program, Arlington, Virginia. Available at: http://www.estcp.org/documents/techdocs/199713.pdf EPA. 2000. *Environmental Technology Verification Report on Explosives Detection Technology, Research International, Inc., Fast 2000*. EPA/600/R-00/045, United States Environmental Protection

Table 5.16. (contd.)

Technology	General Description	Example Vendor/Reference Information
		Agency, Office of Research and Development, Washington, D.C. Available at: http://www.estcp.org/documents/techdocs/ETV_Report_RII.pdf http://costperformance.org/monitoring/pdf/elisa_2.pdf Rogers KR and CL Gerlach. 1996. Environmental Biosensors: A Status Report. *Environ. Sci. Techno*l., 30(11):486A-491A. Available at: http://pubs.acs.org/hotartcl/est/96/nov/envir.html Rogers KR and CL Gerlach. 1999. "Update on Environmental Biosensors." *Environ. Sci. Technol*. 33(23):500A-506A. Available at: http://pubs.acs.org/cgi-bin/article.cgi/esthag-a/1999/33/i23/html/gerl.html
Analytical – Infrared Spectroscopy – MIRAN SapphIRe Ambient Air Analyzer	Gas analyzer using infrared spectroscopy to measure/identify inorganic and organic compounds. Targeted at industrial use (hospitals, industrial hygiene), not waste site characterization.	ThermoElectron Corp. Available at: http://www.thermo.com/com/cda/product/detail/1,,22553,00.html
Analytical – Laser Ablation/Laser-Induced Fluorescence (LA-LIF)	Field portable instrument for measuring the isotopic composition of uranium compounds. May apply to other contaminant as well (e.g., sodium). Analysis of complex samples can be difficult because of spectral overlap of different luminescing compounds. Detection limits will vary between sites. Extensive experience required for proper system operation. Sensors limited to a maximum depth of 150 ft because of attenuation in optical fiber cord.	http://www.technet.pnl.gov/sensors/chemical/projects/es4lalif.stm
Analytical – Laser-Induced Breakdown Spectroscopy (LIBS)	Atomic emission spectroscopy that uses a highly energetic laser pulse as the excitation source. LIBS can analyze any matter regardless of its physical state, be it solid, liquid or gas. Even slurries, aerosols, gels, and more can be readily investigated. Because all elements emit light when excited to sufficiently high temperatures, LIBS can detect all elements, limited only by the power of the laser as well as the sensitivity and wavelength range of the spectrograph and detector. Operationally, LIBS is very similar to arc/spark emission spectroscopy.	Martin M, S Wullschleger, C Garten Jr., A Palumbo, B Evans, H O'Neill, and J Woodward. 2002. "Environmental and Biological Applications of Laser-Induced Breakdown Spectroscopy." In: *Proceedings of the Workshop on Advances in Laser Technology and Applications*, Redstone Arsenal, Alabama, August 21-22, 2002. Available at: http://www.ornl.gov/~webworks/cppr/y2001/pres/115067.pdf DeLucia Jr. FC, AC Samuels, RS Harmon, RA Walters, KL McNesby, A LaPointe, RJ Winkel Jr, and AW Miziolek. 2005. "Laser-Induced Breakdown Spectroscopy (LIBS): A Promising Versatile Chemical Sensor Technology for Hazardous Material Detection." *IEEE Sensors J.*, 5(4):681-689. Yueh F-Y, JP Singh, and H Zhang. 2000. "Laser-Induced Breakdown Spectroscopy, Elemental Analysis." In: *Encyclopedia of Analytical Chemistry: Applications, Theory, and Instrumentation*, RA Meyers,

Table 5.16. (contd.)

Technology	General Description	Example Vendor/Reference Information
		(Ed.). John Wiley & Sons, New York. pp. 2066-2087. http://www.oceanoptics.com/Products/libs.asp
Analytical – Laser-Induced Fluorescence (LIF)	LIF uses the light emission from atoms or molecules to quantify the amount of the emitting substance in a sample. Fluorometry is a spectroscopic technique in which the electronic state of a molecule is elevated by absorption of electromagnetic radiation. Enhanced sensitivity is achievable because the fluorescence signal has a very low background. When the molecule returns to its ground state, radiation is emitted to produce a distinctive excitation and emission spectrum.	http://en.wikipedia.org/wiki/Laser-induced_fluorescence Löhmannsröben H-G and T Roch. 2000. "In Situ Laser-Induced Fuorescence (LIF) Analysis of Petroleum Product-Contaminated Soil Samples." *J. Environ. Monitor*. 2(1):17-22. Ko E-J, K-W Kim, and U Wachsmuth. 2004. "Remediation Process Monitoring of PAH-Contaminated Soils Using Laser-Induced Fluorescence." *Environ. Monit. Assess*. 92(1-3):179-191. Lemke M, R Fernández-Trujillo, and H-G Löhmannsröben. 2005. "In-Situ LIF Analysis of Biological and Petroleum-Based Hydraulic Oils on Soil." *Sensors* 5:61-69.
Analytical – Microsensors	The sensor system consists of an array of miniature sensors, called chemiresistors that can detect volatile organic compounds (VOCs). Each chemiresistor is fabricated by mixing a commercial polymer dissolved in a solvent with conductive carbon particles. The ink-like fluid is deposited and dried on wire-like electrodes on a specially designed integrated circuit. When VOCs are present, the chemicals absorb into the polymers, causing them to swell. The swelling changes the electrical resistance that can then be measured and recorded. The amount of swelling corresponds to the concentration of the chemical vapor in contact with the polymers. The process is reversible, and the polymers will shrink once the chemical is removed, reverting the resistance to its original state.	http://www.sandia.gov/sensor/MainPage.htm
Analytical – Near-Infrared Spectrometer	Remote, real-time detection and characterization of organics in soils based on measurements in the near-infrared spectrum. The system includes a reflectance sensor, a field-rugged Fourier transform infrared (FTIR) spectrometer operating within a spectral region of 1.4 and 2.2 µm, and low-loss silica fibers. The system was designed as a hand-held tool, but other configurations are available. Reflectance spectroscopy is well suited for such measurements because it can detect and identify both the host soils and organics, and does not require sample handling or preparation. Technology can be coupled with a spectral library to discern soil types or minerals. Can couple technology with aerial multi spectral surveys. Can help discern natural from man-emplaced soils and debris. Technology is under development at the demonstration stage.	Schneider I, G Nau, TVV King, and I Aggarwal. 1995. "Fiber-Optic Near-Infrared Reflectance Sensor for Detection of Organics in Soils." *IEEE Photonics Technology Letters* 7(1):87-89.

Table 5.16. (contd.)

Technology	General Description	Example Vendor/Reference Information
Analytical – Photo Ionization Detector (PID)	A PID measures the change of signal as analytes are ionized by an ultraviolet lamp. It can be used alone to give a general idea of levels of soil contamination, but cannot identify the individual constituents that are present. The PID can detect VOCs and petroleum hydrocarbons. A PID can also be used in conjunction with a gas chromatograph to identify and quantify the individual constituents causing the soil contamination.	http://www.envirotools.org/factsheets/Remediation/testtech.shtml#soilscreen http://www.newmoa.org/cleanup/advisory/gc.htm
Analytical – Photoacoustic Infrared Analyzer	Detection of chlorinated VOCs in the headspace of a water sample (or possibly any gas sample). In the instrument's measurement cell, the gas is irradiated with electomagnetic energy at frequencies that correspond to resonant vibration frequencies of VOC compounds in the gas. A portion of the incident energy is absorbed, causing some of the molecules of the gas to be excited to a higher vibrational energy state. These molecules subsequently relax back to the lower-energy, vibrational state through a combination of radiative and kinetic processes. The kinetic energy decay process results in increased heat energy of the gas molecules and a corresponding temperature and pressure increase in the gas. The incident infrared source is modulated and the resulting pressure is also modulated. The varying pressure in the cell produces an acoustic wave that is detected with a high-sensitivity microphone. Compound specificity is achieved by using band-pass filters tuned to the energy absorption bands of target compounds, and quantification is done by measuring the intensity of the resulting acoustic signal. Sample composition must be known since the measurement technique is susceptible to interference from unknown VOCs in the sample.	Einfeld W. 1998. *Environmental Technology Verification Report: Photoacoustic Spectrophotometer*. EPA/600/R-98/143, U.S. Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Las Vegas, Nevada. Available at: http://costperformance.org/monitoring/pdf/type1312_2.pdf http://www.innova.dk/1412_details.gas_monitoring4.0.html
Analytical – Raman Spectroscopy	Measurement of the wavelength and intensity of scattered light from molecules. When electromagnetic radiation passes through matter, most of the radiation continues in its original direction. However, a small fraction is scattered in other directions. Using Raman spectroscopy, the Raman probe detects many organic and inorganic chemicals in the media surrounding the probe. The probe uses laser light beamed through a sapphire window. When the light hits the sample, it causes molecules to vibrate in a distinctive way, creating a "fingerprint." The fingerprint is captured and transmitted via fiber optic cables to an analyzer, where it is compared to known signals. Can be used to provide direct evidence of NAPL. Data interpretation can be complex. Only a few analyte groups can be identified.	DOE. 1999. *Raman Probe*. DOE/EM-0442, Innovative Technology Summary Report 1544, U.S. Department of Energy, Office of Science and Technology, Washington, D.C. Available at: http://apps.em.doe.gov/ost/pubs/itsrs/itsr1544.pdf http://www.cpeo.org/techtree/ttdescript/ramprob.htm

Table 5.16. (contd.)

Technology	General Description	Example Vendor/Reference Information
Analytical – Ultraviolet (UV) Fluorescence	Fluorescence is a standard analytical technique that can be used to measure the concentration of various analytes in many different matrices. For PAHs, only UV light is required to excite the emission of visible light. When UV light is passed through a sample, the sample emits light (fluoresces) proportional to the concentration of the fluorescent molecule in the sample. UV fluorescence is based on the measurement of fluorescence observed following UV excitation of organic solvent extracts of sediments. Rapid results can guide sampling locations. There is the potential for high data density for mapping. The technique is matrix sensitive and requires site-specific calibration.	http://costperformance.org/monitoring/pdf/uvfluorescence_2.pdf
Analytical – NAPL Characterization – dyes, Sudan IV, or Oil Red O	Sudan IV or Oil Red O dye can be added to samples, which turn orange-red in the presence of NAPL, to qualitatively identify separate phases. Qualitative assay on soil sample.	http://clu-in.org/download/char/GWMR_Fall_109-123.pdf

Table 5.17. Enabling Technologies: Subsurface Access

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Subsurface Access – Direct Push – Cone Penetrometer (CPT)	Truck-mounted, hydraulically powered, direct push technology for insertion of sensors into the subsurface. Insertion cone/rod diameter of up to about 2 in. Originally developed for real-time determination of soil/moisture properties, the technology has evolved to employ additional sensors for characterizing contamination. Wireline CPT allows multiple CPT tools to be interchanged during a single penetration, without withdrawing the CPT rod string from the ground.	Less expensive than drilling; good vertical delineation. Wireline tools allow use of many different sensors/sampling devices. May not be able to penetrate debris. This technology is commonly used for environmental applications. Relatively inexpensive except in debris areas.	http://www.conepenetration.com/ http://www.cpeo.org/techtree/ttdescript/conpent.htm Applied Research Associates (Wes Braton, www.ara.com, 509-942-1841) http://www.itrcweb.org/Documents/SCM_2_For Web.pdf http://apps.em.doe.gov/OST/pubs/itsrs/itsr316.pdf http://www.frtr.gov/site/3_3_1.html Petersen et al. (2001) (BHI-01484, Rev. 1)
Subsurface Access – Direct Push – GeoProbe	Hydraulically powered, direct push machines that use both static force (hydraulic systems) and/or percussion to advance sampling and logging tools into the subsurface. Hole diameter may be from 1- to 3.25 in. May go to depths of 100 ft (30m) or more where the geology and soil conditions are appropriate. GeoProbe is a brand name, but is often used in a general sense to refer to direct-push boreholes used for down-hole sensors and/or monitoring wells.	No cuttings are produced during the sampling process. Probing is fast: typical penetration rates are from 5 to 25 ft (2 to 8 m) per minute. Mobilization is quick and economical. The sampling process is fast; 20 to 40 sample locations per day. Probing machines are easy to operate and relatively simple to maintain. Probing tools create small diameter holes that minimize surface and subsurface disturbance. Most applicable in unconsolidated sediments; penetration is limited in semi-consolidated sediments and is generally not possible in consolidated formations. May also be limited in unconsolidated sediments with high percentages of cobbles and boulders or soils high of very high density.	http://www.geoprobe.com/what_is/directpush.htm http://www.itrcweb.org/Documents/SCM_2_For Web.pdf

Table 5.17. (contd.)

Technology	General Description	Advantages/Disadvantages, Effectiveness and Limitations	Example Vendor/Reference Information
Subsurface Access – Drilling	Methods include mud/water rotory, air rotory, cable-tool, hollow-stem auger, and resonant sonic.	Good penetration. Produces large borehole for logging tool insertion. This technology is commonly used for environmental applications. Relatively expensive.	Water Development Corporation (WDC), Woodland, California. PROSONIC (http://www.prosoniccorp.com/PDF/HTML/ Leader_in_Sonic_Drilling/) Boart Longyear (http://www.boartlongyear.com/html/drilling_services/sonic_services.php) Petersen et al. (2001) (BHI-01484, Rev. 1)
Subsurface Access – Test Pits	Limited excavation (i.e., with a backhoe) to provide access to the subsurface. May be used for sample collection, visual inspection, dig face assays, etc.	Provides subsurface access for sample collection and more detailed determination of vertical distribution of contaminants/debris. Has previously been used successfully at the Hanford Site. Limited to about 4 m depth. Generates significant secondary waste.	Christy AD, LA McFarland, and D Carey. 2000. "The Use of Test Pits to Investigate Subsurface Fracturing and Glacial Stratigraphy in Tills and Other Unconsolidated Materials." *Ohio J Sci*. 100(3/4):100-106. Multiple vendors (i.e., backhoe operators with proper Radiation Worker training). http://hanford-site.pnl.gov/envreport/2002/pdf/14295/14295-71.pdf IAEA. 1998. *Characterization of Radioactively Contaminated Sites for Remediation Purposes*. IAEA-TECDOC-1017, International Atomic Energy Agency, Vienna, Austria. Available at: http://www-pub.iaea.org/MTCD/publications/PDF/te_1017_prn.pdf

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Appendix A

Cross Reference to 200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix, and Supporting Documentation, dated March 30, 2005

Appendix A

Cross Reference to 200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix, and Supporting Documentation, dated March 30, 2005

The collaborative workshop document provides a description of activities and considerations for revising the RI/FS Work Plan. Table A-1 lists the specific items that are addressed, in part, by the information herein.

Table A.1. Description of How the Technology Survey Supports Resolution of Specific Items from the *200-SW-1 and 200-SW-2 Collaborative Workshops—Agreement, Completion Matrix, and Supporting Documentation*, dated March 30, 2005. Text in the first three columns is directly from the collaborative workshop document.

Section	Description (Ecology)	Details (DOE)	Role of Technology Survey
1.2 Scope and Objectives, *OR in* 2.0 Background and Setting	Add a table of "Key Assumptions" that drive your scope/cost/schedule See Idaho OU7-13-14 for example of key assumptions Note that in EPA's guidance on RI/FS, they suggest a work plan section titled "Costs and Key Assumptions." It may be appropriate to add such a section to this work plan, to the extent that certain cost information would helpful. For example, if treatability investigations are anticipated, and the cost would be in the range of $20MM per year (the INEL figure), that would be information that would be critical for scheduling the RI/FS.	DOE will develop a table of key assumptions that drive scope, schedule, cost. During the DQO process, these key assumptions will be developed jointly by Ecology and DOE. Costs DOE will provide summary level cost estimates to support funding requests to complete the RI/FS, and for managing the project.	The technology survey provides information in Tables 2 and 4 that will assist in evaluating the need and scope of potential treatability testing. Technology information sources are provided in Table 2 to assist in gathering information needed to develop cost estimates.
4 Work Plan Approach and Rationale	Develop logic for vadose zone sampling to confirm conceptual site model for potential threat to groundwater. Propose some deeper (beyond the bottom elevation of trenches) data collection to characterize the depth of contamination, tying the sampling locations to those locations where infiltration is more of a concern (e.g., where there is a record of flooding)	DOE agrees to provide a more developed data collection logic to characterize depth of contamination below trenches in the waste sites. Specific sampling location/methodologies will be developed through the DQO process.	The technology survey provides a thorough compilation of characterization options in Tables 6 through 18 that can be used to develop appropriate characterization approaches.

Table A.1. (contd)

Section	Description (Ecology)	Details (DOE)	Role of Technology Survey
4.1.1A. Data Uses	Identify data uses for treatability investigations. Cross-reference to: Section 5.0 RI/FS Study Process: where there should be a separate section on treatability investigations. Cross-reference to: Section 5.5 Post-Record of Decision Activities: where there should be a discussion of Post-ROD treatability investigations for design. Ecology's comments that pilot tests may be needed because of the limited usefulness of INEL and M-091 cost data.	DOE will update the workplan to include the process that will be used to evaluate the need for treatability studies (see discussion under Section 5.0.A). DOE will evaluate the value of pilot test data versus the relatively (compared to bench scale tests) large cost of these types of tests. This will be done through a qualitative evaluation – based on what we know, data available that is applicable, no data available but can make assumptions. Currently envision that this data will be captured in the treatability table and treatability subsection.	The technology survey provides information in Tables 2 and 4 that will assist in evaluating the need and scope of potential treatability testing.
4.1.1B Data Uses	Explain how the data will allow an evaluation of each likely response scenario. Including problems with potential for worker exposure	DOE will explain how proposed data collection will allow balancing between short-term effectiveness, long-term effectiveness, cost, and implementability. Attachment 1 (*Table 3.1 from the DQO)*	The technology survey provides a listing of likely response scenarios and supporting technologies in Table 4. A summary description of the supporting technologies and technology information sources are provided in Table 2 to assist in the evaluation of effectiveness, implementability, and cost.
4.1.2A Data Uses	Ecology thinks that some of the data from potential 618-10/11 technology deployment might satisfy the data needs that will be identified in the DQO for this work plan. If so, describe what data will come out of 618-10/11 technology deployment and how it will be used in this RI/FS.	DOE will identify data needs and determine if other projects such as 618-10 and 618-11 can provide that information.	The technology survey identifies in Table 2 where relevant information from the 618-10/11 project may be available.
4.1.2C Data Needs	Discuss whether data are needed to refine estimates of transuranics. Is the likely percentage of RTD waste that would designate as TRU a key parameter in cost estimates? If so, what additional data are needed to develop more accurate estimates?	DOE will evaluate *in situ* technologies for assaying transuranics.	The technology survey includes a compilation of technologies potentially appropriate for assaying transuranics in Tables 15 and 16.
4.2 Characterization Approach *OR* 4.1	Discuss available characterization approaches, and justify why some approaches were discarded and why the selected approach was chosen.	DOE agrees to provide characterization approaches rationale in a format similar to Section 7.0 (add a column that describes why technique wasn't selected) of the DQO. (Attachment 2)	The technology survey provides a thorough compilation of characterization options in Tables 6 through 18 that can be used to develop appropriate characterization approaches.
5.0A RI/FS Study Process	Include a separate section on treatability study investigations.	DOE will add this as a separate section and treatability needs will be discussed as well (Attachment 3*)*	The technology survey provides information in Tables 2 and 4 that will assist in evaluating the need and scope of potential treatability testing.

Table A.1. (contd)

Section	Description (Ecology)	Details (DOE)	Role of Technology Survey
5.5 Post-ROD Activities	Discuss long-lead time activities including potential treatability investigations for design.	DOE will describe the concept of phasing a response for different areas and how the lead time on treatability investigations for design could make some BGs come later in the overall response DOE will explain how the need for post-ROD treatability investigations won't prevent them from meeting the requirement for substantive and continuous remediation 15 months post-ROD	The technology survey provides information in Tables 2 and 4 that will assist in evaluating the need and scope of potential treatability testing.
6.0A Schedule	▪ Add optional "treatability investigations" with a typical duration, showing the critical path relationship. ▪ It's okay to distinguish between treatability investigations required for the FS, and those required for remedial design. ▪ Show activities to two WBS levels below treatability investigation, to allow evaluation of the "typical" duration. Two levels below might include: - Draft Test Plan - Regulatory review/approval cycle for test plan - Procurement - Testing - Draft Test Report - Regulatory review/approval cycle for report - The predecessor-successor relationship to the feasibility study	▪ If DOE can establish in the DQO that a treatability investigation is not needed, then this level of detail is not required. ▪ If needed, DOE will provide the treatability test plan schedule consistent with the level of detail currently in the work plan.	The technology survey provides information in Tables 2 and 4 that will assist in evaluating the need and scope of potential treatability testing.

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