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DOE In Situ Remediation Integrated Program
In Situ Manipulation Technologies
Subprogram Plan

Jesse L. Yow, Jr.

December 22, 1993

Lawrence
Livermore
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Laboratory

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DOE *In Situ* Remediation Integrated Program

***In Situ* Manipulation Technologies
Subprogram Plan**

Prepared for
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December 22, 1993

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ACRONYMS AND ABBREVIATIONS

ANL	- Argonne National Laboratory
BNL	- Brookhaven National Laboratory
DNAPL	- Dense Nonaqueous 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
ER	- Office of Energy Research
ESD	- Environmental Sciences Division
FMPC	- Feed Materials Productions Center
FUSRAP	- Formerly Utilized Sites Remedial Action
HSRC	- Hazardous Substance Research Consortium
INEL	- Idaho National Engineering Laboratory
IP	- Integrate Program of the Office of Technology Development
ISM	- <i>In Situ</i> Manipulation
ISPCT	- <i>In Situ</i> Physical/Chemical Treatment
ISRP	- <i>In Situ</i> Remediation Integrated Program
ITEP	- International Technology Exchange Program
LLNL	- Lawrence Livermore National Laboratory
LNAPL	- Light Nonaqueous Phase Liquids
ORNL	- Oak Ridge National Laboratory
NAPL	- Nonaqueous Phase Liquids
OSHA	- Occupational Safety and Health Administration
OTD	- Office of Technology Development
QA/QC	- Quality Assurance/Quality Control
QAPF	- Quality Assurance Project Plan
R&D	- Research and Development
RCRA	- Resource Conservation and Recovery Act
SBIR	- Small Business Innovated Research
SR	- Savannah River Laboratory
USAEC	- U.S. Army Environmental Center
VOC	- Volatile Organic Compound

PREFACE AND ACKNOWLEDGMENTS

The first draft of the *In Situ* Manipulation (ISM) Technologies Subprogram Plan was prepared between March and July, 1993 in support of the Strategic Program Plan for the DOE Office of Technology Development's *In Situ* Remediation Integrated Program (ISRP). The draft was revised during the first quarter of FY 1994 to reflect review comments and to incorporate more information about relevant areas of the ISRP. This ISM plan focuses the development of *in situ* manipulation and enabling technologies for use in soil and ground water remediation in the DOE complex. This revised version of the plan summarizes ISM technologies and technology needs for a major part of the ISRP. The plan is intended to be a living document and will be revised further as more information becomes available, as the technical needs of the ISRP, DOE EM-50, and DOE EM-40 evolve, and as the program achieves its objectives.

Preparation of this draft ISM plan was assisted by technical and programmatic input from a number of people at LLNL and other organizations. Mark Gerber and Mary Peterson at PNL, Richard Thorpe and Dennis Kelsh at SAIC, and Robert Siegrist at ORNL were particularly helpful during the development of this document. Technical and programmatic input and guidance from Jef Walker, DOE/EM-54 Program Leader for the ISRP, have been instrumental in the direction of this plan as well as in the success of the program.

1.0 INTRODUCTION

1.1 Purpose and Scope

The *In Situ* Remediation Integrated Program (ISRP) supports and manages a balanced portfolio of applied research and development activities in support of DOE environmental restoration and waste management needs. ISRP technologies are being developed in four areas: containment, chemical and physical treatment, *in situ* bioremediation, and *in situ* manipulation (including electrokinetics). The focus of containment is to provide mechanisms to stop contaminant migration through the subsurface. *In situ* bioremediation and chemical and physical treatment both aim to destroy or eliminate contaminants in groundwater and soils. *In situ* manipulation (ISM) provides mechanisms to access contaminants or introduce treatment agents into the soil, and includes other technologies necessary to support the implementation of ISR methods. Descriptions of each major program area are provided below to set the technical context of the ISM subprogram; Table 1 identifies typical ISM needs for major areas of *in situ* remediation research and development.

Containment technology focuses on barriers (including barriers which are permeable or impermeable to water) to prevent the subsurface migration of contaminants. Examples include vertical diffusion (hydraulic) barriers, dynamic soil compaction, and cryogenic barriers. DOE has also developed *in situ* vitrification technology to immobilize or limit the migration of contaminants. Other innovative approaches, such as reactive or gated barriers, are currently being developed. Data are still limited on the applicability of these technologies to remediation problems under certain soil and groundwater conditions.

Physical and Chemical Treatment methods have traditionally involved pumping ground water to the surface for *ex situ* treatment. More innovative techniques involving vapor extraction for volatiles, sometimes enhanced with air or steam injection, are being demonstrated in some applications. Proposed mechanisms to achieve *in situ* treatment include thermal destruction, thermal enhancement of extraction processes, oxidation/reduction to immobilize (or mobilize) contaminants, permeable or gated subsurface barriers, and electrochemical processes.

Bioremediation focuses on cleanup of sites contaminated with hazardous organics and mixed waste (hazardous organics with metals or radionuclides), including chlorinated hydrocarbons and non-aqueous phase liquids (NAPLs). The ability of natural agents to destroy or alter contaminants has been demonstrated under certain conditions. However, understanding of bioremediation processes in more general situations (such as in the vadose zone and in tight soils) and knowledge of explicit mechanisms that relate biological processes to the fate of contaminants are still incomplete.

In situ manipulation provides technology for addition, dispersion, or recovery of materials in soil or ground water in the subsurface, as well as complementary enabling technologies to design and assure the performance of *in situ* processes. Thus, ISM technologies are instrumental to the success of *in situ* remediation technologies in each of the program areas described above. Existing physical ISM technologies include special drilling techniques derived from the construction and mining industry, and electrokinetic techniques adapted from civil engineering. Electrokinetics (including electroosmosis and electrophoresis phenomena) provides a mechanism to achieve ionic migration in ground water and soil with potential use for contaminant removal or *in situ* chemical treatment techniques. Although drilling capabilities for environmental applications are becoming generally established, performance criteria needed to assess the efficacy of drilling, injection, and mixing technologies for subsurface manipulation and subsequent remediation are not as mature.

TABLE 1. Major Areas of Innovation in Remedial Technologies

Program Area	Example Technologies	Typical <i>In situ</i> Manipulation Needs
Containment	chemical precipitation grouting/slurry walls surface barriers/covers <i>in situ</i> vitrification	<ul style="list-style-type: none"> • Successful emplacement of grout components to achieve desired degree of continuity. • Successful emplacement of energy in heterogeneous media to achieve complete vitrification.
Physical/Chemical Treatment	electrical heating steam sweeping vapor extraction chemical flushing electrokinetics	<ul style="list-style-type: none"> • Successful emplacement of chemical surfactants or other components to desired degree of continuity, or to achieve desired degree of mixing. • Successful emplacement of energy in heterogeneous media to avoid leaving cold spots untreated.
Bioremediation	Microbial Filter	<ul style="list-style-type: none"> • Successful emplacement of microbes or microbial nutrients in heterogeneous media.

1.2 Approach

The ISM subprogram plan is intended to identify DOE needs and research opportunities for ISM technologies. Generic areas of need include:

- Technologies for *in situ* introduction, transfer, or mixing of mass or energy.
- Enabling technologies (including measurement and simulation tools) for performance design, monitoring, or optimization.
- Research to address basic scientific challenges that impede the success or development of ISM technologies.

Appropriate research and development activities will be planned and conducted to provide the technologies necessary to resolve the first two of these generic need categories. To that end, this plan identifies and assesses the state of the practice for ISM technologies; gaps that are identified in available technologies can be addressed in a program call for proposals or with other technology acquisition activities. The third generic need area, involving more basic research, can be compared against research in progress in DOE and other basic research programs to identify strategies for resolution.

2.0 ASSESSMENT OF DOE NEEDS

2.1 Containment Technologies

Much of DOE's waste and/or contaminant plume "source terms" are associated with the vadose zone. There is a need to develop technologies that will be effective in containing the spread of the existing plumes and controlling source terms. Such a technology would satisfy needs for redundancy in engineered containment barriers for waste disposal and would also satisfy needs to contain residual contamination remaining in the vadose zone following restoration. Contaminants are transferred through the vadose zone by diffusive and advective mechanisms in the meteoric ground water that percolates downward through the emplaced waste or contaminant plume location. Containment concepts involve emplacing a permeable physical, chemical, or biological barrier in the vadose zone below or adjacent to (surrounding) the source location to attenuate, retard, or stop contaminant movement in soil and ground water.

ISM technology needs in support of containment methodologies include the following:

- Technologies capable of introducing physical, chemical, or biological agents into the subsurface as barriers surrounding the waste or plume location. These technologies could include drilling, jet grouting, or auger mixing.
- Nondestructive (e.g., geophysical) techniques to confirm the suitable emplacement, configuration, and immediate performance of barrier materials.
- Performance measures to establish the long-term effectiveness of emplaced barriers.

2.2 Physical/Chemical Treatment Technologies

Contamination of soil and ground water by organics, inorganic ions, and radionuclides is an almost ubiquitous problem at DOE sites. Due to advection of percolating water, contaminant migration poses a greater risk for site releases in humid regions. However, contamination of deep aquifers in arid regions has also occurred. Alternatively, contamination of unsaturated soil well above the water table is a problem particular to the arid sites. TCE, PCE, and CCl₄ are organic contaminants of particular concern at many DOE sites. Chromium (VI), uranium (VI), mercury, other heavy metals, and nitrate are inorganic species of widespread interest at the various sites, along with radionuclides ¹³⁷Cs, ⁹⁰Sr, and ³H. These contaminants are found both individually and in various combinations, depending on the site.

Current state of the practice for treating ground water contamination involves pumping water to the surface for *ex situ* treatment. Techniques such as vapor extraction have been developed for collecting volatile organic compounds from soils, and are being tested at over 70 Federal and industrial sites across the U.S. However, both of these treatments require separation of the contaminant from the media and transport to the surface. Electrokinetic techniques may be able to provide *in situ* separation techniques in some situations, but these applications are still under development. Consequently, cleanup progress is limited by the ability of contaminants to be separated from underground host media

In situ destruction and treatment techniques may be able to reduce or eliminate the amount of contaminated soil, ground water, and vapor that must be extracted and treated on site. As examples, destruction techniques could be used to eliminate organics from soil and ground water; *in situ* treatment of inorganics could reduce their mobility in the soil and ground water.

Treatment could be performed alone or in hybrid combinations with other technologies such as vapor extraction, ground water extraction, or biological treatment.

ISM technology needs in support of physical/chemical treatment methodologies include the following:

- Technologies for introducing physical, chemical, or biological agents into the subsurface waste or contaminant plume location. Technologies are also needed for adding energy (e.g., thermal or electrical) to subsurface systems.
- Technologies for more effectively extracting agents or fluids from subsurface waste or contaminant plume locations (e.g., electrokinetics or permeability enhancements through ultrasonic, hydrofracturing, or pneumatic fracturing processes).
- Nondestructive (e.g., geophysical) techniques to confirm the emplacement and performance of agents in the subsurface.

2.3 Bioremediation Technologies

Operations at DOE research, production, and operations facilities over past decades generated significant volumes of organic wastes that were routinely discharged to the ground in ponds, trenches, and other disposal facilities. Leaks from tanks and process piping, leachate from burial grounds or storage areas, and large-scale liquid discharges to the soil have resulted in widespread contamination of soils and ground water at many DOE sites. These organic wastes included chlorinated solvents such as TCE, PCE, CCl₄, and CHCl₃, and petroleum hydrocarbons such as gasoline, diesel fuel, kerosene, and lubricating oils. Some of these organic contaminants leaked or were discharged to soils both as pure product and as aqueous-phase contaminants. Pure product or non-aqueous phase liquids (NAPLs) in the subsurface have the potential to significantly degrade ground water quality by providing a long-term, continual source of aqueous contamination up to the contaminant's solubility limit. Cleanup of NAPL-contaminated soil and ground water is a high priority for site remediation, especially for dense NAPLs (DNAPLs) from chlorinated solvents. DNAPLs are particularly problematic in aquifers because of their tendency to sink below the water table, making recovery virtually impossible by conventional pump and treat methods.

Biodegradation techniques are effective for *ex situ* treatment of a wide range of organic contaminants dissolved in ground water and aqueous waste streams. However, the potential for *in situ* remediation of NAPLs has not been fully evaluated. Some microorganisms have been shown to tolerate high concentrations of (or free phase) organic contaminants in certain cases, and may eventually provide an effective means of destroying NAPLs *in situ*. Biofilm formation around NAPL deposits may provide a means of containing and slowly destroying these sources of long-term pollution.

ISM technology needs in support of bioremediation methodologies include the following:

- Technologies for introducing biological agents or nutrients into the subsurface waste or contaminant plume location.
- Technologies for adding energy (e.g., thermal or electrical) to subsurface systems to thermally enhance biodegradation, or to move microbe populations to desired locations by electrophoresis.

- Nondestructive (e.g., geophysical) techniques to confirm the emplacement or performance of biological agents in the subsurface.

2.4 General ISM Technology Needs

For most efficient and effective cleanup of many DOE sites, radionuclides, metal, and organic contaminants need to be treated in place or removed and recovered for above-ground treatment without requiring large-scale site disturbance. *In situ* adaptations of available *ex situ* processes (e.g., soil flushing, chemical treatment, bioremediation) have been shown to work above ground for many contaminants. However, the engineering problems of adding, dispersing (mixing), and recovering treatment materials and residuals with minimal site disturbance currently prevent the *in situ* application of many treatment processes. Technologies need to be demonstrated, developed, modified, or tested for adding, dispersing, and recovering liquids and gases in soils. Means for adding and dispersing solids in soils may also be needed in support of some innovative cleanup schemes. Table 2 lists current (FY 1993) ISRP activities and provides a representative indication of ISM needs associated with each activity.

TABLE 2. Typical *In Situ* Manipulation Needs for FY 1993 *In Situ* Remediation Integrated Program Technical Task Plans

TTP	Technical Activity Title	Typical <i>In Situ</i> Manipulation Need
AL-2310-08	Evaluation of Two New Flowable Grout Technologies for <i>In Situ</i> Barrier Construction	Barrier emplacement and performance diagnostics.
AL-231009	Electrokinetic Remediation of Heavy Metal Contamination in Unsaturated Soil	Control system for water added at electrodes.
AL-9310XX	Injected <i>In Situ</i> Permeable Treatment Systems	Mass emplacement technology.
CH-331001	Regulatory Issues and Assumptions Associated with Barriers in the Vadose Zone Surrounding Buried Waste	Assurance of continuity of barrier emplacement and performance.
OR-1011-08	Demonstration of Comatabolic Techniques	
RL-331005	<i>In Situ</i> Redox Manipulation: Enhancement of Contaminant Destruction and Immobilization	Performance diagnostics through <i>in situ</i> monitoring of redox conditions.
RL-330254	Modeling Strategies for Optimizing In-Situ Bioremediation	
RL-331002	Chemically Enhanced Barriers: Chemically Enhanced Barriers to Minimize Contaminant Migration	Barrier emplacement and performance diagnostics.
RL-331006	<i>In Situ</i> Corona for <i>In Situ</i> Treatment of Nonvolatile Organic Contaminants	Predictable energy emplacement in heterogeneous media.
RL-431001	<i>In Situ</i> Chemical Treatment: Evaluation of the <i>In Situ</i> Chemical Treatment Approach for Remediation of Soils and Groundwater	Mass emplacement and mixing, and performance diagnostics.
SF-2011-01	<i>In Situ</i> Microbial Filters	Microbe emplacement techniques for heterogeneous media.
SF-231001	Optimal Remediation Design: Methodology and User-Friendly Software for Contaminated Aquifers	
SR-1310-03	Field Demo of Electrokinetic Migration Technology at Old TNX Basin	Engineered emplacement in heterogeneous media.

ISM technology needs in support of *in situ* remediation can be generalized to include the following:

- Delivery and recovery systems for treatment materials, nutrients, and flushing/extraction agents in unsaturated soils (vadose zones).
- Dispersal systems to mix materials or agents for uniform contact with soils.

- Systems to control the movement of liquid or gaseous treatment materials in unsaturated soils so as to avoid or minimize dispersal from the treatment area.
- Separation of Reaction Products/Residuals: How can reaction products/residuals be separated from soil particles *in situ* so that they can be removed from the soil.
- Monitoring systems performance assessment and process control.
- Models or simulators for process design, optimization, and assessment.

2.5 Timing of DOE Needs for ISM Technology

Recent DOE needs assessments (DOE, 1993) indicate in a general way how soon various EM-40 programs need better technologies for environmental remediation. Histograms that illustrate these needs are included in Appendix A of this plan. These data are very general, and indicate that some of DOE's needs for remedial technology are too imminent to be met by this program. However, in each technical category addressed by the assessment, there are a significant number of remedial needs occurring in future years or that are anticipated but not yet assigned to a particular year. These are the needs that can be most profitably targeted by the ISRP and by the ISM subprogram as it supports DOE's development and application of *in situ* remediation methods.

3.0 TECHNOLOGY DEVELOPMENT STATUS

3.1 Features of ISM Technologies

As implied by the general descriptions of needs in Section 2.0, ISM technologies embrace a wide range of emplacement technologies such as boreholes or soil mixing and a spectrum of enabling technologies such as electrokinetics, geophysical tools, or numerical simulators. Emplacement technologies include a number of methods for introducing fluids (water, air, steam, etc.), reagents, or energy into soil or groundwater. Similar methods are used to recover fluids, contaminants, or excess reagents from these zones. Enabling technologies include electroosmotic or electrophoretic methods for manipulating fluids or particles in the subsurface (particularly under saturated conditions); ultrasonic, hydrofracturing, and pneumatic fracturing methods for permeability modification; point sensor, borehole logging, and underground imaging systems for process monitoring and control; and numerical models for natural and engineered remedial processes.

Emplacement methods of particular interest for ISM include borehole drilling and soil mixing technologies, which are described in the following subsections. Table 3 outlines the relative zone of influence that can be accomplished with some of these technologies when applied in remedial systems. Other, relatively well-established emplacement technologies include bulk excavation, French drain construction, and percolation/infiltration technologies, but these are not reviewed in this plan.

TABLE 3. Systems for *In Situ* Dispersal of Treatment Agents (after Yow, 1992)

General Technique	Typical Radius of Influence	Typical Depth of Application
auger mixing	one meter $\pm$	up to 20 m $\pm$
jet mixing	one meter $\pm$	up to 20 m $\pm$
multiwell injection systems	tens of meters	meters to 100s of meters
multiple hydrofracturing	tens of meters	10s to 100s of meters

3.2 Status of Development and Commercialization

While many of the technologies to be used for ISM applications come from the civil construction, mining, or petroleum fields, site cleanup investigations and operations pose special challenges that require adaptation of conventional approaches. Hazards posed by contaminants, unusual characterization and operational requirements associated with innovative processes, and the extraordinary visibility of work conducted under regulatory and public scrutiny all affect the perceived status, definitions of success, and considerations of risk of failure for ISM technologies. These factors often require modification or additional development of conventional technologies already accepted in other industries before the methods can be commercialized for environmental use. The following figure portrays the status of several innovative technologies for enhanced recovery, most of which are being adapted from successful commercial application in other fields.

Well construction technology, for example, is used to emplace injection and extraction wells. These are proven technologies used for hydraulic control of groundwater, hydrologic capture of contaminant plumes, or manipulation of groundwater regimes. Drilled boreholes are also used for injecting reagents into the ground to construct subsurface barriers (permeation

grouting) or to immobilize contaminants in soil. Extraction/injection well systems are versatile and can be used to contain, remove, divert, or minimize development of a plume under a variety of site conditions. Wells are also used to provide access for equipment used to excavate subsurface chambers or mix reagents with soil *in situ* (e.g., jet grouting). Boreholes also provide a means to introduce characterization and monitoring equipment into the subsurface.

Adaptation of well construction technology to hazardous waste remediation is currently underway. The main issues imposed by this application are the need for accurate placement of wells that are sometimes separated from one another by only a few feet, the need to minimize cost, and the need to minimize the generation of drilling spoils that consist of contaminated soil or sediment. This latter issue is particularly important if the contaminants are radioactive. A current focus in adapting well emplacement technology is in constructing relatively shallow (<100 ft deep) horizontal wells that can be located underneath a contaminant source term at a site. These wells may be particularly useful for the construction of containment floors and for enabling treatment technologies such as vapor extraction, soil flushing, and even ground water extraction from relatively thin strata of contaminated sediment. Much of the technology adaptation has focused on drilling in unconsolidated soils for these applications.

Technique	Concept and Bench Studies	Controlled Field Experiments	Large Scale Site Trials or Scientific Reports	Accepted Use
Electrokinetics	██████████	██████████		
Hot water or steam flushing	██████████	██████████		
Hydrofracturing	██████████	██████████		
Surfactant mobilization	██████████	██████████		
Altering chemical conditions	██████████			
Pneumatic fracturing	██████████			
Solvent mobilization	██████████			

Status of Research and Development for Enhanced Recovery Technologies (after EPA, 1993)

Vertical Borehole Drilling

Vertical drilling is the standard technique for installing groundwater extraction and injection wells, vapor extraction wells, and certain kinds of *in situ* vertical barriers. Many of the vertical drilling techniques can also be used to drill angled borehole which are applicable to the installation of angled barriers. Table 4 lists common vertical drilling methods; most of these are discussed briefly below.

Auger methods involve rotating an auger attached to a shaft to penetrate the subsurface. Hand auger and rotary auger bucket systems are periodically removed from the hole to empty dirt from the auger; the spiral auger continuously removes dirt from the hole as the auger rotates.

Hollow stem augers have the added capability of collecting samples or installing a well casing inside the hollow shaft (EPA, 1985).

Impact driven methods include driven well points and cable tools. Hand and machine driven points are forced into the subsurface, displacing the surrounding soil with some consequential compaction of soil immediately adjacent to the hole. The cable tool method involves raising and lowering a string of drilling tools suspended on a cable in the wellbore, followed periodically by the bailing the cuttings from the hole. The California stove pipe method is a variation of the conventional cable tool system, in that the casing is forced into the borehole using jacks instead of using the impact tools; a mud scow is used as both a drill bit and a bailer; and a thin pipe-within-a-pipe is used as casing as compared to standard casing approaches (EPA, 1985).

TABLE 4. Drilling Methods for Vertical Boreholes

Type	Variations	Geologic Material	Nominal Diam.	Max. Depth	Casing Placed	Comments
Auger	Hand Operated	Soil, no boulders or running sand	≤6 in	≤20 ft	After drilling	
	Rotary Auger Bucket	Soil, no boulders	≥3 in	≤30 ft	During drilling	Usually ≤24 in. diameter
	Spiral Auger	Soil, no boulders or running sand	~48 in	≤90 ft	After drilling	Use with other methods below water table
Driven	Hand Driven Point	Soil, no boulders	≤3 in	≤30 ft	During drilling	
	Cone Penetrometer	Soil	~3 in	150 ft	During drilling	
	Cable Tool	Any type			During or after drilling	Can monitor or log while drilling
	Cable Tool (Calif. Stove Pipe)	Any type			During drilling	Faster & less costly than conventional cable tool
Jetting	Self Jetting	Soil	~8 in	≤50 ft	During drilling	Often needs less development
	Wellpoint/Riser	Soil	~8 in	≤50 ft	During drilling	Needs large amount of water
	Separate Jetting Pipe (temporary)	Soil	~8 in	100 ft	After drilling	
	Separate Jetting Pipe (permanent)	Soil	~8 in	100 ft	During drilling	
	Rotary Hole Puncher	Soil & friable sandstones	~24 in	200 ft	During drilling	
Rotary	Conv. Hydraulic	Any type	≥3 in	100s ft	After drilling	Use for deep wells
	Reverse Hydraulic	Lost circulation can be problem	≤60 in	100s ft	After drilling	Can need large amount of water
	Air Rotary	Any type	~12 in	100s ft	After drilling	Very fast method
	Pneumatic Hammer	Any type	~8 in	100 ft	After drilling	Very fast method
Sonic	Sonic	Unindurated soil incl. gravels and cobbles	9.5 in	200 ft	During drilling	

Jet methods utilize the cutting action of a downward-directed stream of water to create the borehole. The casing is lowered into the hole as it is constructed and serves as a conduit for removing water and cuttings from the well. Variations of the jet method differ primarily in whether the drop tube or jetting pipe is left in the borehole following jetting. In addition, the jet pipe may have cutting teeth at the bottom and can be rotated back and forth to aid the jetting process in indurated soil (EPA, 1985).

Rotary drilling methods involve the use of a rotating bit with a circulating fluid to cool the bit and transport the cuttings to the surface. Hydraulic rotary drilling uses water or a drilling mud as the fluid. This conventional method transports the mud from the surface through the rotating drill pipe and to the drill bit. The fluid and cuttings are carried to the surface through the annulus between the borehole and the drilling pipe. In the reverse method the fluid flows from the surface to the drill bit via the annulus and returns with the cuttings through the drill pipe. However, this is susceptible to significant loss of fluid circulation in soil and rock containing large voids or an extremely open porous matrix (e.g., gravel or rubble zones). The air rotary drill method uses compressed air to blow the cuttings upward from the bottom of the borehole; this method is good for consolidated rock drilling (EPA, 1985). The air percussion rotary or downhole hammer is combination of impact and rotary drilling using a hydraulic or air rotary drill system and a reciprocating hammer connected to the bit (EPA, 1987). A casing hammer can be used to drive the casing through difficult to drill formations such as unconsolidated surface deposits, then using the rotary drilling method for hole completion (EPA, 1985).

Sonic drilling uses a combination of mechanically generated vibrations and rotary power to penetrate the soil. The drill head consists of two counter-rotating rollers that cause the drill pipe to vibrate. The rollers are synchronized with each other to ensure that the vertical force component is transmitted downward along the drill pipe. The frequency of the vibration is tuned to the resonant frequency of the drill pipe. The drill pipe can also be rotated to facilitate penetration. Displaced soil enters the drill string casing through an open faced drill bit and is contained in an inner core tube that rests on the inside shoulder of the bit. When the core barrel is filled it is retrieved to the surface using a wireline retrieval system; these samples can be used for logging the hole. Alternatively, a split-spoon sampler can be lowered inside the drill pipe.

Horizontal Borehole Drilling

Horizontal borehole drilling encompasses a number of drilling methods that can place horizontal holes at depths ranging from near the surface to over 100 ft deep. Horizontal drilling systems use a variety of methods to create horizontal boreholes; installation of a horizontal well requires that the desired depth be accessed as part of the drilling effort. This is accomplished by three principle methods. The first method consists of starting the borehole at the surface, either vertically or at an angle, and then using a specially designed jet or downhole rotary motor capable of drilling straight or curved boreholes. Specially designed steering mechanisms are used to steer the motor along a selected path to achieve a horizontal attitude at the appropriate depth and lateral location and to continue drilling horizontally in the desired direction. The second method also begins with a vertical orientation and is drilled down to a predetermined depth. The drilling pipe is then replaced with a pipe bent to a desired radius which is placed in a drilling guide housing and placed in the hole. The bent drilling pipe causes the drilling head, which includes a pressure jet drilling system, to progress along the desired curve radius as it progresses from the guide housing, reaching horizontal at the desired depth. The third method involves drilling a large-diameter vertical hole from the surface to the desired depth for the horizontal borehole. A horizontal hole is then drilled into the side of the vertical borehole in the desired direction.

A recent workshop sponsored by OTD's Arid Site Integrated Demonstration provides a good overview of commercially available systems (Jensen et al., 1992). This workshop focused on systems capable of drilling horizontal holes at depths greater than 100 ft. System components discussed included drill rig and down hole drilling tools, casing and screen material, directional measurement devices, and fluid circulating systems. There are at least 64 U.S. Companies with horizontal drilling capabilities (30 with capabilities functional at depths greater than 100 ft). Table 5 summarizes the basic methods discussed at the workshop, and also includes an alternative method that uses a whipstock and deformed casing (Dickinson et al., 1986). Other information and selection criteria were summarized by Wilson and Kaback (1993).

TABLE 5. Summary of Horizontal Drilling Systems

Deviation Method	Drilling Tool	Starting Angle from Vertical	Radius of Curvature	Drilling Fluid	Nominal Diameter
Angled insert or steered drilling	Downhole Rotary Motor	0-75°	100 ft	Drilling mud	12 in
	Jet System			Bentonite mud or water	4 to 36 in
Guide housing or bent sub	Downhole Rotary Motor	0-45°	50 ft	Air	5 to 11 in
Bent sub	Downhole Rotary Motor	0-75°	200-240 ft	Drilling mud	3 to 12 in
	Jet System	0-75°	200-240 ft	Drilling mud	3 to 12 in
Deformed tubing	Jet System	0-90°	1.0 ft	Water	3 in
Horizontal insert from caisson	Rotary Drill	90°	NA	Water	3 to 36 in

Electrokinetics

Clays and silts ("tight" soils) complicate site remediation schemes that involve fluid injection, mixing, or extraction, since their low hydraulic permeabilities make flow through these soils extremely slow. Electrokinetic processes are an attractive approach for moving water and ionic materials through these fine-grained soils because electroosmosis and electrolyte migration transport processes are largely independent of this range of pore sizes. Electroosmosis has been applied to dewater soils in civil construction for several decades (Winterkorn and Fang, 1975), but electrokinetic technologies are now receiving new attention for environmental applications.

Electrokinetic processes are applied in the field by installing electrodes in the desired saturated soil horizons and applying a DC voltage (usually a few tens of volts at field scale) to the system. Under the applied potential field, water tends to migrate towards the cathodes (negative electrodes) in the system, where it can be removed by vacuum extraction or other pump systems. Electrode designs, cathode and anode spacing, and system operation are engineered to deal with site-specific conditions.

Laboratory-scale research has shown that mercury in sand/kaolinite soil mixtures can be moved by application of an electrical field and trapped for recovery in a specially-designed electrode system. Bench-scale experiments have also demonstrated that electrode chemistry plays an important role in effective transport of contaminants to electrode wells for recovery (Probstein and Hicks, 1993). However, propagation of pH changes through the soils away from the electrodes can cause the accumulation of metals in certain regions of the soil. Design approaches are being developed to deal with and perhaps exploit this effect. Additional

experimental work indicates that these approaches may not be limited to saturated soils, but may in fact be applicable in partially-saturated geologic media.

In Situ Soil Mixing or Processing

In situ soil mixing includes technologies that physically mix the soil while adding fluids or chemical reagents to the soil mass. The three principle methods are generally classified as area mixing, shallow mixing, and deep soil mixing.

Area mixing is the simplest method for *in situ* mixing of reagents and soil. This process involves delivery of the reagents to the surface of the soil to be stabilized and then mixing them with the soil using a backhoe. The degree of mixing is subjective in nature and left to the best judgment of the backhoe operator (EPA, 1989). While this method is relatively simple and inexpensive it is not generally considered to be an efficient method of mixing.

Shallow soil mixing systems differ from area mixing in that specially designed soil mixing systems are mounted on a backhoe or a bulldozer, and the reagents are added through the mixing system. One commercial system includes a rotary auger mounted on the front end of a bulldozer. The system mixes the soil and reagents in 8 to 12 inch lifts. Other commercial systems include a mixing unit mounted on a backhoe. The mixing unit in this case consists of five injection tubes, each with a separately controlled feed system, a dust control system, and a sludge/additive dispersion mixer. Impellers and augers at the outlet of the unit are designed to mix the reagents with the soil. A third commercial system includes a series of pneumatic injectors mounted on a backhoe. The soil is mixed by a combination of the back and forth motion of the injector in the soil and the force of the pneumatic delivery (EPA, 1989). Backhoe systems are routinely used to treat sludge and soil to a depth of about 10 feet, but greater depths may be achievable depending on the reach of the backhoe.

Deep soil mixing is a technology originally developed for the construction industry that has been adapted to site remediation. Remedial system applications include *in situ* fixation of contaminated materials and cut-off wall construction for containment. A typical deep soil mixing system consists of a guided assembly of two or more hollow stemmed auger and mixing paddles. As the augers penetrate the soil, grout is injected through the tip of the auger blades. The augers lift the soil and grout to the mixing paddles, which homogenize the two components. The mixing process takes place both during penetration of the soil (during which about 30% of the intended grout is injected) and during withdrawal (during which the remainder of the grout is injected). The entire assembly is guided by a crane-supported set of leads, similar to the equipment used for drilling foundation caissons in civil construction. The process minimizes the amount of soil that is actually excavated from the ground. When constructing a cut-off wall, secondary columns are placed between primary columns so that the secondary columns overlap both adjacent primary columns in a split-spacing scheme.

ISR Performance Monitoring and Process Control

In situ remediation performance monitoring includes measurement and characterization techniques that can be used to monitor the progress of a treatment or verify the integrity of site containment measures. This technology area also includes sampling strategies that can be used on site to provide a satisfactory level of confidence that adequate performance has been obtained. Techniques can be classed as either invasive or noninvasive, and can provide either point or spatially integrated measurements of selected parameters. Examples of invasive techniques include monitoring wells and soil coring for sample collection; noninvasive techniques include electromagnetic, electric, and seismic tomography, or hydraulic testing of barriers. Table 6 summarizes many of the available field methods for remedial process monitoring and control.

TABLE 6. Field Methods for Remedial Process Monitoring/Control (after Yow, 1992)

General Technique	Geometry	Information Measured or Inferred
Underground Imaging (crosshole electromagnetic)	2D or 3D interpolation	moisture content changes soil layer and water table locations electrochemical changes
Underground Imaging (crosshole seismic)	2D interpolation	large moisture content changes soil layer and water table locations
Borehole Logging	1D line scan	soil density and stratigraphy moisture content radioactivity
Chemical Sensors	point measurement	detection of chemical species species concentrations
Hydrologic Sensors	point measurement	moisture content piezometric head
Tilt Sensors	surface measurement	soil skeleton deformation; can be related to pore pressure
Thermal Sensors	point measurement	temperature
Radiation Sensors	point measurement	presence of radionuclides

3.3 Related Domestic Research and Development Programs

Several Federal agencies conduct programs of research, development, testing, and technology demonstration that relate either directly or indirectly to ISRP and ISM needs. These programs and their sponsoring agencies include:

TABLE 7. Related Federal Research and Development Programs

Sponsoring Agency	Program Office
U.S. Air Force	• Air Force Center for Environmental Excellence
US Army	• Army Environmental Center (Aberdeen Proving Grounds)
	• Corps of Engineers Waterways Experiment Station
US Navy	• Civil Engineering Laboratory (Port Hueneme, CA)
EPA	• Several laboratories and office either administer contract research, conduct R&D, or both. • Regional Hazardous Waste Research Consortia
DOE	• OBES Office of Geosciences • OHER Subsurface Science Program • OTD Integrated Demonstrations • OTD Characterization Integrated Program

Relevant interagency research includes the Strategic Environmental Research and Development Program (SERDP) which involves DOD, DOE, and EPA participants.

4.0 R&D PROGRAM FOR ISM TECHNOLOGIES

4.1 Linkage to other Subprograms

The ISM subprogram exists to meet the needs of the other subprograms of the *In Situ* Remediation Integrated Program for *in situ* manipulation and enabling technologies. Technical needs of the other subprograms are communicated to the ISM subprogram formally through program planning and review processes, development and execution of calls for proposals, and proposal review and selection processes, and informally through communications between ISRP participants. Table 2 is a partial example of the results this communications process; the general ISM needs listed for ISRP activities in Table 2 were compiled during a mid year review of FY 1993 funded activities.

The ISM subprogram will also develop plans to meet technical needs communicated from other OTD Integrated Demonstrations and Integrated Programs, from DOE EM-40, and from DOE EM-30. Those activities will be included in program implementation and planning according to their relative priority and as resources permit.

4.2 Technical Gaps and Issues

Technical gaps and issues to be addressed by the ISM subprogram can be sorted into three major categories: mass or energy introduction and transfer technologies, enabling technologies, and research issues. The research issues include underlying scientific questions or problems that affect the success or feasibility of technical approaches to ISM; the technology issues *per se* tend to be driven by questions of feasibility, cost, or effectiveness.

Mass or Energy Introduction and Transfer

- Emplacement technologies for *in situ* treatment agents such as chemical agents, surfactants, grout components, microbes, microbial nutrients, thermal energy, or electrical energy.
- Drilling or penetrometer technologies for economic, safe, effective access to the subsurface.
- *In situ* mixing or processing methods for use at depth, particularly with avoidance of aquifer fouling or destruction.
- Permeability enhancement, reduction, or modification to help control flow and transport processes (including liquid and gas phases in porous media).
- Hydrofracturing or pneumatic fracturing in soils to create engineered permeability modification through oriented or multiple fractures.
- Ultrasonic modification of soil structure for permeability enhancement.
- Electrokinetics (electroosmosis and electrophoresis), including system design and emplacement, contaminant recovery processes and control (fundamental understanding as well as system engineering), and field tests for specific classes of contaminants.

Enabling Technologies

- Monitoring and control technologies for *in situ* processes, including point measurements (sensors), line scans (borehole logging), and 2D and 3D underground imaging, if not provided by the Characterization Integrated Program.
- Modeling support for design, optimization, or performance assessment, including selection and justification of key performance parameters and discriminators.
- Component, system, and life cycle cost analyses

Research Issues

- Effects of laminar flow on contaminant dispersal or reagent introduction. Some scientific evidence supports the idea that saturated flow in subsurface porous media is laminar under most hydraulic gradients. Under what conditions do laminar flow regimes dominate, and how might gradients or saturations be manipulated to create turbulent flow and enhance *in situ* mixing without destroying the soil skeleton of the aquifer?
- Heterogeneities (hydrogeologic, geochemical, or biological) such as mineralogical layering of soil, anisotropic permeability, localized microbial ecosystems, relic fracturing, or desiccation cracking can affect the success of *in situ* treatments (e.g., unexpected hydrologic short circuits, interference with chemical processes, or biological predation on agents of biodegradation). How can these factors be anticipated and identified so that solutions can be devised to facilitate ISR processes?
- Special problems associated with vadose zone or NAPL behavior, including contaminant buoyancy and sinking effects, migration and smearing through sinuous flow channels, and rate limiting factors affecting contaminant extraction or destruction.

4.3 Research and Development Opportunities

The gaps and issues identified in the preceding section each pose research questions in their own right. The bullets listed below amplify some of the ideas to help frame R&D opportunities. These opportunities will be prioritized as the ISM plan is revised to reflect evolving DOE needs and successes and failures in technology development.

- Hydrogeologic heterogeneities complicate remediation by causing variability in subsurface flow and transport phenomena; *in situ* hydraulic conductivities and flow velocities at a site can vary by orders of magnitude. How can fingering and bypassing be avoided during injection or extraction operations? Can mixing be induced among combinations of fluids in the subsurface?
- Geochemical heterogeneities may degrade cleanup effectiveness; variabilities in soil chemistry can affect the performance of injected reagents. Can inadvertent *in situ* buffering or sequestering effects be nullified or turned to advantage?
- The sharpness of transitions from one property regime to another within heterogeneous media may influence the effect of the heterogeneities on the remediation scheme. The types of gradients operative within the heterogeneous system can also influence the effect and success of mass or energy emplacement or extraction. What discriminators or site data are necessary to assess the significance of this problem?

- Hydrologic short circuits such as desiccation cracks or relic fracture systems within materials having otherwise predictable hydraulic performance. Can these be used to advantage or avoided in subsurface processing?
- Anisotropic hydraulic behavior. How can we anticipate and account for variations in soil permeability (as a function of orientation) in fluid injection and extraction schemes?
- Biological heterogeneities may involve spatial or temporal changes in subsurface hydrochemical conditions as the microbial ecosystem evolves adjacent to contaminant plumes, injected nutrients, or remedial chemistries. How can this be anticipated with robust bioremediation approaches?
- Sorption or capillary effects can impede contaminant extraction; wetting phase effects during water table fluctuations can trap contaminants below the water table.
- Detection and anticipation of conditions such as underlying fractured or cavitose materials that could lead to piping or settlement failures of materials emplaced for containment (Drummi, et al., 1987),

4.4 Subprogram Funding and Milestones

Overall ISRP funding and milestones are described in the program strategy and implementation plan for the ISRP, which is supported by this subprogram. Additional details are provided in calls for Technical Task Plans, Annual Reports, and other documents prepared by the ISRP and its subprograms.

4.5 Expected Impact of Unresolved Issues

In general, unresolved ISM issues may delay the successful field testing, demonstration, or application of *in situ* remediation technologies leading to a loss of the benefits in cost savings or cleanup effectiveness that are expected from these approaches. These impacts will be quantified, to the extent useful and feasible, on a case-by-case basis as ISM technologies are prioritized and matched up with specific DOE needs. Unresolved issues can have a more insidious impact, though, by causing unexpected and unexplained failures of innovative technologies, leading to a loss of credibility for the site owners or technology development program. Again, these scenarios will be anticipated to the extent possible during ISRP development and implementation.

4.6 Key Assumptions

ISM research and technology development will be coordinated by the DOE/EM-54 ISRP Program Manager with support from DOE and contractor staff. Activities of the subprogram will be fully integrated with activities of the other ISRP subprograms to avoid unnecessary redundancies and to ensure that DOE needs for ISM technologies are fulfilled. Funding for this subprogram is expected to fluctuate from year to year according to the anticipated life cycle of individual projects that are initiated and conducted within this technical area. This subprogram will be motivated and defined by the needs of DOE EM-40 and EM-50 for cost-effective and timely ISM technologies.

4.7 Drivers and Regulations

The development and eventual application of ISM technologies by DOE and its contractors must be done in a manner that complies with regulatory requirements and wins approval for application where needed in the DOE complex. Siskind and Heiser (1993) summarized many of the regulatory issues (at a national level) associated with *in situ* barriers for waste containment; these issues apply to other ISRP technologies as well. Regional- and state-level regulatory constraints can also affect the development, field testing, and eventual use of ISM technologies. Examples of these constraints include the application of ground water non-degradation policies in California and other states.

The ISM subprogram will identify and address regulatory and other drivers during the technology development process by involving representative regulatory stakeholders (from national and state levels) in program reviews and other forums for cooperative discussion. This will allow technology development plans to be modified to reflect regulatory needs and constraints early in the development process in anticipation of eventual field application of successful technologies. In addition, The ISM subprogram will work with other cognizant DOE/EM program elements to share lessons learned and to communicate evolving needs, constraints, and drivers that affect the work of the subprogram.

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Appendix A: Timing of DOE Needs for Environmental Remediation Technology

This appendix includes needs histograms showing DOE/EM-40 needs for remediation technology by geographic area, problem type, and year (DOE, 1993). The large number of "too early to tell" or no response data imply that technology needs are not yet defined well enough to determine the actual need or deadline for many DOE environmental restoration problems.

**Soil and Ground Water Contaminated by Volatile Organics
(Eastern Area Program, Problem 2)**

Remediation Technologies

**Burial Grounds
(Eastern Area Program, Problem 3)**

Remediation Technologies

**Soil Contaminated with Radionuclides
(Eastern Area Program, Problem 4)**

Remediation Technologies

**Ground Water Contaminated with Radionuclides
(Eastern Area Program, Problem 7)**

Remediation Technologies

**Measurements, Modeling, and Treatment for Solvents and Radioactivity
(Eastern Area Program, Problem 8)**

Remediation Technologies

**Ground Water Contaminated with Metals
(Eastern Area Program, Problem 10)**

Remediation Technologies

**Soil Contaminated with Metals
(Eastern Area Program, Problem 11)**

Remediation Technologies

**Remediation Methods for Explosives
(Eastern Area Program, Problem 13)**

Remediation Technologies

**In Situ Treatment/Immobilization Methods for Soil
Contaminated with Organics
(Southwestern Area Program, Problem 1-4)**

**Soil Contaminated with Plutonium
(Southwestern Area Program, Problem 1-5)**

Remediation Technologies

**In Situ Treatment of Ground Water Contaminated with Tritium and Hazardous Constituents
(Southwestern Area Program, Problem 3-3)**

In Situ Treatment Technologies

**In Situ Isolation Methods for Burial Grounds with Low Level Waste
(Southwestern Area Program, Problem 2-5)**

In Situ Containment and Immobilization Technologies

**In Situ Immobilization of Contaminants in Ground Water
(Northwestern Area Program, Problem 4-A)**

Containment and Immobilization Technologies

**Subsurface Barriers for Isolation of Waste and Ground Water
(Northwestern Area Program, Problem 4-B)**

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