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Office of Technology Development

In Situ Remediation Integrated Program

In Situ Physical/Chemical Treatment Technologies for Remediation of Contaminated Sites: Applicability, Development Status, and Research Needs

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June 1994

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In Situ Physical/Chemical Treatment Technologies for Remediation of Contaminated Sites: Applicability, Development Status, and Research Needs

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ACRONYMS AND ABBREVIATIONS

AFESC	-	Air Force Engineering and Services Center
ANL	-	Argonne National Laboratory
BNL	-	Brookhaven National Laboratory
CERCLA	-	Comprehensive Environmental Response Compensation and Liability Act
CRADA	-	Cooperative Research and Development
CROW	-	Contaminated Recovery of Oily Wastes (CROW™)
CT	-	carbon tetrachloride
DCA	-	dichloroethane
DCE	-	dichloroethene
DNAPLs	-	dense, non-aqueous-phase liquids
DOD	-	U. S. Department of Defense
DOE	-	U. S. Department of Energy
EM	-	Office of Environmental Restoration and Waste Management
EM-40	-	Office of Environmental Restoration within EM
EM-50	-	Office of Technology Development within EM
EPA	-	U. S. Environmental Protection Agency
EPRI	-	Electric Power Research Institute
ER	-	Office of Environmental Restoration
FEMP	-	Fernald Environmental Management Project
FMPC	-	Feed Materials Production Center
FY	-	fiscal year
GRI	-	Gas Research Institute
HS	-	Hanford Site
INEL	-	Idaho National Engineering Laboratory
IP	-	Integrated Program (Office of Technology Development)
ISPCT	-	in situ physical/chemical treatment
ISR	-	in situ remediation
KCP	-	Kansas City Plant
LLNL	-	Lawrence Livermore National Laboratory
LUST	-	leaking underground storage tank
MWLID	-	Mixed Waste Landfill Integrated Demonstration
NATO/CCMS	-	North Atlantic Treaty Organization/Committee on Challenges to Modern Society
NSF	-	National Science Foundation
NTS	-	Nevada Test Site
OER	-	Office of Energy Research
ORNL	-	Oak Ridge National Laboratory
ORR	-	Oak Ridge Reservation
OTD	-	Office of Technology Development
PAD	-	Paducah Gaseous Diffusion Plant
PAH	-	polycyclic aromatic hydrocarbon
PCBs	-	polychlorinated biphenyls
PCE	-	perchloroethylene (tetrachloroethene)
PIN	-	Pinellas Plant
PNL	-	Pacific Northwest Laboratory

ACRONYMS AND ABBREVIATIONS (cont.)

PORTS	-	Portsmouth Gaseous Diffusion Plant
PTX	-	Pantex Plant
R&D	-	research and development
RCRA	-	Resource Conservation and Recovery Act
RD&D	-	research, development and demonstration
RFP	-	Rocky Flats Plant
RREL	-	Risk Reduction Engineering Laboratory
SBIR	-	small business innovative research
SITE	-	Superfund Innovative Technology Program
SNL	-	Sandia National Laboratories
SRL	-	Savannah River Laboratory
SVOC	-	semivolatile organic compound
TCA	-	trichloroethane
TCE	-	trichloroethene
TTP	-	technical task plan
USAEC	-	U.S. Army Environmental Center
USAF	-	U.S. Air Force
USATHAMA	-	U.S. Army Toxic and Hazardous Materials Agency (now the USAEC)
UV	-	ultraviolet
VISITT	-	Vendor Information System for Innovative Treatment Technologies
VOC	-	volatile organic compound
WHC	-	Westinghouse Hanford Corporation
WSRC	-	Westinghouse Savannah River Company

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PREFACE

The In Situ Remediation Integrated Program (ISR IP), instituted by the U. S. Department of Energy's Office of Technology Development, focuses research and development on the in-place treatment of contaminated environmental media, such as soil and groundwater, and the containment of contaminants to prevent the contaminants' spread through the environment. Using in situ technologies to clean up DOE sites minimizes adverse health effects to workers and the public by reducing contact exposure. The technologies also significantly reduce the costs for cleanup by eliminating the need for waste excavation, transport, and disposal; and enable the remediation of relatively inaccessible areas, such as the deep subsurface and areas beneath structures.

This document was prepared under the ISR IP and describes technologies in one of four program areas within the ISR IP. The four program areas are in situ physical/chemical treatment technologies, bioremediation, containment technologies, and in situ manipulation/enabling technologies. In situ physical/chemical treatment technologies address processes that will remove or extract, destroy, and immobilize contaminants. The bioremediation area includes biological processes to destroy organic contaminants and mobilize or immobilize heavy metals and radionuclides. Containment technologies encompass both surface and subsurface barriers, as well as sorbent or permeable barriers and drainage systems. The in situ manipulation/enabling technologies include those technologies that will enable the addition, mixing, and transfer of reagents or energy into the subsurface, and those that can be used to monitor and measure the performance of in situ technologies. These documents summarize the current state-of-the-art for each program area and the research and development requirements to advance the technologies to the point of demonstration and deployment. These documents will be used by the ISR IP as planning guides and will be revised and updated annually.

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EXECUTIVE SUMMARY

The U. S. Department of Energy (DOE) In Situ Remediation Integrated Program (ISR IP) was established in June 1991 to facilitate the development and implementation of in situ remediation technologies for environmental restoration within the DOE complex. Within the ISR IP, four subareas of research have been identified: (1) in situ containment, (2) in situ physical/chemical treatment (ISPCT), (3) in situ bioremediation, and (4) subsurface manipulation/electrokinetics. Although set out as individual focus areas, these four are interrelated, and successful developments in one will often necessitate successful developments in another.

In situ remediation technologies are increasingly being sought for environmental restoration due to the potential advantages that in situ technologies can offer as opposed to more traditional ex situ technologies. These advantages include limited site disruption, lower cost, reduced worker exposure, and treatment at depth under structures. While in situ remediation technologies can offer great advantages, many technology gaps exist in their application. These include inadequate information, particularly at field scale, in the areas of performance potential, implementation constraints, limitations to applicability, and verification of performance. This document presents an overview of ISPCT technologies and describes their applicability to DOE-complex needs, their development status, and relevant ongoing research. It also highlights research needs that the ISR IP should consider when making funding decisions. Preparation of this document was accomplished through acquisition, review, and synthesis of a variety of information associated with DOE-complex needs and the stage of development of ISPCT technologies. This effort included an assessment of the physical conditions and site characteristics of specific DOE sites. The technology developmental status of ISPCT processes potentially applicable to DOE-complex needs was assessed through review of technical literature and personal inquiries, review of information sources regarding technology research and development (R&D) activities, review of national R&D programs, and review of recent and ongoing R&D projects. The needs information was synthesized with the technology development status to enable identification of technical gaps and definition of the research needs for ISPCT within the ISR IP. It is envisioned that this report will be updated periodically to reflect R&D advances and necessary and appropriate changes in program objectives, scope, and schedule.

ISPCT processes can remediate subsurface contaminants without excavation of the contaminated soils or pumping of the groundwater. ISPCT involves additions to or alterations of the subsurface that change the physical and/or chemical properties of the subsurface environment. The contaminants of interest can either be treated in place or transferred to the surface via a secondary carrier phase for subsequent treatment. ISPCT processes can either be applied as an alternative to in situ biological processes or as pre- or post-treatment to facilitate bioremediation. ISPCT can be used in environments where microorganisms fail to thrive, can treat recalcitrant organic and inorganic compounds, and can accomplish treatment more rapidly and extensively than in situ bioremediation.

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ACKNOWLEDGMENTS

This document was prepared as a planning guide for identifying in situ physical/chemical treatment processes applicable to various U. S. Department of Energy (DOE) needs, to summarize their development status, to identify ongoing research, and outline research needs. It is anticipated that this document will be revised and updated on an annual basis.

This document was prepared through the combined efforts of scientific and engineering staff at Oak Ridge National Laboratory (ORNL), with sponsorship provided by the In Situ Remediation Integrateed Program of the DOE Office of Technology Development. Mr. Jeffrey Walker, Program Manager, and Ms. Mary Peterson, Program Coordinator, are acknowledged for their guidance and oversight. Both internal and external peer reviewers are also acknowledged for their contributions.

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1. INTRODUCTION

1.1 PURPOSE AND SCOPE

Contamination of soil and groundwater media by a wide variety of organic and inorganic substances is prevalent at commercial and industrial sites throughout the United States and abroad. At facilities within the U.S. Department of Energy (DOE) complex, contaminated land presents serious challenges to science and engineering due to the nature of the contamination and the complexity of the sites involved. In situ remediation (ISR) technologies are increasingly being sought for environmental restoration due to the potential advantages that ISR technologies can offer compared to more traditional ex situ technologies. These advantages include limited site disruption, lower cost, reduced worker exposure, lower secondary-waste generation, and treatment potential at depth or under obstructed sites.

The DOE In Situ Remediation Integrated Program (ISR IP) was established in June 1991 to facilitate the development and implementation of ISR technologies for environmental restoration within the DOE complex. According to the ISR IP strategic program plan, "ISR technologies shall contain, destroy, immobilize, recover, or neutralize contaminated soil, groundwater, or related environmental media" (DOE 1993). The ISR IP program includes research and development (R&D) from proof of concept through field demonstration.

In situ treatment processes can remediate subsurface contaminants without excavation of the contaminated soils or extraction of the groundwater. The contaminants of interest can be either treated in place or transferred to the surface via a secondary carrier phase for subsequent treatment. In this context, aboveground treatment of contaminated groundwater (a.k.a. pump and treat) is not considered an in situ treatment; however aboveground treatment of soil-sorbed contaminants (e.g., soil flushing) is considered part of an in situ treatment process.

Within the ISR IP, four subareas of research have been identified: (1) in situ containment, (2) in situ physical/chemical treatment (ISPCT), (3) in situ bioremediation, and (4) subsurface manipulation/electrokinetics (DOE 1993). While set out as individual focus areas, these four are obviously interrelated, and successful developments in one will often necessitate successful developments in another. Of the four focus areas, two are predominately contaminant treatment processes (i.e., in situ bioremediation and ISPCT), whereas the other two areas include techniques that can be used to minimize the impact of existing contamination or facilitate the application of in situ treatment processes. Biological treatment is most often used to degrade organic contaminants, although in situ biological processes to immobilize non-organic contaminants (metals, radionuclides, nitrates) are currently being developed. ISPCT can overcome many of the shortcomings encountered with in situ bioremediation. For example, ISPCT can be used in environments where microorganisms fail to thrive, can treat recalcitrant organic and inorganic compounds, and accomplish treatment more rapidly and extensively than in situ bioremediation. ISPCT processes can be applied either as an alternative to in situ biological treatment or as a pre- or post-treatment in conjunction with biological treatment.

The overall goal of ISPCT research within the ISR IP should be to develop a portfolio of ISR technologies employing physical/chemical processes for treatment of contaminants in situations that are common at DOE sites. These processes may be categorized as in situ contaminant transfer (e.g., extraction), destruction (e.g., chemical oxidation), or immobilization (e.g., microencapsulation) and may be employed individually or in combination with other processes to form an ISR technology. An example is the in situ treatment of dense, non-aqueous-phase liquids (DNAPLs), which may require temporary containment during treatment followed by effective subsurface manipulation to deliver and disperse appropriate chemical and biological treatment agents.

The purpose of this document is to provide a foundation for establishing R&D priorities for ISPCT of contaminated soil and groundwater within the ISR IP. No attempt was made to differentiate between soil treatment and groundwater treatment; rather, the needs of the DOE complex were evaluated as a whole. This report includes several elements: (1) an assessment of DOE needs for which ISPCT may be applicable, (2) a discussion of the stage of development of selected ISPCT processes and technologies, (3) a discussion of ongoing R&D related to ISPCT, (4) identification of technical gaps that exist and for which ongoing R&D will likely not provide solutions, and (5) recommendations for current priorities. This document is intended to be used as a source of information during DOE's planning process.

1.2 APPROACH

Preparation of this document was accomplished through acquisition, review, and synthesis of a variety of information associated with DOE-complex needs and the stage of development of ISPCT technologies. Complex-wide needs assessments and site-specific technology logic diagrams were reviewed to gain a broad perspective of DOE-complex needs and the perceived priority of in situ remediation technologies as stated by those actually responsible for implementing environmental restoration technologies. This effort also included an assessment of the physical conditions and site characteristics of specific DOE sites. This type of site-specific review was deemed necessary to better define the contamination and physical conditions as related to the applicability of ISPCT technologies. The main sources for this information were the environmental reports issued annually by each facility in compliance with DOE orders. A synopsis of DOE contamination characteristics and an assessment of technology needs and constraints associated with application of ISPCT are given in Section 2.0.

The technology developmental status of ISPCT processes potentially applicable to DOE-complex needs was assessed through the following means: (1) review of technical literature and personal inquiries, (2) review of information sources regarding technology R&D activities in the United States and abroad, (3) review of national R&D programs, and (4) review of recent and ongoing projects. The information from these sources was assimilated to yield an understanding of the development status of ISPCT technologies. A comprehensive technical discussion of each technology is beyond the scope of this document and may be found elsewhere in the literature. A synopsis of this effort is presented in Section 3.0. The needs information was synthesized with the technology development status to enable identification of technical gaps and definition of research needs for ISPCT within the ISR IP. Section 4.0 presents a description of the proposed research needs.

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This document represents the first edition covering ISPCT technologies within the ISR IP. It is intended that it will be updated periodically to reflect necessary and appropriate changes. R&D needs with regard to in situ physical/chemical processes will change as projects are completed and progress is made. Priority needs will undoubtedly change as technologies become available for solving some environmental restoration problems. R&D is currently being funded within the ISR IP. Additional R&D will be funded in the years ahead. This existing and future work should be integrated to accomplish the objectives outlined in this report.

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2. ASSESSMENT OF DOE NEEDS

To enable examination of needs within the DOE complex for which ISPCT technologies may be applicable, it was necessary to define both the common contaminants and soil and groundwater conditions (Table 2.1). The most predominant sources of contamination at selected DOE sites appear to be the various liquid and solid-waste management units such as liquid-waste disposal facilities (e.g., land treatment units, surface impoundments, retention ponds, burning pits, and french drains) and buried waste deposits (e.g., pits, trenches, and landfills). A number of these waste management units have been "closed" under the Resource Conservation and Recovery Act (RCRA), with a closure strategy that included surface capping. However, since these were not clean closures, the facilities are required to monitor the groundwater surrounding the sites to ensure effectiveness of the cap in isolating the waste disposal unit. Other sources of contamination include leaking liquid-waste pipelines, high-use areas (areas surrounding waste treatment facilities, test firing sites) and leaking underground storage tanks (LUSTs). The latter do not seem to be causing wide-spread groundwater contamination in most facilities, only affecting soils surrounding tanks. Leachates from the land treatment units and burial sites have in many cases resulted in contamination of subsurface media, including soil and groundwater (Table 2.1). In addition, there are situations where contamination of surface-water sediments has occurred due to off-site releases.

Simple characterization of these contaminated media is precluded by the diversity of conditions encountered. In considering the priority of the problem, the potential environmental impact of contamination must be considered. In Table 2.1, wherever possible, the perceived environmental impact is provided. The prevalence of contaminants and mixtures are highlighted in Table 2.2. As shown, the most prevalent classes of contaminants are: (1) radionuclides, (2) chlorinated hydrocarbons [including volatile organic compounds (VOCs)], and (3) anions (specifically non-routine anions). Mixtures of contaminants are also very common (see Tables 2.1 and 2.2).

The problems and needs of the DOE complex are diverse and challenging for any remediation technology, including in situ technologies. Even though these challenges confront all remediation technologies, it is important to recognize that to be feasible and effective and to contribute to ER progress within the DOE complex, ISPCT must be developed and implemented within the framework of needs outlined in Table 2.3. As will be discussed in subsequent sections of this report, the above framework is applicable to ISPCT alone or in combination with other forms of in situ remediation. In fact, for many of the needs, ISPCT technologies represent the only viable form of remediation based on treatment.

Table 2.1. Physical and contamination conditions at selected DOE facilities.

DOE Facility	Hydraulic conductivity (K) of subsurface materials [a]	Site complexity and heterogeneity	Depth of contamination	Extensive areal groundwater contamination[b]	Environmental impact
ANL	Low K layer (silty-clay glacial till) overlying high K zone (dolomite)		< 30 m[c]		Underlying aquifer (dolomite) is a domestic water-supply source.
BNL	High K zone (sands)		< 60 m[c]		BNL is a recharge area for a "sole-source aquifer."
FMPC/ FEMP	Low K layer (silty-clay glacial till) overlying high K layer (sand and gravel). Pockets of clay exist in the high K zone.		~ 45 m[d]	U plume in Great Miami aquifer	Underlying Great Miami aquifer is a water source for local farms, homes, and businesses.
HS	High K layers (600 to 3000 m/d) separated by low K layers (0.1 m/d)	heterogeneous	~ 106 m[e]	H-3, Tc-99, CCl_4, DNAPL, chloroform, cyanide, nitrate plumes	Groundwater seeps to Columbia River.
INEL	Interbedded high K layers (sedimentary deposits) and low K zones (basaltic rocks)	complex fracture flow in Snake River Plain aquifer	~ 270 m[e]	H-3, Sr-90, Na, nitrate plumes in Snake River Plain aquifer	Snake River Plain aquifer is an important water source in southeastern Idaho.
KCP	Low K zone (0.3 m/d; sand-clay-silt) overlying high K layer (basal gravel)		< 12 m[c]	TCE plume, PCBs in soils	
LLNL	High K zone (1 to 6 m/d)	heterogeneous, interbedded layers of clay, silt, sand, and gravel	< 119 m[c]	VOC plume	
LLNL, Site 300	High K zones (aquifers) in deep underlying formation	complex and very heterogeneous	shallow	TCE (DNAPL) plume	Drinking and process water obtained from underlying Neroly Lower Blue Sandstone aquifer.

Table 2.1. Physical and contamination conditions at selected DOE facilities (continued).

DOE Facility	Hydraulic conductivity (K) of subsurface materials [a]	Site complexity and heterogeneity	Depth of contamination	Extensive areal groundwater contamination[b]	Environmental impact
NTS	Low to high K zone (0.02 to 1 m/d estimated from transmissivity and thickness of the Valley Fill aquifer) overlying high K zone (carbonate)			Areally extensive H-3, Pu in soil	Potential for migration of Pu-contaminated soils.
ORR	Low K zones (<0.1 m/d)	heterogeneous fracture flow with matrix diffusion	150m[d]	Nitrate and VOC (DNAPL) plumes	Potential migration of radioactive contaminants through shallow subsurface storm flow to the Clinch River.
PAD	High K zones (4 m/d) interbedded in low K zones (10^{-6} m/d); underlying high K zone (regional gravel aquifer)	heterogeneous	< 60 m[e]	TCE (DNAPL), Tc-99 plumes in regional gravel aquifer	A number of residences use water from the regional gravel aquifer for domestic and agricultural purposes.
PTX	High K zones(aquifers) in deep underlying formations	heterogeneous	~ 100 m[d]		Overlies the Ogallala aquifer, which is a principal water supply on the high plains.
PIN	High K zone (shelly sands)		< 27 m[c]		Overlies the Floridan aquifer which is a water source for Pinellas County.
PORTS	Low K zones (10^{-4} to 10^{-3} m/d) separating high K zones (1 m/d)		< 30 m[d]	TCE plume in the Gallia Sand	
RFP	Low K zone (10^{-2} m/d)		< 30 m[d]	TCE and radionuclide (U) plume	

Table 2.1. Physical and contamination conditions at selected DOE facilities (continued).

DOE Facility	Hydraulic conductivity (K) of subsurface materials [a]	Site complexity and heterogeneity	Depth of contamination	Extensive areal groundwater contamination[b]	Environmental impact
SNL	Low to high K zone (0.001 to 1 m/d)	complicated by fault blocks	> 150 m[e]	TCE plume	
SRL	Low K zones (10^{-5} to 10^{-2} m/day) interbedded with high K zones (0.2 to 10 m/day)	heterogeneous	< 30 m[d]	TCE (DNAPL) and nitrate/H-3 plumes	Groundwater discharges to Savannah River.

Information was derived from recent site environmental monitoring reports as listed in the source materials (Sect. 5).

[a] Zones with K values less than 1 m/d (1.1×10^{-3} cm/s) are considered as low permeability zones. If K values are unavailable, the conductivity is inferred from the aquifer material type.

[b] Includes the presence of DNAPLs.

[c] Depth of contamination based on the depth to the base of the contaminated hydrogeologic zone.

[d] Depth of contamination based on the depth of groundwater monitoring wells.

[e] Depth of contamination based on the depth to the water table.

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Table 2.2. Prevalence of contaminants encountered at selected DOE facilities.

DOE facility	Predominant class of contaminants	Contaminant mixtures	Chlorinated hydrocarbons	Fuel hydrocarbons	Radionuclides	Anions	Metals
ANL	Chlorinated hydrocarbons, radionuclides		TCA, 1,1-DCA, TCE		H-3, Sr-90	Cl	Cr, Cu, Fe, Mn, Pb, As
BNL	Chlorinated hydrocarbons	Chlorinated hydrocarbons/ fuel hydrocarbons; chlorinated hydrocarbons/ radionuclides	TCA, PCE, TCE	benzene, toluene, xylene, ethylbenzene	Sr-90		Fe
FMPC/ FEMP	Radionuclides	Radionuclides/ metals/ chlorinated hydrocarbons	DCE, TCE	benzene, xylene	U, Th, Ra, Tc-99, Sr-90	SO_4	Ba, Ca, Mg, Cd
HS	Radionuclides, chlorinated hydrocarbons, anions	Radionuclides/ anions/ chlorinated hydrocarbons	CCl_4 (DNAPL), chloroform		Tc-99, Pu, U, H-3, Sr, Co, I-129	NO_3	Cr
INEL	Radionuclides, anions	Radionuclides/ anions/ chlorinated hydrocarbons/ metals	CCl_4, 1,1,1-TCA, TCE, PCE	toluene, benzene	H-3, Co-60, Cs-137	SO_4, Cl, NO_3	Cr, Na
KCP	Chlorinated hydrocarbons, PCBs	Chlorinated hydrocarbons/ PCBs	TCE, 1,2-DCE, chloroethane	benzene			
LLNL	Chlorinated hydrocarbons		TCE, PCE, 1,1,1-TCA, CCl_4, chloroform	NSH			
LLNL, Site 300	Chlorinated hydrocarbons		TCE (DNAPL)				
NTS	Radionuclides				H-3, Pu-238, Pu-239		
ORR	Radionuclides, anions, chlorinated hydrocarbons	Radionuclides/ anions/ chlorinated hydrocarbons	TCE (DNAPL), PCE, CCl_4, 1,2-DCE, 1,1,1-TCA, chloroform	NSH	U, H-3, Tc, Ra, Np, Am, Sr, Co	NO_3	Hg, As, Ba, Cd, Cr, Pb, Ni

The information shown was derived from recent site environmental monitoring reports among those listed as source materials in Sect. 5.

NSH: Non-specified hydrocarbons.

Table 2.2. Prevalence of contaminants encountered at selected DOE facilities (continued).

DOE facility	Predominant class of contaminants	Contaminant mixtures	Chlorinated hydrocarbons	Fuel hydrocarbons	Radionuclides	Anions	Metals
PAD	Chlorinated hydrocarbons, radionuclides	Chlorinated hydrocarbons/ radionuclides	TCE (DNAPL)		Tc-99		
PTX	Chlorinated hydrocarbons, radionuclides		TCE, 1,2-DCA		U-238		Cr
PIN	Chlorinated hydrocarbons		VOCs				
PORTS	Chlorinated hydrocarbons	Chlorinated hydrocarbons/ radionuclides	TCE, 1,1,1-TCA, 1,1-DCE, CCl_4, chloroform		Tc-99, U		
RFP	Radionuclides, chlorinated hydrocarbons	Radionuclides/ chlorinated hydrocarbons	TCE, PCE, CCl_4		U, Cs-137, Am, Pu, Ra		Cr, Li, K, Sr, Mn, Na, As, Ni, Se, Zn, Cu, Fe, Mg
SNL	Chlorinated hydrocarbons		TCE				Hg
SRL	Chlorinated organic compounds, radionuclides	Radionuclides/ anions	TCE, PCE, CCl_4 (DNAPL)		Ra, U, H-3	NO_3, SO_4	Pb, Hg

The information shown was derived from recent site environmental monitoring reports among those listed as source materials in Sect. 5.

NSH: Non-specified hydrocarbons.

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Table 2.3. Needs framework for ISPCT technology development.

Site physical conditions
Low subsurface hydraulic conductivity (e.g., silts and clays)
Substantial site complexity and heterogeneity (e.g., interbedded and fractured media)
Deep and vertically extensive contaminated regions (e.g., 53 m)
Relatively extensive areal regions of contamination (e.g., mile-long plumes)
Sites obstructed by surface and subsurface features (e.g., utilities, roads, buildings)
Contaminants of key concern
Mixtures of low-level radioactive substances (e.g., U, Tc) and hazardous volatile organic compounds (e.g., TCE, TCA, MC, CT)
Radioactive isotopes (e.g., H-3, Sr-90, Cs-137)
DNAPLs (e.g., TCE, PCE)
Hazardous heavy metals (e.g., Hg, Cr, Pb)
Hazardous organic compounds that are more refractory (e.g., PCBs)
General technology features
In situ processes that are proven in the field and able to reliably achieve desired performance
Technologies conducive to monitoring and process control and performance verification
In situ processes that are less costly than ex situ processes

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3. TECHNOLOGY DEVELOPMENT STATUS

3.1 FEATURES OF ISPCT TECHNOLOGIES

ISPCT involve additions to or alterations of the subsurface that change the physical and/or chemical properties of the subsurface environment. In response, the contaminants of concern are either *transferred* to another waste stream for subsequent treatment, *destroyed* and/or rendered non-toxic, or *immobilized* in a dispersed, stabilized matrix that isolates contaminants and prevents further subsurface migration. The subsurface can be physically manipulated using processes such as heating, freezing, mixing, or fracturing. Chemical properties that can be altered include pH, ionic strength, oxidation-reduction (redox) potential, and chemical equilibria. Excellent reviews of in situ physical/chemical processes have been published previously (e.g., Handbook of In Situ Treatment of Hazardous Waste-Contaminated Soils, EPA 1990 and The Superfund Innovative Technology Evaluation Program: Technology Profile Fifth Edition, EPA 1992). For the purposes of this report, brief descriptions of the ISPCT processes are given below, while a summary of physical/chemical treatment processes with realized or potential application for in situ remediation within the DOE complex is given in Table 3.1. Many of the technologies listed in Table 3.1 are in either the conceptual or bench-scale stage. It should be noted that success at these scales does not always translate to success in the field because of site heterogeneities and complexities.

3.1.1 In Situ Contaminant-Transfer Processes

The ultimate objective of physical/chemical, in situ contaminant-transfer processes is to transfer the contaminant(s) of concern from the host matrix (soil or groundwater) to a secondary or carrier phase that can be retrieved and further processed. The carrier can be a gas phase such as air or steam, as is the case with volatilization processes. Volatilization processes are applicable to organic compounds with relatively high vapor pressures. Injection and extraction wells are often placed in the zone of contamination to facilitate volatilization. In some cases, a vacuum is applied to the extraction wells or at the surface to increase natural air flow through the contaminated medium (vacuum extraction), while in other instances clean air is pumped through contaminated groundwater (air sparging) to increase the transfer of VOCs to the gas phase. Thermal enhancement of volatilization processes include mechanisms to heat soils (e.g., microwave, radio-frequency heating) to increase the rate of volatilization of contaminants into the carrier phase. Once off-gases containing volatilized organic compounds are collected aboveground, the contaminants can then be destroyed or treated for disposal.

An aqueous carrier matrix is used with in situ soil flushing or leaching processes. In general, soil flushing is achieved by injecting water into the contaminated soil and collecting the water in extraction wells located adjacent to the treated area. Reagents can be added to the carrier water, such as surfactants to increase organic compound solubilization in the carrier phase or chelating agents to increase metals mobilization and collection. In some instances, the addition of either acidic or basic aqueous solutions is sufficient to facilitate the transfer of the contaminants of interest into the carrier phase. A somewhat related in situ physical/chemical process is electrokinetic separation. A subsurface electrical field is established to enhance the migration of charged contaminant species to implanted electrodes, where they can be collected with pore fluids. If

Table 3.1. Examples of ISPCT processes.

Treatment process area[a]	Representative technology
In Situ Transfer Processes	
Volatilization/ solvation	Air sparging Vacuum extraction Hot air or steam extraction Thermally enhanced a. microwave b. radio frequency Supercritical fluids
Adsorption	Granular activated carbon Zeolites Organic sorbents
Leaching	Surfactants Chelating agents Acids or bases
Combinations of transfer processes	Reactive membranes Saponification Washing and adsorption
Ion exchange	Zeolites
Electrokinetics	
Constructed wetlands	
In Situ Destruction Processes	
Chemical oxidation-reduction	Hydrogen peroxide Ozone Potassium permanganate Solvated electrons Chlorine dioxide
High temperature destruction	Electrical resistance heating Microwave or radio-wave heating
Photochemical degradation	
Corona discharge	
Neutralization	
Dechlorination	
In Situ Immobilization Processes	
Cryogenic barriers	
Grouting	
Vitrification	
Precipitation	
Microencapsulation	

[a] The ISPCT processes listed have realized or potential applicability to remediation of DOE sites.

sufficient moisture is present, the addition of a carrier phase is not required for electrokinetic separation.

Supercritical fluids (e.g., water or CO_2) can also be used to transfer contaminants from soil into a gaseous carrier for removal and above ground treatment. While in situ application of this process is complex (e.g., maintaining the pressures necessary to keep the fluids supercritical), its potential capability justifies consideration.

In situ physical/chemical processes are being developed that transfer contaminants to the solid phase. In situ contaminant-transfer processes with a solid carrier phase are designed with the expectation that the solid phase will at some point be retrieved for further treatment. This removal of the adsorbed, immobilized contaminant is what distinguishes these processes from in situ contaminant immobilization processes. Adsorbents applicable to in situ treatment include granular activated carbon, zeolites, ion exchange resins, and other specialty materials. These adsorbents can be placed in trenches for shallow contaminants or lowered in canisters or other specially designed containers for deeper contaminants.

3.1.2 In Situ Contaminant-Destruction Processes

In situ contaminant-destruction processes alter or destroy contaminants in place. These technologies are applied to compounds that can either be converted to innocuous species such as CO_2 and water or can be degraded to species that are non-toxic or amenable to other in situ processes (e.g., bioremediation). Chemical oxidation-reduction processes comprise one facet of in situ contaminant-destruction processes. With these processes, reagents such as hydrogen peroxide, ozone, potassium permanganate, and chlorine dioxide are contacted with subsurface contaminants to achieve remediation. In many instances, destruction is achieved by free-radical oxidation with hydroxyl radicals. Delivery and distribution of chemical reagents are critical to the effectiveness of these processes.

Another mode of in situ contaminant-destruction processes is the high temperature destruction of contaminants. These processes are still in the conceptual stage and are envisioned to be capable of destroying a wide variety of contaminants in situ at high temperatures (greater than 600 °C). Several methods have been suggested to reach these high temperatures, such as electrical-resistance and microwave heating. Other contaminant-destruction processes include corona discharge and chemical dechlorination.

3.1.3 In Situ Contaminant-Immobilization Processes

At sites where in situ contaminant-transfer or destruction processes are not feasible options, in situ immobilization processes may sometimes be employed. These stabilization and solidification technologies fall into several categories: cryogenics (e.g., ground freezing); grouting-solidification (e.g., mixing the contaminated medium with cement- or polymer-based materials); microencapsulation (e.g., dispersing encapsulating agents throughout the contaminated medium); and vitrification (e.g., transforming the contaminated medium into a glass-like solid). All immobilization technologies are aimed at isolating contaminants from contact with the environment and at providing

greater physical control of contamination. Stabilization and solidification treatment can be performed as an emergency "quick fix" to halt or reduce the spread of undesirable substances until further remedial action can be taken or for the purpose of long-term burial storage of hazardous and/or radioactive materials.

Conceptual technologies for in situ precipitation of heavy metals and/or radionuclides from soil and groundwater are emerging. In these treatment methods, a precipitating agent (e.g., iron filings or lime) is contacted with the contaminated waste stream using injection wells, trench and fill interception barriers, or chemical barrier linings. The contaminants are bound to the structure of a newly formed phase. Determination of potential clogging of groundwater flow paths is vital to the application of this technology.

Chemical compatibility between the contaminant and the immobilization or stabilization matrix is an important consideration. This compatibility can greatly affect long-term leachability of contaminates fixed by these methods and the water permeability of the stabilized, solidified waste form.

3.2 STAGE OF DEVELOPMENT AND COMMERCIALIZATION

A summary of information reported on the stage of development and applicability of commercially available and emerging ISPCT technologies is given in Appendix A. The information used to derive the summary is largely drawn from existing literature (e.g., U.S. Environmental Protection Agency (EPA) Vendor Information System for Innovative Treatment Technologies (VISITT), June, 1992; Superfund Innovative Technology Program (SITE) Technology Profiles, Nov., 1992; Federal Remediation Technologies Roundtable, May, 1991; NATO/CCMS pilot studies, April, 1988). Innovative technologies are undergoing rapid change and improvement, making it difficult to trace current information on their developmental status and commercial availability. Nevertheless, the limited information revealed that ISPCT technologies comprise only a small portion of the currently developed remediation technologies. For example, only 20 technologies out of 156 listed on the VISITT database and 10 out of 70 from the Federal Remediation Technologies Roundtable were identified as ISPCT. Among the existing technologies, most entries are found in the separation/transfer processes, with volatilization dominating. These technologies often treat one type of contaminant (for example, volatilization is targeted on volatile and semivolatile organic compounds) and cannot handle mixed wastes except with reduced efficiency. Most of the technologies have been field-tested at a site; with a few, only bench-scale testing was finished. Based on the reported information, an assessment of the stage of development and commercialization was made as indicated in Tables 3.2, 3.3 and 3.4.

3.3 OTHER NATIONAL R&D PROGRAMS

A variety of federal government agencies and national institutions sponsor R&D in areas related to ISPCT technologies. To help identify gaps in ISPCT technologies that need to be pursued by the DOE ISR IP, information was sought from other potential sponsors. These included the following groups: (1) DOE; (2) EPA; (3) U.S. Department of Defense (DOD) (Air Force and Army); (4) Gas Research Institute (GRI); (5) Electric Power Research Institute (EPRI); and (6) National Science Foundation (NSF). The highlights of this review are presented in Table 3.5, while further explanation is provided in Appendix B.

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Table 3.2. Assessed stage of the development and applicability of in situ contaminant-transfer processes for remediation of DOE sites.

In situ contaminant-transfer processes		Radio-nuclides	Metals	Chlorinated hydrocarbons	Fuel hydro-carbons	Nitrates	PCBs
Volatil-ization	Air sparging	-	-	+ F	± F	-	-
	Vacuum extraction	-	-	+ F	± F	-	-
	Hot air or steam extraction	-	-	+ F	± P	-	-
	Thermally enhanced a. microwave b. radio frequency	-	-	+ P	± C	-	-
Adsorption	granular activated carbon	+ B	+ B	+ B	± C	-	+ B
	Zeolites	NDF	NDF	NDF	NDF	NDF	NDF
	Other materials	NDF	NDF	NDF	NDF	NDF	NDF
Leaching	Surfactants	-	-	+ B	+ B	-	NDF
	Chelating agents	+ B	+ P	-	-	NDF	NDF
	Acids or bases	+ B	+ B	-	-	NDF	-
Combinations of transfer processes	Reactive membranes	± C	+ B	-	-	NDF	NDF
	Saponification	-	-	+ P	+ P	-	+ B
	Washing and adsorption	-	+ F	+ P	+ P	NDF	NDF
Ion exchange	Zeolites	+ B	+ B	-	NDF	NDF	NDF
Electrokinetics		+ P	+ P	+ P	NDF	NDF	NDF

Radionuclides: tritium, uranium, strontium, plutonium, cesium, cobalt, technetium
Metals: lead, chromium, arsenic, zinc, copper, mercury, cadmium, nickel
Chlorinated hydrocarbons: trichloroethylene, 1,1,1-trichloroethane, 1,2-dichloroethylene, chloroform, dichloromethane
Fuel hydrocarbons: benzene, toluene, xylenes, ethylbenzene

F: Field-scale demonstrations completed
P: Pilot-scale demonstrations completed
B: Bench-scale experiments completed
C: Conceptual development stage technology

+: technology applicable
-: technology not applicable
±: technology has some applicability
NDF: no data found to evaluate application

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Table 3.5 Highlights of national R&D programs with activities relevant to ISPCT technologies.

Sponsoring agency	Agency unit	Program goals relevant to ISPCT	Relevant ISPCT projects ongoing	Principal ISPCT areas of emphasis [a]
DOE	OTD	Yes	Yes	Removal of VOCs, development of horizontal well technologies, destruction of VOCs, thermal enhancement of vapor extraction, supercritical water oxidation, stabilization of metals and radioactive nuclides, and removal of metals and radioactive nuclides.
	OER	Yes	Yes	Basic research on biosorption, scavenging colloids, supercritical fluid processes, complexation of radionuclides with organic and inorganic compounds, heating, and oxidation.
	Site ER	Yes	Yes	Variable depending on site-specific needs.
EPA	Office of Exploratory Research	Yes	Yes	Solubilization of PAH using surfactants, prevention of bacteria or precipitate well-aquifer interface plugging, destruction of chlorinated hydrocarbons, removal of heavy metals, transport of heavy metals, oxidation of organics using supercritical oxidation. A majority of the funded projects investigated the removal of heavy metals from the environment.
	SITE Demo Program	Yes	Yes	Immobilization of metals using reduction, enhanced volatilization using physical processes, fracturing for improving subsurface mass transfer, radio frequency heating, destruction of VOCs, and the CROW™ process.
	SITE Emerging Technology Program	Yes	Yes	Destruction of organic contaminants using oxidation and catalytic processes, fracturing, CROW™ process, and the use of electric or acoustic fields for removal of heavy metals.
DOD	Air Force	Yes	Yes	Measurement of subsurface mass transfer, soil-vapor extraction (including ambient and soil heating techniques), immobilization of heavy metals, and contaminant destruction using catalytic and ultraviolet light oxidation methods.
	Army	Yes	Yes	Stabilization of metals in sediments and soils, treatment and removal of organic compounds from sediments, investigation of leaching processes, modeling of seepage and groundwater flow, evaluation and development thermal stripping techniques for remediation of hydrocarbon- and solvent-contaminated soils.

[a] Additional information regarding the programs listed can be found in Appendix B.

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Table 3.5 Highlights of national R&D programs with activities relevant to ISPCT technologies (continued).

Sponsoring agency	Agency unit	Program goals relevant to ISPCT	Relevant ISPCT projects ongoing	Principal ISPCT areas of emphasis [a]
EPRI		Yes	Yes	Remediation techniques for PAH and fuel contamination at coal-gas sites and LUST sites.
GRI		Yes	Yes	Physical/chemical treatment interests include CROW™ process, UV/oxidation for destruction of metal cyanide complexes, Fenton's reagent for degradation of hydrocarbons.
NSF		No	No	Some relevant basic and applied research but not focused on environmental restoration needs.
SBIR		Yes	No	Individual agency programs include ISPCT R&D.

[a] Additional information regarding the programs listed can be found in Appendix B.

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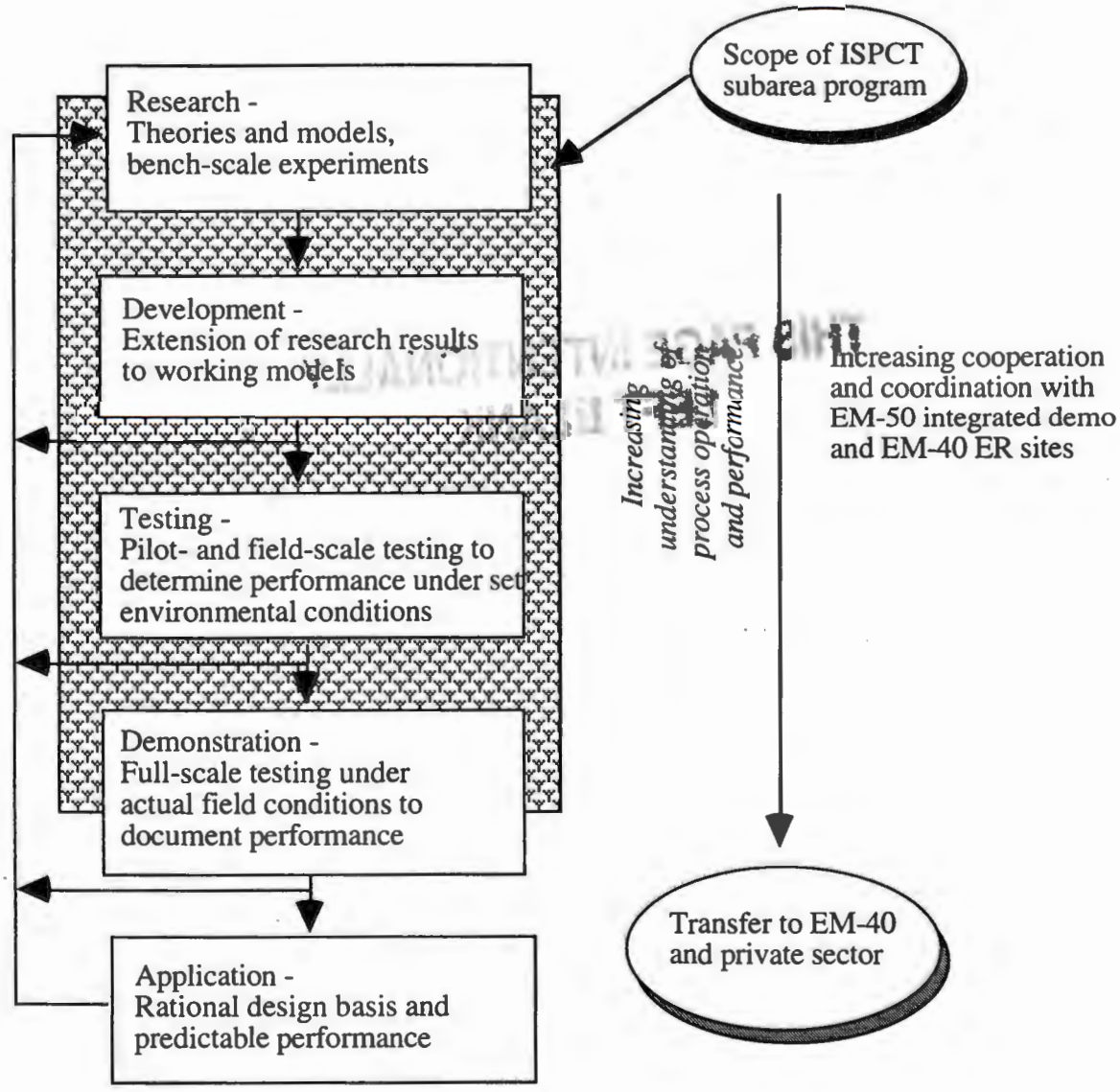

Fig. 4.1. Technology development stages and scope of ISPCT subarea.

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Table 4.1. Current and near-term gaps in technology development for ISPCT technologies.

Process area	Example technology	Illustrative technical gaps[a]
Transfer		
Volatilization	Vapor extraction	Mass-transfer efficiency in heterogeneous and low-permeability media; effects of energy enhancements; applicability to DNAPL treatment; co-processing with biodegradation
Adsorption	Zeolites and reactive sorbents	Sorbent selectivity and interferences; flow and distribution control of contaminants across the media; mass transfer across media/sorbent interfaces; fouling of sorbents associated with subsurface system geochemistry
Leaching	Soil flushing	Surfactants, chelating agents, and other agents to mobilize bound and particulate material; delivery of reagents to the soil
Extraction	Supercritical fluids	Mass-transfer efficiency for contaminant removal by supercritical fluids
Destruction		
Chemical oxidation-reduction	Oxidation	Site-specific geochemical effects on reaction kinetics and thermodynamics of liquid-phase and gas-phase oxidants; in situ catalysis and generation of free-radical oxidants; technical viability of gas-phase oxidation processes
	Reduction	Reaction kinetics and thermodynamics of transition-metal catalysts for dechlorination of halogenated organic compounds and precipitation of metals and radionuclides
High-energy	Pyrolysis	Energy consumption as affected by site-specific matrix properties; nature and extent of incomplete combustion byproducts
Immobilization		
Precipitation		Geochemistry of injected agents and homogeneity of agent/media mixtures

[a] The information shown is for illustrative purposes only. The order of presentation does not represent the priority of the technical gap. Although some information is available on these technical gaps, additional specific information is necessary. This table is undergoing further development and refinement and will be updated periodically.

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Table 4.2. Currently funded projects within the DOE ISR program that focus on ISPCT technologies (continued).

Title	Project TTP number	Principal investigator	Approx. funding: FY, $	Comments
Physical/Chemical Treatment				
NAPL remediation using foam	CH241003	R. Peters ANL	FY94, 250K	Use of foams to release and mobilize NAPL contaminants in the subsurface coupled with bioremediation.
In situ redox manipulation	RL331005	J. Fruchter, Battelle	FY93, 425K FY94, 730K FY95, 500K	Development and testing of immobilization of inorganic compounds and destruction of organic compounds by altering system chemistry.
In situ chemical treatment: evaluation of in situ chemical treatment approach for remediation of soil and groundwater	RL431001	E. Thorton, WHC	FY93, 170K FY94, 300K FY95, 170K	Development of an in situ treatment approach involving injection of reactive gases.
In situ corona for in situ treatment of non-volatile organic contaminants	RL331006	R. Moss, Battelle	FY93, 250K FY94, 107K FY95, 250K	Development of a technique for decomposing nonvolatile and bound organic compounds using gas-phase oxidants generated in situ by electrical corona.
In situ chemical oxidation of soils	OR141001	D. Gates ORNL	FY94, 300K	Study to determine the conditions when chemical oxidation can be effectively utilized as an in situ treatment process for soils contaminated with hydrocarbons and/or metals.
Remediation of DNAPL in low permeability media	OR131007	R. Siegrist ORNL	FY94, 536K	Testing and evaluation of in situ remediation technologies for both source control and mass removal of DNAPLs.
Mixed contamination in groundwater	OR141002	R. Siegrist, N. Korte ORNL	FY94, 310K	Evaluation of horizontal wells for inducing groundwater recirculation and development of below-ground treatment modules for VOC and radionuclide removal.

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Table 4.3. R&D opportunities for ISPCT technologies.

Technology area	Target contaminants (media)	Technical gap[a]
Near-term		
Volatilization	VOCs, DNAPLs (soil, low permeability media)	Heating and directed-energy methods to enhance mass transfer of volatile contaminants
Chemical oxidation-reduction	TCE, PCE, CT ... Tc-99 ... (groundwater)	Elemental metal catalysts for reductive dechlorination and precipitation of chlorinated organic compounds, metals, and radionuclides
	VOCs, Organic compounds Metals (soil, groundwater)	Liquid-phase, stable oxidation-reduction agents to destroy organic compounds and mobilize metals for recovery, or immobilize metals
	VOCs, Heavy metals (soil)	Gas-phase oxidation-reduction to enhance dispersal of agents throughout contaminated soil regions within source areas
Adsorption	Heavy metals, Radionuclides (groundwater)	Zeolite and sorbent media with increased selectivity and efficiency and reduced fouling potential
Leaching	TCE and PCE DNAPLs (soil and groundwater)	Surfactants for enhancing mobilization and recovery of TCE and PCE DNAPLs
Electrokinetics	Heavy metals, Radionuclides (soil)	Chelating agents and other agents to enhance electrokinetic-enabled migration and removal of bound and particulate materials in different geochemical settings
Longer-term		
Filtration	U, Tc, (groundwater)	Reactive membranes
Extraction	Non-volatile organic compounds (soil)	In situ supercritical fluid extraction processes to enable removal of non-volatile organic compounds from subsurface regions
Combinations	U, Tc, Cr, VOCs (groundwater)	Reactive colloids to migrate preferentially through contaminated regions and to effect treatment

[a] The information shown was derived from DOE-complex needs and technology development status; at this time, it is for illustrative purposes only. The order of presentation does not represent the priority of the technical gap. This table is undergoing further development and refinement and will be updated periodically.

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4. *Vapor Phase Catalytic Oxidation of Mixed Volatile Organic Compounds.* Greene, H. University Of Akron, Akron, Ohio, September 1989. NTIS: ESL-TR-89-12

6.2.4 U. S. Army Published Reports

1. *Demonstration of Thermal Stripping of JP-4 and Other VOCs from Soils at Tinker Air Force Base, Oklahoma City, Ok: Final Report, U S Army Toxic An Hazardous Materials Agency.* March 1990. USATHAMA: CETHA-TS-CR-90026
2. *Economic Evaluation of Low Temperature Thermal Stripping of Volatile Organic Compounds from Soil: Technical Report.* Marks, P. J. And J. W. Noland. U S Army Toxic And Hazardous Materials Agency. August 1986. USATHAMA: AMXTH-TE-CR-86085
3. *Pilot Investigation of Low Temperature Themal Stripping of Volatile Organic Compounds from Soil. U S Army Toxic and Hazardous Materials Agency. Task 11.* June 1986. USATHAMA: AMXTH-TE-TR-86074
4. *Arsenic Contaminated Treatment Pilot Study at the Sharpe Army Depot Lathrope, CA: Final Report.* U S Army Toxic And Hazardous Materials Agency. December 1990. USATHAMA: CETHA-TS-90184

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APPENDICES

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APPENDIX A:
TECHNOLOGY DEVELOPMENT AND COMMERCIALIZATION

Tables A.1 to A.3 are each divided into six categories: technology and vendor or developer, status, waste media (contaminants), capacity and cost, program, and comments. The definitions of each category are listed and discussed here. Technology includes the following features: separation and transfer, destruction, and immobilization. In this survey, vendors from private sectors and developers from government agencies and laboratories who have developed and fully tested a technology were included. The status of each technology refers to the development status of an physical/chemical treatment technology and comprises three categories: bench scale (B), a technology shown to be feasible with bench-top equipment in the laboratory, but available data cannot be used to develop field-scale use in the absence of additional pilot-scale experience for similar applications; pilot scale (P), technology for which available equipment is of sufficient size to verify technology feasibility and establish the design and operating conditions for the field-scale system; and field scale (F), technology for which available equipment is sized and commercially available for actual site remediation.

The waste media refers to the actual or potential types of media treated: soil, sludge, solid, and groundwater. The contaminants include VOCs, solvents, heavy metals, radioactive metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), etc. Capacity and cost are listed as given by vendors or developers; attempts are not made to normalize them. The costs vary considerably because some included capital cost and others considered only the maintenance cost. The program refers to an innovative technology demonstration program sponsored by a federal agency under which the technology is developed. If a program is not identified, the box was left blank. Finally, the comments include either highlights of the technology or limitations of the technology.

Table A.1 Reported stage-of-development information for ISPCT technologies that rely on contaminant-transfer processes.

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Adsorption					
Dynaphore, Inc. (804)-672-3464	P	groundwater (heavy metals, radioactive metals)	100-10,000 gal/h $0.001-0.02/gal	SITE	For low oily substance and moderate concentration; 3 times deduction
Environmental Fuel Systems, Inc. (512)-796-7767	F	groundwater/soil (VOCs, solvents)	$0.4-4/gal, 20-2000 g/h		Concentrate and absorb VOCs, depend on permeability, VOC pressure, and concentration
EPS Environmental, Inc. (201)-368-7902	F	soil/solid/sludge (mercury)	NA		Absorb mercury vapor
Volatilization					
Accutech Remedial Systems, Inc. (908)-739-6444	F	soil (VOCs)	NA	SITE	Pneumatic fracturing extraction and catalytic oxidation
Billings and Associates, Inc. (505)-345-1116	F	soil/sludge (gasoline, diesel fuels, and halogenated organics)	NA	SITE	Soil vacuum extraction combined with in situ biodegradation
Battelle, PNL (509)-376-0554	B	soil/sludge (VOCs, PAHs, solvents)	NA		Thermally enhanced soil-vapor extraction
EM&C Engineering Associates (714)-957-6429	P	soil/solid/sludge (VOCs, PAHs, solvents)	NA		Steam injection
EM&C Engineering Associates (714)-957-6429	B	soil/solid/sludge (organics)	NA		Use of in situ down-hole burners
Groundwater Technology, Inc. (609)-587-0300	F	groundwater (VOCs, solvents)	$40-70 /yd^3 10-100 lb/h		Air sparging
Halliburton NUS (713)-492-1888	F	soil/groundwater VOCs	NA		In situ air stripping or sparging combined with in situ biodegradation
Hughes Environmental Systems, Inc. (714)-536-6547	F	soil/groundwater (VOCs, SVOCs, gasoline, diesel fuels, solvents)	NA	SITE	Steam injection coupled with recovery; oxidation processes
Hill Air Force Base Demonstration (504)-283-4628	F	soil (fuels and TCE)	$15-85 /ton	AFESC	Soil venting, up to 40 ft for permeable soil

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Table A.1 Reported stage-of-development information for ISPCT technologies that rely on contaminant-transfer processes (continued).

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Volatilization (cont.)					
Illinois Institute of Technology Research Institute./Halliburton NUS (615)-483-9900	F	soil (VOCs, SVOCs)	NA	SITE	Radio-frequency heating to volatilize organic contaminants from soil in vadose zone
IIT Research Institute, USA	P	soil (solvents, gasoline-kerosene mixture)	NA	NATO/ CCMS	Using radio-frequency heating to remove hydrocarbons
Lawrence Livermore National Laboratory	P	soil (gasoline)	NA	RD&D	Vacuum extraction with thermal oxidizer
NOVA Terra (213)-328-9433	F	soil/solid (VOCs, PAHs, solvents)	5-20 yd^3/h \$100-300/yd^3	SITE	Steam and hot air; up to 30 ft deep
Oak Ridge National Laboratory	F	soil (VOCs)	15 - 40 yd^3/h \$150-200/yd^3	RD&D	Ambient and hot air; mixed regions up to 40 ft deep
Terra Vac (609)-530-0003	F	soil/sludge (VOCs, PAHs, solvents)	\$10-100 /ton	SITE	Vapor extraction with low vacuum; for H>0.0001
Toxic Treatments, Inc. (415)-391-2113	P	soil (VOCs)	NA	SITE	Steam/air stripping; up to 27 ft
Twin Cities Army Ammunition Plant (301)-671-2054	P	soil (VOCs)	\$15-85 /ton	USAEC	Soil venting with vacuum; up to 40 ft for permeable soil
Udell Technologies, Inc. (415)-653-9477	F	soil/sludge (VOCs, PCBs, PAHs, solvents	\$50-125 /yd^3	SITE	Steam injection, vacuum extraction; up to 90 ft
Western Research Institute (307)-721-2281	P	soil (light and dense organic liquids, petroleum by-products)	NA	SITE	Steam and hot water injection; may be coupled with biological treatment
Westinghouse Savannah River Co. (803)-725-5190	P	soil/groundwater (VOCs, TCE, PCE)	\$20 /lb, capital \$500K to 650K	RD&D	Air stripping with horizontal wells; good for high permeability
Ion Exchange					
Scientific Ecology Group, Inc. (412)-247-6255	B	soil (heavy metals, radionuclides)	NA		Cation exchange; avoid low permeability

Table A.1 Reported stage-of-development information for ISPCT technologies that rely on contaminant-transfer processes (continued).

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Electrokinetics					
Electrokinetics, Inc. (504)-388-3992	P	soil/sludge (metals, VOCs, radionuclides)	50-100yd^3/h $90-140 /yd^3	SITE	Use of DC current; not good for mixtures
Andco Environmental Processes, Inc. (716)-691-2100	P	groundwater (chromium and other heavy metals)	50-120 gal/min	SITE	Electrochemical reactions to generate ions for reduction of metals
Isotron Corporation (504)-254-4624	P	soil/sludge /groundwater (metals, radionuclides)	NA		Use of DC current; not good for uncharged organics
Combinations					
Waste-Tech Services, Inc. (303)-279-9712	P	soil (PCBs, PAHs)	$75-200 /yd^3		For shallow aquifer; oil removal by alkaline-polymer-surfactant agents
Soestduinen, the Netherlands		soil (cadmium)	NA	NATO /CCMS	Infiltration of acid, water, withdrawal of percolate, water treatment by ion-exchange
Geochem (303)-988-8902	P	groundwater (metals, arsenic, cyanides)	NA		Precipitation, ion-exchange, and sorption
Magnetic					
S.G.Frantz Co., Inc. (609)-882-7100	B	soil/solid/sludge (metals, radionuclides)	0.05-2 tons/h $6-6000 /ton		For dry powder; avoid oily substance and moisture

[a] B: bench scale or emerging
P: pilot scale
F: field scale.

[b] VOCs: volatile organic compounds
SVOCs: semivolatile organic compounds
PAHs: polycyclic aromatic hydrocarbons

[c] AFESC: Air Force Engineering and Services Center (administrated by U.S. Air Force)
RD&D: Research, Development and demonstration (administrated by DOE)
NATO/CCMS: North Atlantic Treaty Organization/Committee on Challenges to Modern Society
SITE: Superfund Innovative Technology Evaluation (administrated by EPA)
USAEC: U.S. Army Environmental Center (administrated by U.S. Army Corps of Engineers, formerly the U.S. Army Toxic and Hazardous Materials Agency, USATHAMA)

NA: not available

Table A.2. Reported stage-of-development information for ISPCT technologies that rely on destruction processes.

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Oxidation-reduction					
EnviroMetal Technologies, Inc. (519)-824-0432	B	groundwater (VOCs)	NA		Degradation of chlorinated VOCs with metallic formulation
ETUS, Inc. (407)-321-7910	F	soil/solid/sludge (heavy metals, radionuclides)	$50-100 /ton, 1-100 yd^3/h		Chemical reduction
IT Corporation (615)-690-3211	F	soil (aldehydes, ketone, alcohols, phenols,)	NA		H_2O_2 oxidation, high to moderate permeability
Oak Ridge National Laboratory	F	soil (VOCs)	15 - 40 yd^3/h $150-200/yd^3$	RD&D	H_2O_2 oxidation, percolation or mixed region injection
Thermal					
Hrubetz Environmental Services, Inc. (214)-363-7833	P	soil (VOCs, SVOCs)	NA	SITE	Thermally enhance air stripping and gas combustion at 1500 °F
Neutralization					
EM&C Engineering Associates (714)-957-6429	F	soil/sludge/solid (heavy metals, batteries)	NA		Acid neutralization using lime and ammonia; for waste battery site

[a] B: bench scale or emerging
P: pilot scale
F: field scale.

[b] VOCs: volatile organic compounds
SVOCs: semivolatile organic compounds

[c] RD&D: Research, Development and demonstration (administrated by DOE)
SITE: Superfund Innovative Technology Evaluation (administrated by EPA)

NA: not available

Table A.3. Reported stage-of-development information for ISPCT technologies that rely on immobilization processes.

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Cryogenic					
Layne-Northwest Company (414)246-4646	P, F	soil		none	
Grouting					
GKN Keller GmbH Hamburg, FRG	?	soil (phenols)	NA	NATO/ CCMS	Soil/water treatment by oxidation, jet grouting in peat layers
Vitrification					
Contamination Control Services, Inc. (803)-859-2048	B	soil/solid/sludge (metals, radionuclides)	$425-500 /ton		For non-volatile compounds
Pacific Northwest Laboratory (509)-376-0492	F	soil (organic and inorganic compounds and radionuclides)	$150-350 /ton 100 tons/d	RD&D	Converting contaminated soil to glass through melting the soil by joule heating
Battelle Pacific Northwest Lab, USA	?	soil (PCBs)	NA	NATO/ CCMS	Complete pyrolysis of organic substances
Bio-electrics, Inc. (816)-474-4895	P	soil/solid/sludge (organic compounds, metals, radionuclides)	$100-400 /ton 2000-3000 lb/h		Volatilize, decompose, and vitrify organic compounds; not for underwater sediment
Geosafe Corporation (509)-375-3268	F	soil/solid/sludge (organic compounds, metals, radionuclides)	$300-500 /ton 4-6 tons/h	SITE	Melting contaminated solid, organic decomposition by pyrolysis; for <10% organic
EM&C Engineering Associates (714)-957-6429	B	soil/solid/sludge (metals, organic compounds radionuclides)	NA		Operated at low temperature
Solidification					
Hazardous Waste Control (203)-366-7020	F	soil (metals, sulfates, nitrates)	NA	SITE	Use specially formulated cements, sands and aggregates
International Waste Technologies (316)-269-2660	P	soil/solid/sludge (organic compounds and metals)	$194 /ton	SITE	Used proprietary treatment chemicals to create a crystalline inorganic polymer

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Table A.3. Reported stage-of-development information for ISPCT technologies that rely on immobilization processes (continued).

Technology and vendor or developer	Status[a]	Waste media (contaminants)[b]	Capacity and cost	Program[c]	Comments
Solidification (cont.)					
Millgard Environmental Corporation / Chemical Waste Management, Inc.	F	soil (VOCs, metals)	15 - 40 yd^3/h $150-200/yd^3$	RD&D	Grout injection during soil mixing
S.M.W. Seiko, Inc. (415)-591-9646	P	soil (metals and semivolatile organic compounds)	90-140 yd^3/d	SITE	Inject solidification and stabilization agents to form monolithic block; up to 100 ft

[a] B: bench scale or emerging
P: pilot scale
F: full scale.

[b] VOCs: volatile organic compounds
SVOCs: semivolatile organic compounds

[c] RD&D: Research, Development and demonstration (administrated by DOE)
NATO/CCMS: North Atlantic Treaty Organization/Committee on Challenges to Modern Society
SITE: Superfund Innovative Technology Evaluation (administrated by EPA)

NA: not available

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APPENDIX B:
OTHER RELEVANT R&D PROGRAMS

A number of research projects are ongoing within the DOE Office of Technology Development (OTD) that are presently directed at developing physical/chemical treatments for in situ use, or could possibly be modified for in situ use. The technical task plans (TTPs) can be divided into six major categories: removal of VOCs, development of horizontal well technologies, destruction of VOCs, thermal enhancement of vapor extraction, stabilization of metals and radioactive nuclides, and removal of metals and radioactive nuclides. Three active projects were identified that are evaluating and developing in situ VOC stripping methods. These TTPs were conducted to improve, model, or determine cost of stripping of VOCs from the subsurface. Three TTPs were identified as developing horizontal well techniques. Horizontal wells are used in three industries: petroleum, pipeline, and utility (e.g., telephone). These TTPs either compared directional drilling technology of the three industries or evaluated its use in different types of soils (arid and non-arid). Four TTPs were identified that developed efficient treatments of VOCs after removal from the ground. The processes developed for aboveground destruction of the contaminants could be modified for example, for use in a recirculation well. Three TTPs were identified that investigated the use of electric or steam heating to aid in the recovery of VOCs from the subsurface. These TTPs were directed at in situ use of the technology. Seven TTPs were directed at the removal of radioactive nuclides, while one TTP was directed at stabilization. The stabilization TTP used grouting to immobilize contaminants. One Cooperative Research and Development (CRADA) was active to evaluate and develop methods for removal of paramagnetic actinides. Four TTPs were focused on removal of actinides by leaching or soil washing. Adsorption and reactive/adsorbent barriers were the subjects of the last two TTPs.

Basic research in support of applied environmental restoration and waste management is sponsored by the DOE Office of Energy Research (OER). Research needs were defined by the Office of Environmental Restoration (ER) and grouped into five areas: (1) environmental transport and transformations; (2) advanced sampling, characterization, and monitoring methods; (3) new remediation technologies; (4) performance assessment; and (5) health and environmental effects. Within the new remediation technologies area, basic research was identified that was deemed "... necessary to improve the effectiveness and/or reduce the cost associated with environmental remediation." The report went on to state that "... major gaps in fundamental knowledge exist for remediating DOE wastes." The topical areas of research needs were: (1) inactive facilities decontamination and decommissioning, (2) concentrated wastes, (3) treatment of contaminated environments, and (4) containment of contaminated environments. Within the area of treatment of contaminated environments, the research needs included: in situ biosorption; in situ scavenging colloids; in situ supercritical fluid processes; in situ heating; and in situ oxidation.

In addition to research sponsored within the DOE OTD of OER, applied research and demonstration activities are ongoing at various DOE sites with support from ER. Information describing these activities was not readily available at the time of this writing.

EPA conducts and funds significant research and development activities in environmental remediation using physical and chemical means. The Office of Exploratory Research and the Risk Reduction Engineering Laboratory (RREL) were identified as conducting research of in situ treatment using physical and chemical processes. Ongoing research projects in the Office of Exploratory Research were identified in the following areas: solubilization of PAHs using surfactants, prevention of well-aquifer interface plugging by bacteria/precipitate, destruction of chlorinated hydrocarbons, removal of heavy metals, transport of heavy metals, and oxidation of organics using supercritical fluid oxidation. A majority of the funded projects investigated removal of heavy metals from the environment.

Research under the RREL Superfund Innovative Technology (SITE) program occur under two different subprograms: the demonstration program and the emerging technology program. Ongoing research in the demonstration program identified as being an in situ process or having the potential to be used as an in situ process included: immobilization of metals using reduction, enhanced volatilization using physical processes, fracturing for improving subsurface mass transfer, destruction of VOC, and the CROW™ process. Ongoing research in the emerging technology program applicable to the developing in situ program includes: destruction of organic contaminants using oxidation and catalytic processes, fracturing, the CROW™ process, and the use of electric or acoustic fields for removal of heavy metals.

The United States Air Force (USAF) has active R&D programs in environmental remediation. Research efforts include measurement of subsurface mass transfer; soil-vapor extraction (including ambient and soil heating techniques for shallow and deep VOC contamination); immobilization of heavy metals; contaminant destruction using catalytic, ultraviolet/oxidation, advanced oxidation methods, ozonation, or photocatalytic film destruction; an advanced microporous membrane system for removing VOCs from water; and a preliminary guidance manual for DNAPLs.

The United States Army (Army) has active R&D programs in environmental remediation. Efforts that are ongoing include stabilization of metals in sediments and soils, treatment and removal of organic compounds from sediments, investigation of leaching processes, modeling of seepage and groundwater flow, and evaluation and development of thermal stripping techniques for remediation of hydrocarbon- and solvent-contaminated soils.

The Electric Power Research Institute (EPRI) funds research for remediation of soils contaminated with PAHs and fuels. EPRI published a report, EPRI GS-7554, detailing its efforts to develop remediation techniques for PAH contaminated soils entitled *Assessment of Selected Technologies for Remediation of Manufactured Gas Plant Sites.* Prepared by IT Corporation of Knoxville, Tennessee, the report was published in October 1991. Another report was also published detailing EPRI efforts to develop remediation techniques for remediation of underground storage tanks. The report, EPRI CS-5261, is entitled *Remedial Technologies for Leaking Underground Storage Tanks.* This report, published in 1988, is presently being revised.

EPRI report GS-7554 evaluates a number of physical and chemical treatments for treating PAH contamination. The report lists regulatory, transportation, and treatment methods, including the level of development for each technology (bench, pilot, demonstration, in situ, ex situ). Physical/chemical treatments evaluated include chemical oxidation using peroxides/ozone, chlorine-based oxidation methods, chemical reduction, hydrolysis,

photochemical treatments, electrochemical treatments, and wet-air oxidation. Soil extraction technologies are also discussed, including aqueous soil-washing methods, froth floatation methods, hydrogravimetric separations, acid and base soil-washing, sorbent extraction, electrokinetics, non-aqueous soil washing methods, steam flushing, thermal desorption, and in situ thermal desorption. Stabilization methods are also discussed including cementing; the use of lime, fly ash and lime, silicates, clays and sorbents, and organic binders; chemical precipitation; and vitrification.

The Gas Research Institute (GRI) funds R&D programs in remediation of PAH-contaminated sites. Its major research effort is bioremediation with physical/chemical treatment for enhancement of the bioremediation process. Physical/chemical treatment interests include the CROW™ process, UV/oxidation for destruction of metal cyanide complexes, and Fenton's reagent for degradation of hydrocarbons. GRI has also compiled a major document describing applicable processes for treatment of manufactured gas plant sites: *Management of Manufactured Gas Plant Sites, Vol. 1-4*, Remediation Technologies, Inc.

The National Science Foundation (NSF) funds research through competitive grants and through research centers. NSF does not have an active program in environmental restoration, although a small amount of work is conducted under the engineering subprogram.

Eleven federal agencies have small business innovative research (SBIR) programs. The SBIR programs are funded at 1.25% of an agency's extramural R&D budget (if the R&D budget is greater than $100 million) as required by the Small Business Innovation Development Act, Public Law 97-219. Of the different programs surveyed, only EPA has an active program for specifically developing in situ remediation techniques. Of the three awards for 1992 made by the EPA program, In Situ Treatment of Hazardous and Toxic Waste at Superfund Sites, two awards of approximately $5,000 and $45,000 were made for projects related to biodegradation, while the third award ($50,000) was made for a catalytic process for dehalogenation of chlorinated aromatic compounds. DOE has an active program for developing monitors and characterization methods for terrestrial contamination, although there is no explicit program for in situ remediation. DOE made two awards in their program, Advanced Characterization and Monitoring Methods for Subsurface Terrestrial Contamination, of approximately $50,000 to each of two small businesses during 1992.

The following tables list selected DOE- and EPA-funded R&D programs.

Table B.1. U.S. DOE funded physical/chemical research for in situ use or applicable for in situ use.

Title	TTP number	Location	Funding: FY, $	Comments
Groundwater and Cost Modeling at SRI Integrated Demonstration	AL221001	LANL	FY92, 460K FY93, 605K FY94, 605K	Air stripping and bioremediation
SRS Demonstration: Remediation Tasks	SR121106	WSRC	FY92, 2090K FY93, 2090K FY94, 2450K	Air stripping and bioremediation
Arid Integrated Demonstration EPA IAG	HQ31003		FY92, 0K FY93, 283K FY94, 0K	Soil stripping and bioremediation
Utility Industry Directional Drilling	AL221103	SNL/SRS	FY92, 300K FY93, 300K FY94, 300K	Joint project with Ditch Witch, Inc.
Drilling Technology Development	RL421103	WHC	FY92, 1000K FY93, 1700K FY94, 180K	Horizontal wells at arid sites
SRS Integrated Demonstration; Directional Drilling	SR121101	WSRC	FY92, 975K FY93, 900K FY94, 1000K	Evaluation of horizontal well drilling equipment and techniques from petrochemical, pipeline, and small utility sources
Integrated Demonstration for Cleanup of Organics in Soils at Non-Arid Sites: Off Gas Treatment	SR121107	WSRC	FY92, 550K FY93, 675K FY94, 800K	Catalytic, bioremediation, thermal, electrochemical, and carbon regeneration systems
Volatile Organic Carbon Recycle/Recovery	ID121114	EG&G	FY92, 325K FY93, 35K FY94, 0K	

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Table B.1. U.S. DOE funded physical/chemical research for in situ use or applicable for in situ use (continued).

Title	TTP number	Location	Funding: FY, $	Comments
Destruction of CCl_4 and $CHCl_3$ by Steam Reforming	AL221106 LANL	LANL	FY92, 150K FY93, 47K FY94, 50K	
High Energy Corona for Destruction of VOCs in Off Gas	RL321101	PNL	FY92, 80K FY93, 220K FY94, 0K	
VOC Offgas Membrane Separation	RL42104	PNL	FY92, 0K FY93, 75K FY94, 0K	Membrane separation
In Situ Heating	SR131001	SRTC	FY92, 0K FY93, 750K FY94, 600K	Evaluation of two technologies
Thermal Enhanced Vapor Extraction System	AL221121	SNL	FY92, 500K FY93, 200K FY94, 350K	Electric heating
Dynamic Underground Stripping Demonstration Project	SF211104	LLNL	FY92, 3045K FY93, 100K FY94, 0K	Electric and steam heating
Six-Phase Soil Heating for Enhanced Removal of Contaminants	RL331003	PNL	FY92, 800K FY93, 780K FY94, 140K	Electric heating of soils
In Situ Containment and Stabilization of Buried Waste	CH321101	ANL	FY92, 150K FY93, 200K FY94, 725K	Grouting
Magnetic Separation CRADA	AL124103	LANL	FY92, 100K FY93, 187K FY94, 200K	Removal of paramagnetic actinides
Soil Contaminant Extraction/ Leaching	SR121105	WSRC	FY92, 120K FY93, 150K FY94, 0K	Leaching of uranium

Table B.1. U.S. DOE funded physical/chemical research for in situ use or applicable for in situ use (continued).

Title	TTP number	Location	Funding: FY, $	Comments
In Situ Chemical Treatment: Evaluation of the In Situ Chemical Treatment Approach for Remediation of Contaminated Soils and Groundwater	RL431001	WHC	FY92, 170K FY93, 170K FY94, 300K	Development of new radioactive nuclide and metal chemical treatment
Selective Extraction/ Leaching	OR121105	MMES	FY92, 250K FY93, 450K FY94, 0K	Carbonate and citrate soil washing
Selective Extraction/ Leaching	AL121121	LANL	FY92, 260K FY93, 400K FY94, 0K	Use of chelation, oxidation, and reduction to remove uranium
Chemically Enhanced Barriers/Vadose Zone	RL331002	PNL	FY92-100K FY93-760K FY94-500K	Incorporation of adsorbent or reagent into or next to barrier
Development of High Capacity Selective Sequestering Agents (Solid Sorbents for Selective Separation of Radioactive Nuclides)	RL321701	PNL	FY92-0K FY93-1000K FY94-0K	
NAPL Remediation Using Foam	CH241003	ANL	FY94, 250K	Use of foams to release and mobilize NAPLs
Remediation of DNAPL in Low Permeability Media	OR131007	ORNL	FY94, 536K	Testing and evaluation of in situ technologies for DNAPL remediation
Mixed Contamination in Groundwater	OR141002	ORNL	FY94, 310K	Evaluation of horizontal wells for groundwater recirculation and VOC and radionuclide removal

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Table B.2. EPA Office Of Exploratory Research for 1991 and 1992.

Title	Primary investigator	Project duration	Funding
Solubilization of Polycyclic Aromatic Hydrocarbons Contaminants in Soil-Water Systems Using Surface Active Agents	R. Luthy	2 years	$200K
Problem of Soil Plugging Identified and Mitigated	P. R. Jaffe		
Dechlorination of PCE and PCBs	T. M. Vogel		
Integration of Chemical and Biological Techniques for Removal of Heavy Metals from Contaminated Soils and Aquifers	M. L. Brusseau	2 Years	$170K
Toxic Trace Metals in Anoxic Aqueous Systems	J. O. Leckie	3 Years	$420K
A Thermodynamic Model of Metal Binding by Humic Substances	F. M. M. Morel	3 Years	$330K
In-Situ Chemical Enhancement for Remediation of Chromium Contaminated Aquifers Using Sulfate Extraction	C. D. Palmer	2 Years	$200K
Removal of Heavy Metals from Groundwater Using Magnetic Chitosan Beads	J. D. Way	2 Years	$200K
Inorganic Chemically Active Beads for Heavy Metals Removal at Superfund Sites	L. L. Tarlarides	2 Years	$200K
Removal of Lead from Superfund Sites Using Soil Flushing	M. Matsumoto	2 Years	$200K
Innovative Technologies for Removal of Heavy Metals at Superfund Sites	J O'Shaughnessy	2 Years	$200K
Treatment of Hazardous Chemicals by Oxidation in Supercritical Water	J. W. Tester	2 Years	$110K

Table B.3. SITE program demonstrations for 1991 and 1992.

Technology	Technology description	Target contaminants and media	Primary investigator
Electrochemical in situ chromate reduction and heavy-metal immobilization	Immobilization of chromate and other heavy metals in groundwater using electrical reduction	Heavy metals in flowing groundwater	Andco Environmental Processes, Inc.
Hrubout® process	Injection of 1200°F air into soil	VOCs and SVOCs	Hrubetz Environmental Services, Inc.
Radio-frequency heating	Volatilization of contaminants using electromagnetic energy with treatment of resulting vapors	VOCs and SVOCs in the vadose zone	Illinois Institute of Technology Research Institute/ Halliburton NUS
Steam-enhanced recovery process	Injection of steam followed by treatment of aquifer fluids	VOCs and SVOCs	Hughes Environmental Systems, Inc.
In situ steam-enhanced extraction	Use of vertical wells to inject steam and extract VOCs and SVOCs	VOC and SVOC stripping in vadose and aquifer zones	Udell Technologies, Inc.
In situ steam and air stripping	Soil mixing with steam and air injection for removing VOCs	VOC and SVOC in soils to 27 ft	NOVATERRA, Inc. (formerly Toxic Treatment, Inc.)
Hydraulic fracturing	Hydraulic fracturing using a viscous fluid with sand. After initiation of fracture, an enzyme is added that reduces the fluid viscosity and leaves the sand in place to preserve the fracture	VOC stripping and bioremediation in vadose and aquifer zones	RREL and the University of Cincinnati

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Table B.3. SITE program demonstrations for 1991 and 1992 (continued).

Technology	Technology description	Target contaminants and media	Primary investigator
Pneumatic fracturing, extraction, and catalytic oxidation	Pneumatic fracturing with hot gas injection; used in DNAPL-contaminated aquifers	DNAPL in low permeability formations	Accutech Remedial Systems, Inc.
In situ vacuum extraction	Removal of subsurface fluids (water and air) for aboveground treatment	VOC stripping and bioremediation in vadose and aquifer zones	Terra Vac, Inc.
Subsurface volatilization and ventilation system	Network of injection and extraction wells strip contaminants from the subsurface using air	VOCs in aquifer or vadose zones	Billings and Associates, Inc.
Ultraviolet radiation and oxidation	Oxidation of toxic organic compounds	VOCs and SVOCs	Ultrox Resources Conservation Co.
Contaminated Recovery of Oily Wastes (CROW™)	Adapted secondary oil recovery process	Oily contaminants in the vadose zone and aquifer	Western Research Institute

Table B.4. Emerging Technology R&D for 1991 and 1992.

Technology	Technology description	Target contaminants and media	Primary investigator
Reductive photo-dechlorination treatment	Use of heat and ultraviolet radiation to remove halogens from pollutant molecules	Chlorinated VOCs	M. L. Energia, Inc.
TiO_2 photocatalytic air treatment	Photocatalytic treatment for VOCs and SVOCs	Vapors removed from soil	Nutech Environmental
TiO_2 photocatalytic water treatment	Photocatalytic treatment for VOCs and SVOCs	Aqueous-phase contaminants removed from soil	Nutech Environmental (formerly Matrix Photocatalytic, Ltd.)
Photolytic oxidation process	Photolytic oxidation using a xenon pulsed-plasma flash lamp	Stripped VOCs and SVOCs	Purus, Inc.
Pneumatic fracturing and biodegradation	Fracturing using compressed air or gases	Organic contaminants from vadose zone	Hazardous Substance Management Research Center at New Jersey Institute of Technology
Contaminated Recovery of Oily Wastes (CROW™)	Adapted secondary oil recovery process	Oily contaminants in the vadose zone and aquifer	Western Research Institute
Electrokinetic remediation	Use of electric and acoustic field to cause contaminate migration	Heavy metals	Electrokinetics, Inc.