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# Summary of Illinois Regulations and Review of Treatment Alternatives for Contaminated Soils in Right-of-Ways

Prepared By

**Amanda Hohner**

**Austin Pelletier**

**Idil Deniz Akin**

**Indranil Chowdhury**

**Richard Watts**

**Xianming Shi**

Washington State University

**Brendan Dutmer**

Highland Community College

**James Mueller**

Provectus Environmental Products, Inc.

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<b>16. Abstract</b> Industrial activities and vehicular transportation often pollute roadside soils with toxic mixtures of petroleum derivatives, combustion byproducts, and metal contaminants. Of these contaminants, semi-volatile organic compounds and metallic inorganics are commonly present at levels exceeding regulatory limits and require special handling if found in land to be acquired by the Illinois Department of Transportation (IDOT) for right-of-way (ROW). The objective of this review was to investigate various on-site and in situ treatment alternatives capable of remediating soil contaminated with high-molecular-weight polycyclic aromatic hydrocarbons and/or metals. Current environmental laws, regulations, and remediation best management practices were also reviewed as they pertain to contaminated soils in construction ROWs. The goal of the review was to provide IDOT with the information needed to reexamine the current practice of hauling contaminated soil off site for disposal at sites where contemporary technologies can achieve reductions in cost, time, and nuisance. The ultimate goal was to evaluate both conventional and emerging technologies adaptable for use at construction sites in Illinois, capable of treating soil to the extent it may be reused as fill material in line with state and federal regulations. Findings from this review were used to develop an experimental program and recommend effective on-site treatment options to minimize the generation of non-special, special, and hazardous wastes. The suggested treatments herein are conditionally cost-effective processes that minimize construction delays while demonstrating respect for the environment.					
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Members of the Technical Review Panel (TRP) were the following:

- Doug Dirks—TRP Co-chair, Illinois Department of Transportation
- Jim Curtis—TRP Co-chair, Illinois Department of Transportation
- Doug Liniger—Illinois Department of Transportation
- Greg Dunn—Illinois Environmental Protection Agency
- Viraj Perera—Illinois Department of Transportation
- Tyler Petersen—Illinois Department of Transportation
- Kyle Rominger—Illinois Environmental Protection Agency
- Bart Sherer—Illinois Department of Transportation
- JD Stevenson—Federal Highway Administration
- Heather Shoup—Illinois Department of Transportation
- Megan Swanson — Illinois Department of Transportation
- Dan Wakefield—Illinois Department of Transportation
- Andrew Anderson—Illinois State Geological Survey

The contents of this report reflect the view of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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## EXECUTIVE SUMMARY

Industrial activities and vehicular transportation often pollute roadside soils with toxic mixtures of petroleum derivatives, combustion byproducts, and metal contaminants. Of these contaminants, semi-volatile organic compounds and metallic inorganics are commonly present at levels exceeding regulatory limits and require special handling if found in land to be acquired by the Illinois Department of Transportation (IDOT) for right-of-way (ROW). The objective of this review was to investigate various on-site and in situ treatment alternatives capable of remediating soil contaminated with high-molecular-weight polycyclic aromatic hydrocarbons and/or metals. Current environmental laws, regulations, and remediation best management practices were also reviewed as they pertain to contaminated soils in construction ROWs. The goal of the review was to provide IDOT with the information needed to reexamine the current practice of hauling contaminated soil off site for disposal at sites where contemporary technologies can achieve reductions in cost, time, and nuisance. The ultimate goal was to evaluate both conventional and emerging technologies adaptable for use at construction sites in Illinois, capable of treating soil to the extent it may be reused as fill material in line with state and federal regulations. Findings from this review were used to develop an experimental program and recommend effective on-site treatment options to minimize the generation of non-special, special, and hazardous wastes. The suggested treatments herein are conditionally cost-effective processes that minimize construction delays while demonstrating respect for the environment.

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## ACRONYMS AND ABBREVIATIONS

<b>§:</b>	Section or Part
<b>§§:</b>	Sections or Parts
<b>a.k.a.:</b>	Also known as
<b>AATDF:</b>	Advanced Applied Technology Demonstration Facility
<b>ASTM:</b>	American Society for Testing and Materials (now ASTM International)
<b>BGS:</b>	Below Ground Surface
<b>BOL:</b>	Bureau of Lands
<b>BMP:</b>	Best Management Practice
<b>BTEX:</b>	Benzene, Toluene, Ethylbenzene, Xylene
<b>CAA:</b>	Clean Air Act
<b>CCDD:</b>	Clean Construction or Demolition Debris
<b>CEC:</b>	Cation Exchange Capacity
<b>CERCLA:</b>	Comprehensive Environmental Response, Compensation, and Liability Act
<b>CFR:</b>	Code of Federal Regulations
<b>CL:AIRE:</b>	Contaminated Land: Applications in Real Environments
<b>CMC:</b>	Critical Micelle Concentration
<b>COC:</b>	Contaminant of Concern
<b>CPT:</b>	Cone Penetrometer Testing
<b>CSM:</b>	Conceptual Site Model
<b>CWA:</b>	Clean Water Act
<b>DERP:</b>	Defense Environmental Restoration Program
<b>DNAPL:</b>	Dense Nonaqueous Phase Liquid
<b>DOD:</b>	Department of Defense
<b>DOE:</b>	Department of Energy
<b>DOT:</b>	Department of Transportation
<b>EDTA:</b>	Ethylenediaminetetraacetic Acid
<b>EO:</b>	Executive Order
<b>EPA:</b>	Environmental Protection Agency
<b>EPRI:</b>	Electrical Power Research Institute
<b>ERH:</b>	Electrical Resistance Heating
<b>FID:</b>	Flame Ionization Detector
<b>FR:</b>	Federal Register
<b>FRTR:</b>	Federal Remediation Technologies Roundtable

<b>HEB:</b>	Horizontal Engineered Barrier
<b>HLB:</b>	Hydrophile-Lipophile Balance
<b>HOC:</b>	Hydrophobic Organic Contaminant
<b>HPT:</b>	Hydraulic Profiling Tool
<b>HMW:</b>	High Molecular Weight
<b>HRSC:</b>	High Resolution Site Characterization
<b>HSWA:</b>	Hazardous and Solid Waste Amendments
<b>Ill. Admin. Code:</b>	Illinois Administrative Code
<b>IDOT:</b>	Illinois Department of Transportation
<b>IEPA:</b>	Illinois Environmental Protection Agency
<b>ILCS:</b>	Illinois Compiled Statutes
<b>ISCO:</b>	In Situ Chemical Oxidation
<b>ISCR:</b>	In Situ Chemical Reduction
<b>ISV:</b>	In Situ Vitrification
<b>ITRC:</b>	Interstate Technology and Regulatory Council
<b>LCA:</b>	Life-Cycle Assessment
<b>LDR:</b>	Land Disposal Restriction
<b>LIF:</b>	Laser-Induced Fluorescence
<b>LMW:</b>	Low Molecular Weight
<b>LNAPL:</b>	Light Nonaqueous Phase Liquid
<b>MAC:</b>	Maximum Allowable Concentration
<b>MFH:</b>	Microwave Frequency Heating
<b>MGP:</b>	Manufactured Gas Plant
<b>MIP:</b>	Membrane Interface Probe
<b>NAPL:</b>	Nonaqueous Phase Liquid
<b>NAVFAC:</b>	Naval Facilities Engineering Command
<b>NCP:</b>	National Oil and Hazardous Substances Contingency Plan
<b>NFR:</b>	No Further Remediation
<b>NPL:</b>	National Priorities List
<b>OSHA:</b>	Occupational Safety and Health Act
<b>OSWER:</b>	Office of Solid Waste and Emergency Response (Now OLEM: Office of Land and Emergency Management)
<b>PAH:</b>	Polycyclic Aromatic Hydrocarbon (Note: Illinois EPA uses PNA—Polynuclear Aromatic Hydrocarbon)
<b>PCB:</b>	Polychlorinated Biphenyl
<b>PID:</b>	Photoionization Detector
<b>PIMSTM:</b>	Phosphate-Induced Metal Stabilization
<b>PIP:</b>	Potentially Impacted Property
<b>PL:</b>	Public Law
<b>PRB:</b>	Permeable Reactive Barrier

<b>RCRA:</b>	Resource Conservation and Recovery Act
<b>RFP:</b>	Request for Proposal
<b>RFH:</b>	Radio Frequency Heating
<b>RFQ:</b>	Request for Quotation
<b>ROST:</b>	Rapid Optical Screening Tool
<b>ROW:</b>	Right-of-Way
<b>SARA:</b>	Superfund Amendments and Reauthorization Act
<b>SDS:</b>	Safety Data Sheet
<b>SDWA:</b>	Safe Drinking Water Act
<b>SSA:</b>	Specific Surface Area
<b>SPLP:</b>	Synthetic Precipitation Leaching Procedure
<b>SVE:</b>	Soil Vapor Extraction
<b>SVOC:</b>	Semi-Volatile Organic Compound
<b>S/S:</b>	Solidification/Stabilization
<b>TACO:</b>	Tiered Approach to Corrective Action Objectives
<b>TOC:</b>	Total Organic Carbon
<b>TOD:</b>	Total Oxidant Demand
<b>TCLP:</b>	Toxicity Characteristic Leaching Procedure
<b>TPH:</b>	Total Petroleum Hydrocarbons
<b>TSCA:</b>	Toxic Substances Control Act
<b>UIC:</b>	Underground Injection Control
<b>USC:</b>	United States Code
<b>USDW:</b>	Underground Source of Drinking Water
<b>USFO:</b>	Uncontaminated Soil Fill Operation
<b>UST:</b>	Underground Storage Tank
<b>VEB:</b>	Vertical Engineered Barrier
<b>VOC:</b>	Volatile Organic Compound
<b>XRF:</b>	X-ray Fluorescence
<b>XSD:</b>	Halogen Specific Detector
<b>ZVI:</b>	Zero Valent Iron



# CHAPTER 1: INTRODUCTION

## BACKGROUND

Industrial activities and vehicular transportation often pollute roadside soils with toxic mixtures of petroleum derivatives, combustion byproducts, and metal contaminants (Diamond & Hodge, 2007). Of these contaminants, semi-volatile organic compounds and metallic inorganics are commonly present at levels exceeding regulatory limits and require special handling if found in land to be acquired by the Illinois Department of Transportation (IDOT) for right-of-way (ROW). IDOT (2018) defines a ROW as “All property, whether it is presently being used for highway purposes or not, either under the jurisdiction of the department or owned in fee by the state of Illinois or dedicated to the people of the state of Illinois for highway purposes.” Among the most commonly encountered contaminants are high-molecular-weight polycyclic aromatic hydrocarbons (HMW-PAHs) and metals such as chromium, arsenic, lead, and manganese. The individual properties of these contaminants and co-contaminant interactions yield immense recalcitrance towards conventional soil-treatment technologies. In addition, the recalcitrance of soil contamination towards conventional treatment technologies increases with decreasing soil particle size and permeability, thereby increasing associated complexity, costs, and treatment times. This is especially problematic in Illinois where fine-grained low-permeability soils are predominant and soil regulations are among the most stringent (35 Ill. Adm. Code 1100.Subpart F).

Additionally, ROW projects are often spatially and temporally restrictive, thus requiring in situ treatments viable within short periods, whereas most conventional soil remediation processes are slow, with timelines of one to three years considered average, and some lasting up to 20 years (FRTR, 2007). Consequently, transportation agencies often pursue costly excavation and off-site disposal rather than treatment to prevent extensive delays in construction (IDOT, 2018). Excavation and off-site disposal were the most commonly employed methods for cleaning up non-special, special, and hazardous waste sites prior to 1984 and remain the most cost-competitive options in many urban settings (FRTR, 2007).

However, contemporary issues have led transportation agencies to seek comparatively expeditious and affordable treatment technologies in lieu of excavation and disposal for use at construction sites where contaminated soils are present. For these reasons, this document outlines (1) environmental laws and regulations pertaining to the remediation of Illinois soils; (2) remediation best management practices deemed practically applicable to contaminated sites; and (3) in situ and on-site treatment technologies capable of rapidly addressing Illinois soils contaminated by HMW-PAHs and metals.

## OBJECTIVE

The objective of this review was to investigate various on-site and in situ treatment alternatives capable of remediating soil contaminated with HMW-PAHs and/or metals. Current environmental laws, regulations, and remediation best management practices were also reviewed. The goal of the review was to provide IDOT with the information needed to reexamine the current practice of hauling contaminated soil off site for disposal at sites where contemporary technologies can achieve

reductions in cost, time, and nuisance. The ultimate goal was to evaluate both conventional and emerging technologies adaptable for use at construction sites in Illinois, capable of treating soil to the extent it may be reused as fill material in line with state and federal regulations. In addition, the technologies must be compatible with IDOT and Illinois Environmental Protection Agency policies. Findings from this review were used to develop an experimental program and recommend effective on-site treatment options to minimize the generation of non-special, special, and hazardous wastes. The suggested treatments herein are conditionally cost-effective processes that minimize construction delays while demonstrating respect for the environment.



## CHAPTER 2: REGULATIONS

This chapter introduces federal and state regulations that pertain to the on-site and/or in situ treatment of contaminated soil in the state of Illinois. Included are applicable regulations that may govern aspects of site remediation covering a broad range of contamination scenarios; thus, many regulations may not apply to all sites and should therefore be evaluated on a site-specific basis. The listing of regulations in this chapter should serve only as guidance in familiarizing oneself with the general regulatory framework of remediation and is not guaranteed to be all-inclusive.

### FEDERAL

This section reviews the federal regulations pertaining to site remediation. Included are concise descriptions of each regulation and tables outlining the regulatory elements most likely to apply to IDOT for the remediation of contaminated soils. Authority for supersession of the federal regulations herein by Illinois state regulations has also been presented in this section.

#### **Comprehensive Environmental Response, Compensation, and Liability Act**

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; a.k.a., Superfund) governs the cleanup of closed, uncontrolled, or abandoned hazardous waste sites, accidents, spills, and other emergency releases of contaminants into the environment [42 USC § 9601 et seq.]. Authorized under CERCLA are two types of action: (1) short-term removals where action is necessary in response to a contaminant release or to prevent threatened releases and (2) long-term remediation efforts for the permanent reduction in toxicity at sites listed on the Environmental Protection Agency's (EPA's) National Priorities List (NPL). Sites placed on the NPL are eligible for long-term remedial action financed under CERCLA by either the party responsible for contamination or the Hazardous Substance Superfund. ROW sites where CERCLA may apply include recently acquired lands that were historically contaminated by industries such as laundromats, wood treatment plants, and the like. Several elements of CERCLA that may pertain to IDOT for the treatment of contaminated ROW soils have been outlined in Table 1.

**Table 1. Relevant Regulatory Elements of CERCLA [42 USC § 9601 et seq.]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
<u>Subchapter 1—Hazardous Substances Releases, Liability, Compensation</u>	§§ 9601-9628
- Notification Requirements Respecting Released Substances	§ 9603
- Uses of Fund	§ 9611
- Relationship to Other Law	§ 9614
- High Priority for Drinking Water Supplies	§ 9618
- Federal Facilities	§ 9620
- Cleanup Standards	§ 9621
- Reimbursement to Local Governments	§ 9623
- State Response Programs	§ 9628

## National Oil and Hazardous Substances Contingency Plan

The National Oil and Hazardous Substances Contingency Plan (NCP) serves as the federal blueprint governing response to both oil spills and hazardous substance releases to the extent authorized by CERCLA and the Clean Water Act section 311(c) [40 CFR § 300]. Promulgated under the NCP are methods and criteria for determining the appropriate extent of response when there is the release of (1) a hazardous substance into the environment or (2) any pollutant or contaminant that may present an imminent and substantial danger to the public health or welfare. The NCP does not authorize remedial action for any naturally occurring substances in their unaltered form, or those altered solely through naturally occurring processes in their natural location. Included in the NCP is the Hazard Ranking System used by the EPA to place contaminated sites on the NPL. This system is designed for application at a wide variety of sites, serving as a screening device to evaluate potential harm to human health and/or the environment resulting from the release of uncontrolled hazardous substances. IDOT's role in response to hazardous spills would likely be very limited; however, several elements of the NCP that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 2. Most likely other agencies would respond to hazardous response releases.

**Table 2. Relevant Regulatory Elements of the NCP [40 CFR § 300]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
<u>Subpart B—Responsibility and Organization for Response</u>	§§ 300.100-300.185
- Documentation and Cost Recovery	§ 300.160
- State and Local Participation in Response	§ 300.180
<u>Subpart D—Operational Response Phases for Oil Removal</u>	§§ 300.300-300.335
- Phase I—Discovery or Notification	§ 300.300
- Phase II—Preliminary Assessment and Initiation of Action	§ 300.305
- Phase III—Containment, Countermeasures, Cleanup, and Disposal	§ 300.310
- Phase IV—Documentation and Cost Recovery	§ 300.315
<u>Subpart E—Hazardous Substance Response</u>	§§ 300.400-300.440
- Discovery or Notification	§ 300.405
- Removal Site Evaluation	§ 300.410
- Removal Action	§ 300.415
- Remedial Site Evaluation	§ 300.420
- Establishing Remedial Priorities	§ 300.425
- Remedial Investigation, Feasibility Study, and Selection of Remedy	§ 300.430
- Remedial Design, Action, Operation, and Maintenance	§ 300.435
- Procedures for Planning and Implementing Off-Site Response Actions	§ 300.440
<u>Subpart F—State Involvement in Hazardous Substance Response</u>	§§ 300.500-300.525
- EPA/State Superfund Memorandum of Agreement (SMOA)	§ 300.505
- State Assurances	§ 300.510
- Requirements for State Involvement in Remedial and Enforcement Response	§ 300.515
- State Involvement in EPA Lead-Enforcement Negotiations	§ 300.520
- State Involvement in Removal Actions	§ 300.525
<u>Subpart I—Administrative Record for Selection of Response Action</u>	§§ 300.800-300.825
<u>Subpart J—Use of Dispersants and Other Chemicals</u>	§§ 300.900-300.920
<u>Subpart L—Involuntary Acquisition of Property by the Government</u>	§ 300.1105
- Appendix A: The Hazard Ranking System	
- Appendix C: Effectiveness and Toxicity Tests for Chemical Dispersants and Bioremediation Agents	
- Appendix D: Appropriate Actions and Methods of Remedying Releases	

## Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) serves as the national framework for the continuous control of non-special, special, and hazardous wastes in the absence of more stringent state regulations [42 USC 6921 et seq.]. Regulations promulgated by RCRA are included in Title 40 of the Code of Federal Regulations (CFR) as parts 239–282, which govern wastes at currently operational facilities from their time of generation to disposal or treatment. The regulation of non-special wastes, otherwise defined as solid wastes, is included as 40 CFR §§239-259, and the regulation of hazardous wastes is included as 40 CFR §§260-273. As permitted by RCRA, “the state of Illinois is authorized to administer and enforce a hazardous waste management program in lieu of the Federal program under subtitle C of [RCRA] subject to the Hazardous and Solid Waste Amendments of 1984 (HSWA), (Public Law [PL] 98-616, November 8, 1984), 42 USC 6926 (c) and (g)... as administered by the Illinois Environmental Protection Agency” [40 CFR §§ 272.700-701]. Several elements of RCRA that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 3.

**Table 3. Relevant Regulatory Elements of RCRA [40 CFR §§ 239-282]**

Regulatory Element	Regulatory Citations
<b>Nonhazardous (Solid) Wastes:</b>	–
- Guidelines for the Thermal Processing of Solid Wastes	§ 240
- Guidelines for the Storage and Collection of Solid Waste	§ 243
- Source Separation for Materials Recovery Guidelines	§ 246
- Guidelines for Development and Implementation of State Solid Waste Management Plans	§ 256
- Criteria for Classification of Solid Waste Disposal Facilities and Practices	§ 257
- Criteria for Municipal Solid Waste Landfills	§ 258
<b>Hazardous Wastes:</b>	–
- Hazardous Waste Management System: General	§ 260
- Identification and Listing of Hazardous Waste	§ 261
- Standards Applicable to Generators of Hazardous Waste	§ 262
- Standards Applicable to Transporters of Hazardous Waste	§ 263
- Standards for Hazardous Waste Treatment, Storage, and Disposal Facilities	§ 264
- Interim Status Standards for Hazardous Waste Treatment, Storage, and Disposal Facilities	§ 265
- Standards for the Management of Specific Hazardous Wastes and Management Facilities	§ 266
- Standards for Hazardous Waste Facilities Operating under a Standardized Permit	§ 267
- Land Disposal Restrictions	§ 268
- The Hazardous Waste Permit Program	§ 270
- Approved State Hazardous Waste Management Programs	§ 272
- Standards for Universal Waste Management	§ 273
<b>Research and Development (R&amp;D) Permit Considerations for Innovative Treatment Technologies:</b>	
<i>A. Facility Description</i>	–
- Description of the project	§§ 270.13, 270.14, 270.65
- Description of the facility; location; seismic and floodplain standards; and the underlying groundwater	§§ 264.11, 270.13, 270.14, 264.18
<i>B. Waste Description</i>	§§ 264.13, 270.13, 271.14
<i>C. Process Information</i>	–
- Description of technology, equipment, and proposed site	§ 270.14
- Sampling and analysis plan	§§ 264.13, 270.13, 270.30, 264.73
- Equipment installation	§ 264.13
- Equipment operation and performance monitoring	§ 270.30
- Demonstration schedule and expected results	§ 270.65

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
<i>D. Procedures to Prevent Hazards</i>	–
- Security	§ 264.14
- General inspection	§§ 264.15, 264.174
- Emergency preparedness	§§ 265.50-56, 270.14, 264.30-37
- Prevention of releases, explosions, fires, and general hazards	§§ 264.31, 270.14, 270.17
- Contingency plan	§ 264 Subpart D
<i>E. Groundwater Monitoring</i>	§§ 264.9, 264.101, 270.14
<i>F. Personnel Qualifications</i>	§ 264.16
<i>G. Closure Plan</i>	–
- Maximum quantity of waste	§ 254.112
- Disposal of equipment and structures	§§ 262.34, 264.112
- Closure schedule and certification of closure	§§ 264.112, 264.113
- Post-closure	§§ 264.116-120
<i>H. Records</i>	§§ 264.13, 264.16, 264.53, 264.73
<i>I. Financial Responsibility</i>	§ 264.140

*\*R&D permit section adapted from Parker (2009)*

## **Toxic Substances Control Act**

The Toxic Substances Control Act (TSCA) established reporting, record-keeping, and testing requirements, as well as restrictions relating to the production, importation, use, and disposal of certain toxic chemical substances and mixtures [40 CFR §§700-799]. In accordance with the TSCA, state hazardous waste regulatory programs authorized by the EPA may identify PCBs as hazardous wastes, converse to RCRA [40 CFR 261.8]. The TSCA regulates the use or disposal of asbestos, lead, radon, formaldehyde, mercury, polychlorinated biphenyls (PCBs), and equipment containing PCBs. The TSCA also governs remedial actions for the abatement of lead and requires the users of chemicals and mixtures to evaluate potential health impacts if they present an unreasonable or unknown risk of injury to public health or the environment. Elements of the TSCA that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 4.

**Table 4. Relevant Regulatory Elements of the TSCA [15 USC Ch. 53 & 40 CFR §§700-799]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
- Control of Toxic Substances	subch. I §§ 2601-2629
- Lead Exposure Reduction	subch. IV §§ 2681-2692
- Significant New Uses of Chemical Substances	§§ 721.1-721.11019
- Provisional Test Guidelines	§§ 795.70-795.250
- Chemical Fate Testing Guidelines	§§ 796.1050-796.3500
- Environmental Effects Testing Guidelines	§§ 797.1050-797.1950
- Health Effects Testing Guidelines	§§ 798.2250-798.6560
- Identification of Specific Chemical and Mixture Testing Requirements	§§ 799.1-799.9780

## **Clean Air Act**

The Clean Air Act (CAA) established national primary and secondary ambient air quality standards and limits the emission of hazardous wastes [42 USC § 7401 et seq.]. The release of visible emissions, particulate matter, and toxic pollutants is regulated under this act, including fugitive emissions and dust resulting from operational activities. The CAA requires that all emissions released during

remedial operations be captured and treated by the appropriate emission control equipment. Although the CAA likely will not play a large role for IDOT sites, elements that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 5.

**Table 5. Relevant Regulatory Elements of the CAA [40 CFR §§ 50-99]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
- National Primary and Secondary Ambient Air Quality Standards	§§ 50.1 - 50.19
- Approval and Promulgation of Implementation Plans	§§ 52.719 - 52.750
- National Emission Standards for Hazardous Air Pollutants	§§ 61.01-61.359
- National Emission Standards for Hazardous Air Pollutants for Source Categories	§§ 63.1-63.12099
- Chemical Accident Prevention Provisions	§§ 68.1 - 68.220

### **Clean Water Act**

The Clean Water Act (CWA) established discharge standards to preserve the chemical, physical, and biological integrity of the nation’s waters [33 USC §§ 1251 et seq.]. Regulations promulgated by the CWA are majorly applicable to surface waters, whereas groundwater discharge standards are primarily upheld by RCRA and the Safe Drinking Water Act. Aspects of the CWA pertinent to soil remediation include guidelines for spill control, discharge of process fluids, and sites involving dredged or fill material. Elements of the CWA that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 6.

**Table 6. Relevant Regulatory Elements of the CWA [40 CFR §§110-117, 122-140, and 230-233]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
Spill Prevention, Control, and Countermeasure Plans	§ 112
National Pollutant Discharge Elimination System	§ 122
Toxic Pollutant Effluent Standards	§ 129
Guidelines for Specification of Disposal Sites for Dredged or Fill Material	§ 230

### **Occupational Safety and Health Act**

The Occupational Safety and Health Act (OSHA) serves to verify safe and healthful working conditions by enforcing standards and requiring training, education, and assistance for employees as needed [29 USC ch.15 § 651 et seq.]. IDOT employees are regulated by Illinois’ OSHA-approved state plan, which covers only state and local government workers yet has adopted all federal OSHA standards for general industry and construction in addition to an Illinois-unique record-keeping requirement for state employers [29 CFR 1952.27]. Elements of the OSHA that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 7.

**Table 7. Relevant Regulatory Elements of the OSHA [29 CFR §§ 1900-1926]**

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
<b>Occupational Safety and Health Standards</b>	§ 1910 et seq.
- Hazardous Materials	§ 1910 Subpart H
- Hazardous Waste Operations and Emergency Response	§ 1910.120
- Personal Protective Equipment	§ 1910 Subpart I
- General Environmental Controls	§ 1910 Subpart J
- Toxic and Hazardous Substances	§ 1910 Subpart Z

<b>Regulatory Element</b>	<b>Regulatory Citations</b>
<b>Safety and Health Regulations for Construction</b>	§ 1926 et seq.
- General Safety and Health Provisions	§ 1926 Subpart C
- Occupational Health and Environmental Controls	§ 1926 Subpart D
- Personal Protective and Life-saving Equipment	§ 1926 Subpart E
- Materials Handling, Storage, Use, and Disposal	§ 1926 Subpart H
- Electrical	§ 1926 Subpart K
- Excavations	§ 1926 Subpart P
- Underground Construction, Caissons, Cofferdams, and Compressed Air	§ 1926 Subpart S
- Demolition	§ 1926 Subpart T
- Toxic and Hazardous Substances	§ 1926 Subpart Z

## **Defense Environmental Restoration Program**

The Defense Environmental Restoration Program (DERP) governs the cleanup of contaminated soils on active military installations, formerly used defense sites, and base realignment and closure locations by the Department of Defense (DOD) [10 USC § 2701]. Furthermore, the DOD must be contacted to perform cleanup of sites known or suspected to contain unexploded ordinance, discarded military munitions, or munitions constituents. Although the DERP may not often apply to IDOT projects, on the occasion when a contaminated ROW site coincides with any such instances, the DERP must be used in accordance with section 120 of CERCLA (42 USC 9620). Remediation goals under the DERP include (1) the identification, investigation, research, and cleanup of contamination resultant from hazardous substance releases; (2) the correction of environmental damage which creates an imminent and substantial threat to public health or the environment, such as in the case of munitions constituents and other explosive substances; and (3) the demolition and removal of unsafe buildings and structures at sites previously used by or under the DOD.

## **STATE**

This section reviews the Illinois state regulations pertaining to site remediation. Included are concise descriptions of each regulation and tables outlining the regulatory elements most likely to apply to IDOT for the remediation of contaminated ROW soils. The procedures in this section are applicable to wastes and soils encountered at all state highway projects, local projects on state right-of-way, projects requiring acquisition of right-of-way in the name of the state, and transportation projects affecting state right-of-way or roads under state jurisdiction. Details on state regulations were adapted from the Illinois Compiled Statutes (ILCS) and the Illinois Administrative Code (IAC) as cited in accordance with 5 USC 552(a) and 1 CFR § 51 as part of the state hazardous waste management program under Subtitle C of RCRA, 42 USC 6921 et seq. The following subsections outline (1) relevant chapters of the ILCS, including Chapter 415: Environmental Safety and Chapter 430: Public Safety; and (2) Title 35 of the IAC, Procedural and Environmental Rules.

## **Illinois Environmental Protection Act**

The Illinois Environmental Protection Act serves as the state's primary environmental statute. This act established a unified, statewide program for restoring, protecting, and enhancing the quality of the environment, serving to verify that all adverse effects imposed upon the environment are fully considered and that those responsible are held liable [415 ILCS 5 et seq.]. Pertinent titles include (1)

Title I: General Provisions; (2) Title V: Land Pollution and Refuse Disposal; (3) Title VI-B: Toxic Chemical Reporting; (4) Title XVI: Leaking Underground Storage Tanks; and (5) Title XVII: Site Remediation Program. Further included are titles regarding regulations and permitting; enforcement and penalties; public right-to-know; operational restrictions including but not limited to noise, air, and water pollution; and various other more site-specific inclusions such as for sites containing used tires or petroleum underground storage tanks.

### **Hazardous Substances Construction Disclosure Act**

The Hazardous Substances Construction Disclosure Act describes circumstances during the performance of a construction or excavation contract in which contractors may lawfully breach contract without penalty [415 ILCS 70/2]. These cases are contingent upon encountering previously undisclosed substances and materials which impede the flow of work either directly, by means of rule or regulation, or via threat to human health, assuming such contract contains no provision of allocating responsibility or liability in the event of an undisclosed discovery of such substance or material.

### **Illinois Hazardous Materials Transportation Act**

The Illinois Hazardous Materials Transportation Act requires IDOT to protect the public from risks associated with the vehicular transport of hazardous materials over highways, by minimizing such risk as is practicable and considering both technical feasibility and economic reasonability [430 ILCS 30]. Under this act, “the department shall seek exemptions pursuant to Section 107 of the federal ‘Hazardous Materials Transportation Act’ [PL 93-633] for the transportation of hazardous materials that do not pose a substantial danger to the public health and safety.” Furthermore, state and local agency requirements deemed inconsistent with the federal statute will only receive exemptions if those requirements afford an equal or greater level of protection to the public than offered by this Act [Section 112, 40 USC 1811].

### **Uniform Hazardous Substances Act of Illinois**

The Uniform Hazardous Substances Act of Illinois provides consistent definitions for terms associated with hazardous substances for use by the Illinois Department of Public Health in their investigations [430 ILCS 35]. Terms such as “highly toxic” are provided quantitative values for use in risk assessment, which may be applied by state agencies for assessing potential impacts to public health and safety associated with the transport of hazardous chemicals and various waste products.

### **Illinois Chemical Safety Act**

The Illinois Chemical Safety Act requires all facilities to develop a written Chemical Safety Contingency Plan so that all responsible parties are adequately prepared to respond to the unintentional release of chemical substances into the environment [430 ILCS 45]. Facilities regulated by this act include any site or area where a hazardous substance has been deposited, stored, disposed of, placed, or otherwise come to be located [42 USC § 9601]. Plans developed under this act must include at a minimum (1) a listing of potentially hazardous chemical releases, including both chemical and trade names; (2) a brief description of how the chemicals are being stored and used; (3) information on the probable nature, routes, and causes of any potential release; (4) the response procedures to be

followed on-site, including both guidelines for notifying emergency response agencies and information on all on-site emergency systems/plans; (5) a list of names, addresses, and phone numbers including appropriate persons qualified to act as the sites emergency coordinator, in order of responsibility; and (6) a list of emergency equipment with item descriptions and their on-site location.

### **Hazardous Materials Emergency Act**

The Hazardous Materials Emergency Act requires IDOT to utilize the federal hazardous materials placarding regulations as implemented by the Hazardous Materials Transportation Act [PL 93-633] for interstate and intrastate transportation of hazardous materials [430 ILCS 50]. Under this act, hazardous waste signage is required for all use, storage, and manufacture of hazardous materials. In addition, all files, records, and data gathered by the department pertaining to such hazardous materials must be made available to the Illinois Department of Public Health pursuant to the Illinois Health and Hazardous Substances Registry Act [410 ILCS 525].

### **Illinois Emergency Planning and Community Right to Know Act**

The Illinois Emergency Planning and Community Right to Know Act established a comprehensive program for the disclosure of information on hazardous substances used, stored, manufactured, or encountered within the workplace and community [430 ILCS 100]. The procedures outlined in this act do not pertain to releases contained and affecting only those within the site but do pertain to any releases associated with transportation and transportation-related storage incidents. Sections of this act that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 8.

**Table 8. Relevant Sections of the Illinois Emergency Planning and Community Right to Know Act**

<b>Section:</b>	<b>Description:</b>
<b>10: Release Notification</b>	Requires the site operator to provide immediate notice to the community emergency coordinator and the State Emergency Response Commission upon release of any hazardous chemical listed under Section 304 of the Federal Act or under Section 103(a) of CERCLA. Following release response, the site operator must prepare a written follow-up emergency notice.
<b>11: SDS</b>	Requires the site owner/operator to prepare or have available a safety data sheet (SDS) for all hazardous chemicals on site as required by the OSHA. If hazardous chemicals are above the threshold levels for reporting, either a comprehensive chemicals list or all individual SDS must be submitted to (1) the appropriate local emergency planning committee; (2) the State Emergency Response Commission; and (3) the fire department with site jurisdiction.
<b>12: Inventory Forms</b>	Requires further documentation on any hazardous chemicals in the form of Tier 1 or 2 inventory forms. A Tier 1 inventory form must categorize hazardous chemicals by health and physical hazards, providing an estimated range for the average and maximum amount of hazardous chemicals in each category, in addition to their on-site locations. In addition to the Tier 1 requirements, a Tier 2 inventory form must also include (1) the chemical or common names of all hazardous chemicals as they would appear on an SDS; (2) a brief description about the manner of storage of all hazardous chemicals; and (3) an indication as to whether specifics on any hazardous chemical storage location should be withheld from the public.



## Excavation Fence Act

The Excavation Fence Act simply states that any wells or regions of excavation be covered or surrounded with protective fencing during times of worker absence on site [430 ILCS 165].

## Illinois Administrative Code: Procedural and Environmental Rules

Title 35 of the IAC contains Illinois state regulations that supersede or supplement the federal regulations outlined in the previous section. Elements of 35 IAC that may pertain to IDOT for the treatment of contaminated ROW soils in Illinois have been outlined in Table 9.

**Table 9. Relevant Regulatory Elements of the IAC [35 IAC §§ 101-1740]**

Regulatory Element	Regulatory Citations
<b>Subtitle B: Air Pollution</b>	–
<i>Subchapter f: Toxic Air Contaminants</i>	–
- Toxic Air Contaminants	§ 232
<b>Subtitle G: Waste Disposal</b>	§§ 700-899
<i>Subchapter a: General Provisions</i>	–
- Outline of Waste Disposal Regulations	§ 700
<i>Subchapter b: Permits</i>	§§ 702-718
- RCRA and UIC Permit Programs	§ 702
- RCRA Permit Program	§ 703
- UIC Permit Program	§ 704
- Procedures for Permit Issuance	§ 705
- Waste-stream Authorizations	§ 709
<i>Subchapter c: Hazardous Waste Operating Requirements</i>	§§ 720-729
- Hazardous Waste Management System: General	§ 720
- Identification and Listing of Hazardous Waste	§ 721
- Standards Applicable to Generators of Hazardous Waste	§ 722
- Standards Applicable to Transporters of Hazardous Waste	§ 723
- Standards for Hazardous Waste Treatment, Storage, and Disposal Facilities	§ 724
- Interim Status Standards for Hazardous Waste Treatment, Storage, and Disposal Facilities	§ 725
- Standards for the Management of Specific Hazardous Wastes and Management Facilities	§ 726
- Standards for Hazardous Waste Facilities Operating under a RCRA Standardized Permit	§ 727
- Land Disposal Restrictions	§ 728
- Landfills: Prohibited Hazardous Wastes in Land Disposal Units	§ 729
<i>Subchapter d: Underground Injection Control and Underground Storage Tank Programs</i>	§§ 730-738
- Underground Injection Control Operating Requirements	§ 730
- Underground Storage Tanks	§ 731
- Standards for Universal Waste Management	§ 733
- Petroleum Underground Storage Tanks	§ 734
- Hazardous Waste Injection Restrictions	§ 738
<i>Subchapter f: Risk-based Cleanup Objectives</i>	§§ 740-742
- Site Remediation Program	§ 740
- Tiered Approach to Corrective Action	§ 742
<i>Subchapter h: Illinois “Superfund” Program</i>	–
- Illinois Hazardous Substances Pollution Contingency Plan	§ 750
<i>Subchapter i: Solid Waste and Special Waste Hauling</i>	§§ 807-832
- Solid Waste	§ 807
- Special Waste Classifications	§ 808

Regulatory Element	Regulatory Citations
- Special Waste Hauling	§ 809
- Solid Waste Disposal: General Provisions	§ 810
- Information to be Submitted in a Permit Application	§ 812
<b>Subtitle J: Clean Construction or Demolition Debris Fill Operations</b>	–
- Clean Construction or Demolition Debris and Uncontaminated Soil Fill Operations	§ 1100
<b>Subtitle O: Right to Know</b>	–
- Standards and Requirements for Potable Water Supply Well Surveys and for Community Relations Activities Performed in Conjunction with Agency Notices of Threats from Contamination	§ 1600

#### *Subchapter d: Underground Injection Control and Underground Storage Tank Programs*

The Illinois Underground Injection Control (UIC) Program is established by 35 IAC §§ 730 and 738 in conjunction with §§ 702, 704, and 705. This program parallels the federal UIC Program in accordance with the SDWA [42 USC §300f et seq.]. Requirements enforced under this program are intended to prevent contamination of groundwater resulting from the operation of injection wells. The UIC Program classifies injection wells into five classes from Class 1, commonly referred to as deep wells, which are used to inject hazardous or nonhazardous waste below the lowest underground source of drinking water (USDW), to Class 5, commonly referred to as shallow wells, which are used to inject nonhazardous waste into or above a USDW. Class 4 wells are used to inject hazardous waste into or above a USDW, and thus are banned by regulation. Class 5 wells are the largest class of injection well for they do not require a permit prior to beginning injection; however, they are rule authorized and require submission of a Class 5 Injection Well Inventory Form to the IEPA's Bureau of Land (BOL) prior to beginning injections. Additionally, 35 IAC § 734: Release Response and Corrective Action requires that owners and operators of petroleum or hazardous substance underground storage tanks (UST) must respond to confirmed releases from such tanks in accordance with RCRA corrective action requirements under 35 IAC §§ 724.200, 724.296, 725.296 or 725.Subpart G. Aside from this subpart, most of 35 IAC § 734 has been repealed and thus remedial actions pertaining to sites containing USTs should be carried out in accordance with the federal UST Program. It should be noted that although UIC is relevant to soil contamination, it is not used by IDOT.

#### *Subchapter f: Risk-Based Cleanup Objectives*

The Illinois Site Remediation Program serves to (A) set forth “the procedures for the investigative and remedial activities at sites where there is a release, threatened release, or suspected release of hazardous substances, pesticides, or petroleum and for the review and approval of those activities” [415 ILCS 5/58.1(a)(1)]; (B) provide procedures for the review and approval of remediation costs necessary to apply the environmental remediation tax credit under Section 201(1) of the Illinois Income Tax Act [35 ILCS 5/201(1)]; and (C) administer the Illinois Brownfields Site Restoration Program for providing remediation applicants with financial aid for the investigation and remediation of abandoned or underutilized properties [415 ILCS 5/58.15(B)(a)(1)]. This part is divided into nine subparts with the most pertinent detailing (1) site investigations, determination of remediation objectives, and the preparation of plans and reports; (2) the process requirements for submittal and review of plans and reports; (3) letters of no further remediation and record-keeping requirements; (4) the review of remediation costs for environmental remediation tax credits; and (5) requirements

for the review of remediation costs under the Brownfield Site Restoration Program. Additionally, the Illinois Site Remediation Program provides IEPA review of documents, technical assistance, and no further remediation determinations to remediation applicants. IEPA participation under the site remediation program is paid for by the parties requesting IEPA oversight.

### Tiered Approach to Corrective Action Objectives

The Tiered Approach to Corrective Action Objectives (TACO) is the IEPA's method for developing site-specific risk-based remediation objectives pursuant to 35 IAC § 742. Site remediation objectives may be developed using TACO for any site investigations performed under the Illinois Environmental Protection Act [415 ILCS 5] if used in conjunction with the procedures and requirements of either the Illinois Site Remediation Program [35 IAC § 740, 734] or RCRA Part B Permits and Closure Plans [35 IAC §§ 724-725]. TACO provides site owners and operators flexibility in developing remedial objectives by including (1) options to exclude contaminant exposure and migration pathways from further consideration; (2) the option to consider area background concentrations in developing remedial objectives; and (3) three tiers for selecting applicable remediation objectives [35 IAC §742.110].

The first step to performing site evaluations under TACO is determination of the site-specific human exposure and contaminant migration routes. These routes include inhalation, soil ingestion, groundwater ingestion, and dermal contact with soil. Evaluation of the dermal contact exposure route is necessary to use the risk-based corrective action equations in 35 IAC §742 Appendix C or to perform a formal risk assessment in accordance with section 742.915. In addition, evaluation of the groundwater ingestion exposure route must assess both potential contaminant migration from soil to groundwater and the potential for direct ingestion of the site's groundwater. In this way numerous exposure routes may be determined inapplicable to a site and excluded from consideration prior to any tier evaluation.

Secondly, evaluations conducted in accordance with 35 IAC §742 subparts D through I allow for development of remedial objectives using area background concentrations. For chemicals that do not pose an acute threat to human health or the environment—at sites not intended for future residential land use—remediation objectives may be established using either (1) a statewide area background approach considering the inorganic chemical concentrations listed in 35 IAC §742 Appendix A, Table G; or (2) another statistically valid approach for determining area background concentrations which has been approved by the IEPA. In this way area background concentrations may be used as either a remediation objective or to support requests to exclude the chemical from further consideration as a contaminant due to its naturally occurring background presence. Additionally, any combination of background concentrations with Tier 1, 2, and/or 3 evaluations may be used, and Tier 1, 2, and 3 evaluations are not prerequisites for use of one another.

A Tier 1 evaluation compares the detected contaminant concentrations to the corresponding prescribed remedial objectives for residential and industrial/commercial properties contained in 35 IAC §742 Appendix B. Accordingly, objectives selected under Tier 1 are chosen from tabulated values developed by simple conservative models for a given intended land use. Tier 1 evaluations require determination of (1) the extent and concentrations of the site's contaminants; (2) the site's

groundwater class and land-use classification [35 IAC § 620]; (3) all potential routes of contaminant exposure and migration; and, if applicable, (4) the soil pH. The contaminants to be remediated depend on the materials and wastes managed at the site and any requirements of the program under which the remediation is being performed. Furthermore, each portion of a site where exposure may occur must be classified according to its current and intended post-remediation land use as either residential, conservation, agricultural, or industrial/commercial. IDOT currently uses Tier 1 objectives only given the time constraints of construction projects.

A Tier 2 evaluation is more site-specific, requiring use of the risk-based equations listed in 35 IAC §742 Appendix C for soil screening level and risk-based corrective action. As such, calculating Tier 2 remediation objectives requires determination of all Tier 1 parameters in addition to all site-specific parameters necessary for use of the equations including the physical and chemical properties of the contaminants, the site-specific soil and groundwater parameters, and if institutional controls or engineered barriers are to be used in the remedy. Using more comprehensive site characterization, Tier 2 can achieve less stringent yet equally protective remediation objectives relative to Tier 1. Both Tier 1 and 2 evaluations are applicable only to residential and industrial/commercial properties and thus are not appropriate for conservation or agricultural lands. Furthermore, Tier 1 and 2 remediation objectives developed for industrial/commercial properties additionally require institutional controls under 35 IAC §742 Subpart J to prohibit future residential land use.

Tier 3 evaluations use alternative parameters not available under Tier 1 or 2 evaluations to develop remediation objectives for unique sites. For example, only Tier 3 may be used to develop remediation objectives for conservation and agricultural properties. Tier 3 evaluations are appropriate when physical barriers limit remediation or when full-scale risk assessments and/or alternative modeling is applied. An outline of TACO is shown in Figure 1.

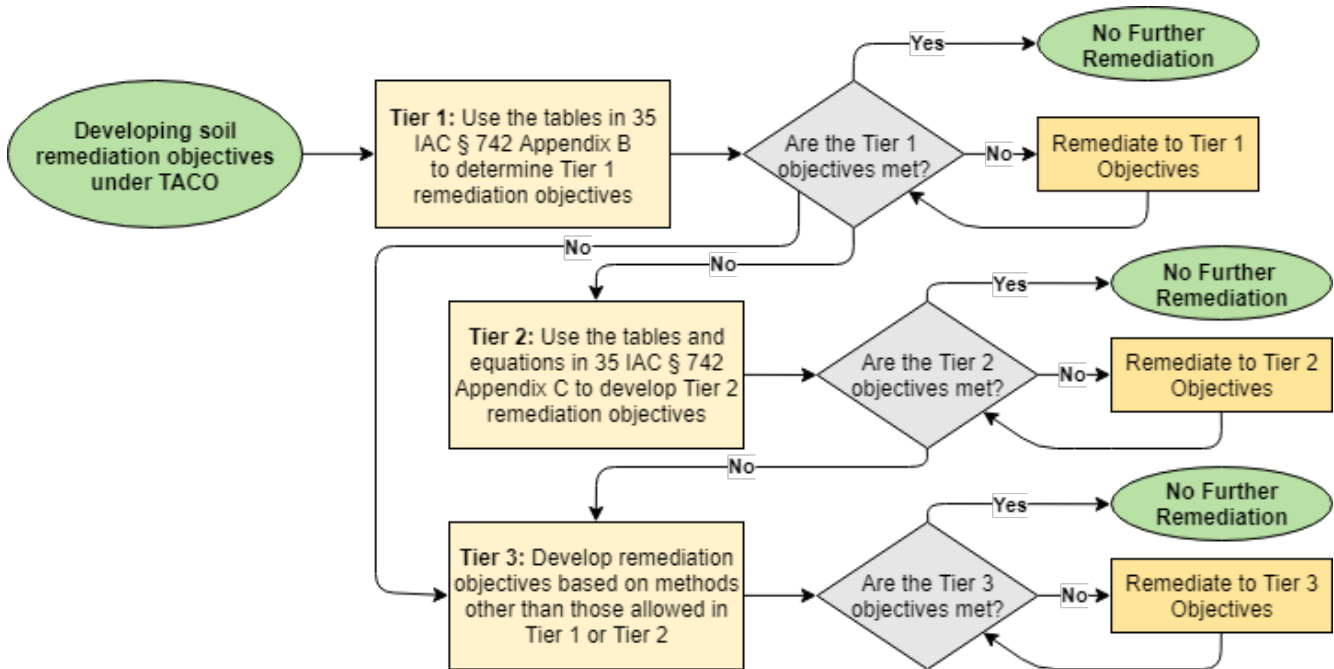


Figure 1. Chart. The Tiered Approach to Corrective Action Objectives (TACO).

After remediation objectives are established under TACO, the site owner or operator may reduce contaminant concentrations to meet such objectives, restrict exposure to contamination through use of engineered barriers and/or institutional controls, take no action if contaminant concentrations do not exceed such objectives, or use a combination of these options in accordance with the appropriate regulations. Once a site has met all applicable program requirements and contaminant concentrations do not exceed the objectives developed under one of the tiers or area background procedures established under 35 IAC §742 Subpart D, the site owner and operator may request a No Further Remediation (NFR) determination from the IEPA's BOL. Additionally, the IEPA's BOL has developed a fact sheet series from 35 IAC §742 to provide concise information on TACO which may be understood in nonlegal terminology. These fact sheets include useful summaries, definitions, examples, and guidance on the use of the TACO method for developing remediation objectives in conjunction with pertinent state and federal regulations. There are currently 12 fact sheets based on, but not a substitute for, 35 IAC § 742, including (IEPA, 1997):

- |                                   |   |
|-----------------------------------|---|
| <b>1. Introduction:</b>           | General overview of the TACO method   |
| <b>2. Risk:</b>                   | How risk is incorporated into the TACO method   |
| <b>3. NFR Letters:</b>            | Requirements for approval of no further remediation by the IEPA   |
| <b>4. Institutional Controls:</b> | What they are and when, how, and why to use them  |
| <b>5. Engineered Barriers:</b>    | What they are and when, how, and why to use them  |
| <b>6. Tier 1:</b>                 | Using tabulated values to develop conservative remediation objectives   |
| <b>7. Tier 2:</b>                 | Calculating remediation objectives for contaminants exceeding Tier 1  |
| <b>8. Pathway Exclusion:</b>      | Requirements for excluding routes of exposure and migration   |
| <b>9. Background:</b>             | Using area background concentrations to develop remediation objectives  |
| <b>10. Compliance:</b>            | Methods for determining if a site has met its remediation objectives  |
| <b>11. Metals:</b>                | Developing remediation objectives for sites contaminated with inorganics  |
| <b>12. Mixture Rule:</b>          | How to develop remediation objectives for multiple similarly acting contaminants that have the same target organ/mode of action |

*Subtitle J: Clean Construction or Demolition Debris Fill Operations*

The designation and use of Clean Construction or Demolition Debris (CCDD) and/or Uncontaminated Soil Fill (USF) at regulated fill operations in Illinois is regulated by 35 IAC §1100.Subtitle J. These regulations primarily govern the disposal and reuse of CCDD and USF generated or encountered when remediating contaminated sites. First, CCDD are defined as uncontaminated broken concrete without protruding metal bars, bricks, rock, stone, reclaimed or other asphalt pavement, and any comingled uncontaminated soil generated from construction or demolition activities [35 IAC §1100]. CCDD does not include uncontaminated soil generated during construction, remodeling, repair, and demolition of utilities, structures, and roads, provided the uncontaminated soil is not comingled with any bulk CCDD or other waste. Comingled uncontaminated soil may include incidental amounts of stone, rock, gravel, roots, and other vegetation [415 ILCS 5/3.160(b)]. Painted CCDD such as reclaimed asphalt roadways is defined as any CCDD that has been painted and is subject to additional regulation pursuant to 35 IAC §1100.212. Secondly, uncontaminated soil is defined as soil either naturally present or generated during construction, remodeling, repair or demolition of utilities, structures and

roads, that does not contain contaminants in concentrations that pose a threat to human health and safety in the environment [415 ILCS 5/3.160(c)].

The standards for designating CCDD and USF as uncontaminated are outlined in 35 IAC §1100 subparts E–F. To be considered uncontaminated, CCDD and USF must comply with the “Maximum Allowable Concentrations for Chemical Constituents in Uncontaminated Soils (MACs)” for each chemical of interest [35 IAC § 1100.605]. To demonstrate a soil’s compliance with the MACs, chemical analyses must be conducted by an accredited environmental laboratory in accordance with “Test Methods for Evaluating Solid Waste, Physical/Chemical Methods” U.S. EPA Publication No. SW-846 as amended. Additionally, CCDD and USF operations are prohibited from accepting soils outside the pH range of 6.25 to 9.0. The MACs for pH-sensitive chemicals are the lowest pH dependent values between Part 742, Appendix B, Table C column range 6.25 to 6.64 and column range 8.75 to 9.0. Therefore, post-treatment pH amendments may often be necessary in addition to the primary remedial action. The MAC values for unlisted chemicals may be obtained from the IEPA by requesting a chemical-specific maximum allowable concentration [35 IAC § 1100.605(c)]. An example MAC is displayed in Table 10.

**Table 10. Maximum Allowable Concentrations of Chemical Constituents in Uncontaminated Soil Used as Fill Material at Regulated Fill Operations [35 IAC § 1100.Subpart F]**

Chemical	MACs (mg/kg)
<b>Benzo(a)pyrene</b>	
within Chicago corporate limits	<b>1.3</b>
within a populated area in a metropolitan statistical area excluding Chicago	<b>2.1</b>
within a populated area in a non-metropolitan statistical area county	<b>0.98</b>
outside a populated area	<b>0.09</b>

CCDD and USF are similarly regulated for reuse as fill material at permitted excavations and/or at the point of disposal. USF operations are defined as excavations where uncontaminated soil, but not CCDD, is used as fill [415 ILCS 5/22.51a(a)(2)], and CCDD fill operations are defined as excavations where CCDD with the potential incidental inclusion of uncontaminated soil is used as fill [415 ILCS 5/22.51(e)(3)]. Excavated soils may be reused on-site as fill material or disposed of in a RCRA Subtitle D solid waste landfill; however, it must be confirmed that CCDD or uncontaminated soil intended for disposal at a CCDD facility was not removed from a site as part of a cleanup or removal of contaminants. Several exemptions to these regulations exist which may apply to IDOT, a county, a municipality, or a township. First, CCDD used as fill below grade is not classified as waste if the filled area is not within the setback zone of a drinking water well and the CCDD is covered with either uncontaminated soil, pavement, or some type of structure within 30 days of fill completion. Secondly, CCDD or USF that has been generated on-site may be used as fill at the same site, exempt from regulation by 35 IAC §1100. Furthermore, uncontaminated soil may be used as set forth in Section 3.160(b) of the Environmental Protection Act [415 ILCS 5/3.160(b)] and no IEPA soil certification forms are required for uncontaminated soil placed outside of CCDD facilities and USF operations. Third, CCDD may be used as fill material so long as its use complies with the IDOT specifications outlined by Articles 107.22: Approval of Proposed Borrow Areas, Use Areas, and/or Waste Areas, and 202.03: Removal and Disposal of Surplus, Unstable, Unsuitable, and Organic Materials of IDOT’s

“Standard Specifications for Road and Bridge Construction” (IDOT, 2016). CCDD or USF can reject any truckload based on observations including the forbidden materials outlines in 35 IAC § 1110 (e.g., color, odor, other criteria). Additional guidelines on the evaluation of regulatory compliance, remedial performance, soil sampling, and chemical analysis are covered in 35 IAC § 1100.610, and the handling of waste or materials other than chemical constituents encountered in soils is covered in 35 IAC § 1100.615.

## CHAPTER 3: ON-SITE AND IN SITU SOIL REMEDIATION

The contents of this chapter introduce elements pertinent to the accelerated on-site and in situ remediation of contaminated ROW soils. Included are sections on (1) best management practices (BMPs) and established field-screening technologies for the safe and rapid identification of soil properties and contaminants; (2) distribution systems for executing remedial actions; (3) enhancements applicable to numerous treatment alternatives; and (4) field-proven on-site and in situ treatment alternatives used to rapidly address soils contaminated with HMW-PAHs and/or metals. Biological treatments have been excluded from this chapter due to their prolonged nature and limited efficacy for both metals and HMW-PAHs sorbed to soil contents, despite ample successes in water/groundwater treatment.

### BEST MANAGEMENT PRACTICES

This section outlines BMPs relevant to the accelerated on-site and in situ treatment of contaminated ROW soils. These BMPs are not programmatic requirements, but rather serve to maximize resource efficiency and technical effectiveness during the execution of remedial projects through development of appropriate risk-based objectives and robust conceptual site models (CSM). Also included in this section are well-established field-screening technologies which may be implemented in accordance with numerous BMPs to achieve relative reductions in the cost, duration, and environmental impacts associated with conventional soil remediation practices.

#### Best Management Practices Recommended for Site Cleanups in Illinois

The IEPA has developed a matrix of practical BMPs for implementation at Illinois site cleanups based on the ASTM International Standard Guide for Greener Cleanups E2893-16e1 and the EPA's Principles for Greener Cleanups. These BMPs, as outlined in Table 11, are intended to yield (1) reduced total energy use and increased renewable energy use; (2) reduced emissions of air pollutants and greenhouse gasses; (3) reduced water use and water quality impacts; (4) improved materials management and waste reduction; and (5) better land management and ecosystems protection.

Of the BMPs outlined in Table 11, the following represent those applicable to any site which should always be implemented to yield maximal benefits from minimal added effort, time, or cost: (1) organize site layout to minimize required excavation, (2) use institutional controls, (3) develop sequencing plan for work to integrate cleanup with construction, and (4) sequence work to minimize double-handling of materials. Additionally, four site remediation projects recently completed in Illinois were evaluated to determine the commonly considered and selected BMPs (Terracon, 2013a, 2013b, 2013c, 2013d). The BMPs selected and considered at each project are outlined in Table 12.



**Table 11. Illinois Environmental Protection Agency’s Best Management Practices for Cleaning Up Contaminated Sites**

<u>IEPA Best Management Practices</u>		<u>Feasibility</u>				<u>Benefits</u>			
<b>Category</b>	<b>Action</b>	<b>Difficulty</b>	<b>Cost</b>	<b>Schedule</b>	<b>Complexity</b>	<b>Air</b>	<b>Water</b>	<b>Land</b>	<b>Energy</b>
Site Assessment	(1) Collect data to perform a site-specific risk assessment	Medium	▲	▼	▲	✓	✓	✓	✓
	(2) Collect data to evaluate waste and debris recycling options	Low	▼	▼	▲	✓	✓	✓	✓
	(3) Collect data to evaluate numerous treatment alternatives	Medium	▲	▼	▲▲	✓	✓	✓	✓
Planning and Design	(1) Develop and quantify “base-case” remediation scenario	Low	▼	▼	▼	✓	✓	✓	✓
	(2) Organize site layout to minimize required excavation	Low	▶▶▶	▼	◀	✓		✓	✓
	(3) Use engineered barriers	Low	◀	◀	◀	✓		✓	✓
	(4) Use permeable barriers	Medium	◀	◀	▲▲		✓		
	(5) Use institutional controls	Low	▶▶▶	▶▶▶	▲	✓		✓	✓
	(6) Use site-specific risk assessments	Medium	◀	◀	▲▲	✓		✓	✓
	(7) Use soil management zones	Low	▶▶	◀	▼	✓		✓	✓
	(8) Develop sequencing plan for work to integrate cleanup with construction	Low	▶▶▶	▶▶▶	▲▲	✓	✓	✓	✓
	(9) Identify salvage options for materials from existing structures	Medium	◀	◀	▼			✓	
	(10) Identify recycling options for waste and debris	Medium	◀	◀	▲▲			✓	
	(11) Consider reuse of existing structures	High	◀	◀	▲▲▲	✓		✓	✓
	(12) Consider reuse of slabs/foundations	High	◀	◀	▲▲▲	✓		✓	✓
	(13) Evaluate active in situ treatment alternatives	High	◀	◀	▲▲▲	✓	✓	✓	
	(14) Evaluate passive in situ treatment alternatives	High	◀	◀	▲▲▲	✓	✓	✓	✓
	(15) Evaluate treatment alternatives that permanently destroy contaminants	High	▲▲▲	▲▲	▲▲▲	✓	✓	✓	
	(16) Perform a life-cycle analysis of cleanup plan	Medium	▲	▼	▲▲	✓	✓	✓	✓

<b>IEPA Best Management Practices</b>		<b>Feasibility</b>				<b>Benefits</b>			
<b>Category</b>	<b>Action</b>	<b>Difficulty</b>	<b>Cost</b>	<b>Schedule</b>	<b>Complexity</b>	<b>Air</b>	<b>Water</b>	<b>Land</b>	<b>Energy</b>
	(1) Impose idling restrictions on construction equipment	Low	▼	▼	▼	✓			✓
	(2) Use low-sulfur diesel fuel	Medium	▲	▼	▼	✓			
	(3) Use alternate fuels (biodiesel, E85)	Medium	▲	▼	▼	✓			✓
	(4) Use construction equipment with enhanced emission controls	Medium	▲	▼	▼	✓			
	(5) Sequence work to minimize double handling of materials	Low	▶▶▶	▶▶▶	▼	✓	✓		✓
	(6) Cover stockpiles and apply dust-control measures	Low	▲	▼	▼	✓	✓		
	(7) Collect rainwater for on-site use	Low	◀	▼	▲		✓		
	(8) Implement a water conservation plan	Low	▶	▼	▼		✓		
Cleanup	(9) Capture and treat greywater for reuse	Medium	◀	▼	▲▲		✓		
	(10) Abandon rather than remove subsurface structures	Medium	▶▶	▶▶	▲▲			✓	✓
	(11) Crush existing structures to optimize recovery and produce fill materials	Medium	◀	◀	▲			✓	✓
	(12) Grind waste wood and other organics for on-site use	Medium	◀	◀	▲			✓	✓
	(13) Use recycled materials for fill	Low	▼	▼	▼			✓	
	(14) Routinely evaluate treatment processes for optimal performance	High	◀	◀	▲▲▲	✓	✓	✓	✓
	(15) Capture free product or emissions for on-site energy recovery	High	◀	▼	▲▲▲	✓	✓	✓	✓
	(16) Incorporate renewable energy sources into treatment systems	High	◀	▼	▲▲▲				✓
	(17) Use energy efficient systems and office equipment in job trailer	Low	▶	▼	▼				✓

Adapted from IEPA (2007): The number of feasibility symbols indicates the relative amount of increase or decrease.

▲ Indicates benefits from the BMP may add cost, time, or technical complexity

▶ Indicates benefits from the BMP may reduce cost, time, or technical complexity

◀ Indicates benefits from the BMP may add *or* reduce cost, time, or technical complexity depending on the project specifics

▼ Indicates benefits from the BMP will not likely impact cost, time, or technical complexity

**Table 12. Green Remediation BMPs Recently Considered and Implemented in Illinois**

Category	Best Management Practice	Selected/Considered
Materials	(1) Salvage uncontaminated objects/infrastructure with potential for recycle, resale, donation, or reuse	1/1 <sup>d</sup>
	(2) Select chemical reagents with lower environmental burden	0/1 <sup>d</sup>
	(3) Steam clean or use phosphate-free soap to decontaminate equipment	3/4 a,b,c,d
	(4) Use dedicated materials when performing multiple rounds of sampling of all matrices	3/3 a,b,c
Power and Fuel	(1) Schedule treatment when groundwater table is lower	0/1 <sup>d</sup>
	(2) Use gravity flow to introduce reagents to the soil when possible	0/1 <sup>d</sup>
	(3) Use biodiesel produced from local waste or cellulose-based products to reduce transportation impacts	3/4 a,b,c,d
Project Planning and Team Management	(1) Establish green requirements as evaluation criteria in the selection of contractors and include language in RFPs, RFQs, contracts, etc.	3/3 a,b,c
	(2) Link remediation activities to site development/construction	1/1 <sup>d</sup>
	(3) Target treatment zone and select appropriate performance standards to minimize treated volume	4/4 a,b,c,d
	(4) Use local staff/subcontractors to minimize resource consumption	4/4 a,b,c,d
Residual Waste	(1) Use alternative methods such as direct-push or sonic technologies for well drilling to minimize drill cuttings that require disposal	1/1 <sup>d</sup>
Analysis	(1) Use local analytical laboratory to minimize transportation impacts	2/2 c,d
Site Preparation and Land Restoration	(1) Minimize clearing of trees throughout remediation	1/1 <sup>c</sup>
	(2) Minimize soil compaction and land disturbance during site activities by restricting traffic to confined corridors and protecting ground surfaces with recycled or biodegradable covers where possible	3/4 a,b,c,d
	(3) Quickly revegetate excavated and disrupted areas using native vegetation and restore as close as possible to original conditions	1/1 <sup>c</sup>
	(4) Use on-site or nearby sources of backfill material for excavated areas, if free of contaminants	3/4 a,b,c,d
Vehicle and Equipment Management	(1) Implement an idle reduction plan	4/4 a,b,c,d
	(2) Minimize diesel emissions with retrofitted engines, low sulfur diesel, alternative fuels, or filter/treatment devices	2/3 a,b,c
	(3) Mix amendments into soil in situ whenever possible to minimize dust generation and emissions	1/1 <sup>d</sup>
	(4) Use biodegradable hydraulic fluids on hydraulic equipment	3/4 a,b,c,d

(a) Terracon (2013a): Soil excavation/disposal, clean backfill, institutional controls on groundwater use

(b) Terracon (2013b): Soil excavation/disposal, clean backfill, institutional controls on groundwater use

(c) Terracon (2013c): Soil excavation/disposal, clean backfill, confirmation samples within excavations

(d) Terracon (2013d): Soil excavation/disposal, ISCO by soil mixing, clay soil cap, institutional controls

### The Triad Approach and High-Resolution On-Site Characterization

The Triad Approach to Decision Making for Hazardous Waste Sites is a widely applicable suite of authoritative BMPs intended to support environmental project management before, during, and after site cleanup (Crumpling, 2004). The Triad Approach integrates systematic project planning, dynamic work strategies, and real-time measurement technologies (Table 13) to develop robust conceptual site models (CSM) and life-cycle assessments (LCAs) for uncertainty reduction during site decision-

making. The approach encourages the use of high-resolution on-site characterization (HRSC) by field-deployable technologies that can gather information on numerous site parameters simultaneously such that time spent and waste generated may be minimized. Furthermore, real-time sharing and interpretation of the data obtained during HRSC allows site owners and operators to optimize further site characterization efforts and treatment alternative selection while site investigation is still underway.

**Table 13. Elements of the Triad Approach to Decision-Making for Hazardous Waste Sites**

Element	Description
<b>Systematic Project Planning:</b>	A holistic yet preliminary CSM is developed to highlight knowledge gaps and aid in initial project decision-making. Workflow and communications are streamlined by early determination of action criteria, key decisions to be made, and methods of data management.
<b>Dynamic Work Strategies:</b>	All-encompassing work plans are developed as a flexible framework that can adapt to new information, both intentionally gathered and unexpectedly encountered, without interrupting workflow. The CSM is continuously updated as new information becomes available, to influence further decision-making and augment communications of progress to stakeholders.
<b>Real-Time Measurement Strategies:</b>	On-site analytical tools are used in lieu of traditional laboratory analyses, allowing for data to be gathered, interpreted, and shared in real time to support dynamic work strategies and iterative evolution of the preliminary CSM.

Crumpling (2004)

HRSC is a BMP applicable to all sites, intended to support the selection, design, and implementation of on-site and in situ treatment alternatives. On-site analytical tools are used for HRSC to increase the rate and efficacy of remediation through scale-appropriate measurements and sample density. Higher sample density allows one to delineate contaminant distributions and site heterogeneities with greater certainty than conventional investigation strategies. Additional costs incurred by the higher sample density of HRSC are offset by the accelerated nature and low cost of field analytical methods relative to traditional laboratory analyses and project cost reductions attainable via improved remedial designs. Similarly, the higher sample density and level of quality control inherent to HRSC under the Triad Approach offset antiquated concerns about the higher detection limits and lower accuracy of field methods versus laboratory analyses. Shown in Table 14 are some of the parameters required for selecting a treatment alternative which would be considered under the Triad Approach in conjunction with the 2014 *Manual for Conducting Preliminary Environmental Site Assessments for Illinois Department of Transportation Infrastructure Projects* (Erdmann et al., 2014). The parameters in Table 14 do not encompass all necessary data requirements nor is determination of all such parameters always necessary; rather, these data may serve as a short list to quickly select or eliminate treatment alternatives from consideration. Numerous field-deployable technologies exist which may determine these parameters and more in a fraction of the time required by conventional laboratory analysis, with the best established being stackable direct-push technologies. Innovative handheld devices like x-ray fluorescence spectrometers yield the most rapid and nonintrusive determination of soil geochemistry and contaminant concentrations with no waste production, at the cost of higher detection limits and limited regulatory acceptance (McComb et al., 2014); however, handheld devices are useful to prescreen sites as guidance for later HRSC using more sophisticated direct-push systems. In this way, paid time for the direct-push rig may be minimized through proper

systematic project planning. The italicized parameters in Table 14 represent a few that may be determined simultaneously in situ from a well-equipped direct-push rig. Further information on stackable direct-push technologies has been provided in Table 15.

**Table 14. Generalized Data Requirements for Selection of a Treatment Alternative**

<b>Soil Data</b>	<b>Contaminant Data</b>	<b>Site Data</b>
• Bulk particle density	• Behavior in site media	• Available surface area
• Cation exchange capacity (CEC)	• <i>Compounds and concentrations</i>	• Available time and budget
• Chemical composition	• <i>Flashpoint</i>	• <i>Bedrock depth</i>
• <i>Hydraulic, electrical, and/or thermal conductivity</i>	• Henry's Law constant	• <i>Buried tanks, utilities, etc.</i>
• <i>Moisture content</i>	• Migration potential	• <i>Homogeneity and isotropy</i>
• <i>Particle density and size distribution</i>	• Octanol-water partition coefficient	• <i>Hydraulic gradient</i>
• <i>Permeability and porosity</i>	• <i>Phase and speciation</i>	• <i>Migration pathways</i>
• <i>pH and buffering capacity</i>	• Potential interactions	• <i>Oil and grease contents</i>
• <i>Redox potential</i>	• Potential intermediates	• Pertinent regulations
• Saturation limit and capacity	• Source and age	• Potential receptors
• Specific surface area (SSA)	• Toxicity, hazards, and risk	• <i>Preferential flow paths</i>
• Total organic carbon (TOC)	• <i>Vapor pressure and volatility</i>	• <i>Proximity to drinking water</i>
• Total oxidant demand (TOD)	• <i>Vertical and horizontal distribution</i>	• <i>Proximity to structures</i>
	• Water solubility	• <i>Water table depth</i>

Watts (1998), FRTR (2007), Erdmann et al. (2014), Kuppusamy et al. (2017)

Stackable probe technologies such as those in Table 15 are dependent upon use of a mobile direct-push rig. In addition to their common use in amendment distribution, mobile direct-push systems offer several avenues for investigating soils and unconsolidated formations down to 100 ft below ground surface. These systems are minimally invasive, utilizing percussion hammers and/or sonic vibratory systems in place of rotary drilling, thereby eliminating non-special, special, and hazardous-waste generation in the form of drill cuttings (ASTM, 2014, 2015d). In this way, no preexisting boreholes are required to install passive sampling instrumentation such as monitoring wells or soil vapor collectors. Similarly, they can be equipped with a wide variety of active sampling and measuring devices including hollow stem augers, coring tools, drop hammers, probes, and anchors to provide the force necessary for performance of cone penetrometer testing. Favored by the Triad Approach, direct-push logging tools exist to perform HRSC with real-time data analysis and sharing to aid in development of the CSM.

**Additional Advantages of Direct-Push Systems:**

- Single-tube direct-push methods for shallow applications (< 20ft) are highly efficient, taking 1 to 2 hours on average for installation, screen development, sampling, and device removal (ASTM, 2015a).
- Direct-push monitoring wells provide representative samples, may be slug tested or repurposed, and often use prepacked well screens to simplify construction and save time (ASTM, 2015e, 2015f).
- Parts used for sampling are easily decontaminated between locations (ASTM, 2015b).

- Temporary borings must be filled with bentonite or grout when abandoned to prevent collapse, yet direct-push systems may also be used for pressure grouting to expedite the process (ASTM, 2015c).
- Direct-push systems may also be used to inject amendments at desired location and depth intervals without requiring permanent wells.

**Table 15. Example Stackable Direct-Push Technologies for Rapid On-Site HRSC**

<b>Cone Penetrometer:</b>	An instrumented cone advanced into soils and sediments by direct-push systems for cone penetrometer testing (CPT). <sup>(a)</sup>
<b>Lithostatic Pressure Sensor:</b>	Measures cone penetrometer tip resistance and sleeve friction to determine soil geotechnical properties such as friction angle, cohesive strength, density, soil behavior type, and layer thickness. <sup>(a)</sup>
<b>Hydraulic Profiling Tool (HPT):</b>	Pore-pressure transducers measure the pressure required to inject water into the soil, and/or hydrostatic pressure under zero flow conditions, as the cone advances to determine soil permeability/hydraulic conductivity, pore water pressure, and water table depth. <sup>(a)</sup>
<b>Electrical Conductivity Sensor:</b>	Measures electrical conductivity and resistivity of the soil pore fluid allowing for determination of ionic strength, salinity, nutrient abundance, and the degree of clay mineralization. Provides further insight into soil stratigraphy, grain size, and contaminant pathways. <sup>(a,b)</sup>
<b>Geophone:</b>	Records seismic responses by converting subsurface acoustic velocity to voltage to determine the position of geologic units and the soil shear wave velocity, shear modulus and Poisson’s ratio. <sup>(a)</sup>
<b>Rapid Optical Screening Tools (ROST):</b>	Use LIF variations to provide a three-dimensional delineation of hydrocarbon contaminants in soils. <sup>(c,d,e)</sup>
• <b>Laser-Induced Fluorescence (LIF):</b>	Emits an ultraviolet light and measures the fluorescent light emitted by LNAPLs composed of PAHs and/or heavy petroleum products in the soil. The strength of fluorescence, wavelength, and decay time are correlated to different chemical compounds and logged with depth. Used for LNAPLs composed of: LMW-PAHs, gasoline, diesel, heating oil, kerosene, jet fuel, no. 6 fuel oil, motor oil, hydraulic oil, and similar compounds. <sup>(e)</sup>
• <b>Tar-Specific Green Optical Screening Tool (TarGOST®):</b>	LIF variation designed to detect monoaromatics and other heavy petroleum products which do not fluoresce in response to standard LIF. Used for DNAPLs composed of HMW-PAHs, coal tar, creosote, crude oil, bunker fuel, heavy distillates, biodiesel, and some phthalate plasticizers. <sup>(c)</sup>
• <b>Dye-Enhanced LIF:</b>	LIF variation designed to detect chlorinated solvent DNAPLs by injecting a fluorescent dye ahead of the ROST to induce fluorescence in nonfluorescent NAPLs. <sup>(d)</sup>
<b>Membrane Interface Probe (MIP):</b>	A heated probe vaporizes VOCs and collects the gas for measurement by an integrated photoionization detector (PID), flame ionization detector (FID), and/or halogen-specific detector (XSD). The MIP logs detector signal with depth to determine concentrations. Detectors (PID: olefins and BTEX; FID: all types of hydrocarbons; XSD: halogenated compounds). <sup>(c)</sup>
<b>Video Imaging Tools:</b>	Illuminated downhole imaging systems allow for visual confirmation of properties determined by other probes and sensors. These tools may be coupled with magnification and/or LIF for resolution of particles and contaminants as small as 20 micrometers on standard monitors. <sup>(a)</sup>

<sup>(a)</sup> ASTM (2015a, 2015g, 2015h, 2015i, 2015j, 2015k)

<sup>(b)</sup> Beck et al. (2000)

<sup>(c)</sup> Dakota Technologies, Inc. (2018a, 2018b, n.d.)

<sup>(d)</sup> Einarson (2016)

<sup>(e)</sup> Stock (2011)

## **Bench-, Pilot-, and Field-Scale Testing**

Treatment alternatives must be selected with extreme care so that compatibility with the physicochemical properties of both the site and contaminants of concern. Inadequate treatment selection can result in worsening site conditions through mobilization of contaminants, increasing site toxicity through unintended transformations with soil contents, increasing contaminant toxicity through intermediate formation by partial mineralization, and even contaminating the site with unreacted reagents and their carriers (ITRC, 2005). For similar reasons, adequate amendment dosing should always be evaluated at the pilot scale prior to field-scale implementation to minimize risk of contaminant rebound and increased toxicity from incomplete reaction. Adequate reagent dosing determined through laboratory testing, pilot-scale trials, and field-scale iterations is necessary to verify complete contaminant removal while maintaining cost-efficacy. Laboratory testing at the bench scale may serve as proof of concept to narrow treatment selection for pilot-scale evaluation; however, pilot-scale investigation is necessary to simulate field conditions due to variability in scale-up from differences in actual procedure and environmental conditions (EPA, 2006). According to the EPA, even pilot-scale conditions such as the appropriate solids-solution ratio, necessary mixing, and achievable contaminant-reagent contact are significantly different than field-scale conditions. Furthermore, no single chemical loading or amendment distribution approach has been developed due to the reliance of remediation on the combined use of site-specific best engineering and scientific judgment in conjunction with trial and error (EPA, 2006). Site features including heterogeneity, hydrogeology, mass transfer, and economic or infrastructure limitations cannot be simulated accurately at the bench nor pilot scale; thus, treatment is an iterative process requiring performance monitoring and sequential identification of remaining contaminants to achieve treatment objectives (EPA, 2006). In accordance with RCRA and state regulations, treatability studies must always be performed by an EPA-accredited laboratory using EPA-approved methodology, with approval by a professional engineer, prior to field-scale implementation to avoid worsening site conditions (EPA, 2006).

## **SOIL AMENDMENT DISTRIBUTION SYSTEMS**

The efficacy of soil remediation depends upon selection of the most effective distribution system for a given treatment technology and site composition. Injection wells and direct-push injection are the most commonly employed distribution systems for introduction of chemical amendments (NAVFAC, 2013). The efficacy of these systems may be improved by technologies that increase site permeability including pneumatic, blast, and thermal fracturing (FRTR, 2007; EPA, 2012k). Soil mixing is highly effective for surface soil contamination and may accelerate implementation times as compared to hydraulic/pneumatic injection systems in exchange for higher operational intensity. Electrokinetics are an innovative distribution system that function in low-permeability fine-grained soils such as clays, silts, muds, sludges, and sediments, which are recalcitrant towards conventional injection systems (Reddy & Cameselle, 2009). Field-proven distribution systems are summarized in Table 16.

**Table 16. Overview of Distribution Systems Applicable to Soils**

System	Description	Disadvantages	Advantages
<b>Injection Wells</b>	Wells inserted into the soil as static locations for hydraulic distribution of chemical solutions	(1) High cost of well materials (2) Well materials require disposal post treatment	(1) Reliable point of distribution (2) Repurposable locations for sampling, monitoring, or successive treatments
<b>Direct Push</b>	Mobile systems that combine percussion-hammer boring with hydraulic injection of chemical solutions	(1) Requires system remobilization for successive injections (2) Small radius of influence	(1) Simple and readily available to treat localized contamination
<b>Infiltration</b>	Passive distribution of chemical solutions by gravity	(1) Requires highly permeable soils	(1) Cost-effective and simple
<b>Recirculation</b>	Use of another distribution system with hydraulic extraction downgradient for recapture of chemical solutions	(1) High cost (2) Limited to saturated soils (3) Process fluids require treatment	(1) Good hydrological control (2) Lowers chemical expenditure by recirculating unspent reagents
<b>Soil Mixing</b>	Mixing of soil with physical/chemical amendments using rotary augers	(1) Limited to shallow soils (2) Loss of soil structural integrity	(1) Overcomes low-permeability media (2) Enhances chemical contact
<b>Air Sparging</b>	Pneumatic injection wells for air or gaseous chemicals	(1) High capital cost of equipment (2) Gaseous chemicals can migrate and be discharged to atmosphere without controls in place.	(1) Gaseous treatments are effective for addressing contaminant NAPLs
<b>Electrokinetics</b>	Use of injection wells with subsurface electrodes to distribute chemical solutions via low-intensity direct current	(1) High capital and operational costs (2) Hindered by buried metal objects (3) System is in developmental stage	(1) Functional in fine-grained soils (2) Good hydrological control (3) Stimulates contaminant desorption (4) Can also extract metal contaminants

Ceulemans and Labeeuw (2013), NAVFAC (2013), Reddy and Cameselle (2009), Yang et al. (2005).

The best management practices for the injection and distribution of amendments are available as published by the Battelle Memorial Institute and NAVFAC Alternative Restoration Technology Team as Technical Report: TR-NAVFAC-EXWC-EV-1303.

## TREATMENT ENHANCEMENTS

The treatment of soils contaminated with PAHs and/or metals is a highly recalcitrant process that typically entails prohibitory timeframes or costs if enhancements are not pursued (Kuppusamy et al., 2017). Enhancements are chemical or physical amendments used to augment treatment technologies and are not an integral part of any singular treatment alternative. Treatment technologies for PAHs and/or metals may be cost-effectively enhanced through the addition of (1) solvents and cosolvents; (2) surfactants; (3) pH amendments; and (4) complexing or chelating agents (ITRC, 2003a; Lee et al.,



2007; Dugan et al., 2010; Kuppisamy et al., 2017). Sequential addition of enhancements is often necessary to address complex contaminant mixtures whose treatment require different chemical regimes (Reddy et al., 2011). For example, soils co-contaminated with anionic and cationic metals require the sequential addition of opposite pH amendments to combat any undesired precipitation.

## **Solvents and Cosolvents**

Solvents are chemicals used to dissolve contaminants into solution. Water functions as a solvent for water-soluble contaminants, whereas nonpolar synthetic solvents are used to dissolve water-insoluble contaminants such as PAHs. Many synthetic solvents are highly toxic or chemically persistent, so cosolvents are often used with water to address hydrophobic contaminants in soil. Cosolvents are chemicals miscible with both the aqueous and nonaqueous phase that are used to augment solvents in solubilizing contaminant NAPLs. For cosolvency to be effective, the volume fraction used should range between 10–20% of the process fluid (Lee et al., 2007). Water and alcohol are conventionally employed as a solvent and cosolvent pairing; however, synthetic esters, carbonates, ketones, aromatics, hydrocarbons, ethers, and dipolar aprotic solvents may also be used if adequately contained, recaptured, and treated (Alder et al., 2016). Green solvents/cosolvents for environmental application include water; alcohols such as pentanol, heptanol, and ethanol; and esters such as glycerol triacetate, glycerol diacetate, isobutyl acetate, amyl acetate, and ethyl lactate (Alder et al., 2016; Lee et al., 2007). In recent years, ethyl lactate has proven to be an exceptionally effective green solvent for addressing petroleum-based contaminants (Ahmadkalei, et al., 2016). Additional contaminant solubilization may be achieved by further pairing solvents and cosolvents with compatible surfactants or oxidants (AATDF, 1997; Ahmadkalei et al., 2017).

## **Surfactants**

Surfactants are chemicals that may be used to increase contaminant mobility or solubility depending on concentration used relative to their critical micelle concentration (CMC). The CMC is an intrinsic property of each surfactant, the concentration above which all additional surfactant added to solution will form micelles rather than monomers. Surfactant monomers increase contaminant mobility by lowering interfacial tension at the solution interface. Surfactant micelles increase contaminant solubility through micellar solubilization (AATDF, 1997). Additionally, surfactant molecules are comprised of a hydrophobic and hydrophilic portion, the relative strength of which is characterized by the hydrophile-lipophile balance number (HLB). Water-insoluble contaminants are solubilized by surfactants with a low HLB, whereas high HLB surfactants are effective for contaminants of higher water solubility (AATDF, 1997). Surfactants are further categorized as either anionic, cationic, nonionic, or zwitterionic based on the charge of their molecular head group. Anionic and nonionic surfactants are relatively nontoxic and demonstrate insignificant sorption to soil surfaces, making them ideal for environmental application (Lee et al., 2007). Zwitterionic surfactants contain both anionic and cationic heads, allowing for interaction between hydrophilic and hydrophobic interfaces. These surfactants are also relatively nontoxic yet can be adsorbed to soil contents and function only as cosurfactants analogous in function to cosolvents. Conversely, cationic surfactants are highly toxic and sorb strongly to soil surfaces, making them a poor choice for environmental application (Lee et al., 2007). As such, surfactants should be specifically selected for each site based on their HLB and dosed according to their CMC to achieve the desired effect.

Improper surfactant selection can lead to increasing site toxicity or decreasing soil permeability through undesirable side reactions and emulsion effects. This is especially significant when surfactants are used to enhance chemical transformation methods such as in situ chemical oxidation (ISCO), as surfactants must either be compatible with the oxidant or applied sequentially (Wang et al., 2013; Yang et al., 2017). Various types of surfactants exist, including (1) surfactant polymers which increase solution viscosity for added directional control; (2) surfactant foams which may be injected into high permeability regions to direct flow into low-permeability soils; (3) biosurfactants such as rhamnolipids and cyclodextrins which are biodegradable and nontoxic; and (4) chemical oxidants which exhibit surfactant like properties such as catalyzed  $H_2O_2$  propagations (CHP). It should be noted that in situ use of surfactants requires a Class V injection permit from IEPA, which may present challenges due to groundwater quality concerns.

### **pH Amendments**

Acidic or basic solutions may be added to the soil to lower or raise soil pH respectively. These amendments may serve to activate or catalyze chemical reactions, alter contaminant speciation for manipulation of mobility or toxicity, or to return the site to neutral conditions post-treatment. The most commonly used bases are various sodium or ammonium hydroxides, silicates, and carbonates; however, sodium hydroxide is considered the most effective due to its low cost and efficacy (Khan & Islam, 2007). To minimize environmental impact, organic acids such as acetic, oxalic, and citric acid should be used to lower soil pH in place of stronger compounds like hydrochloric acid. Furthermore, many organic acids such as oxalic, citric, and ethylenediaminetetraacetic acid (EDTA) dually function as complexing or chelating agents when used to address metal contamination (Nogueira et al., 2007). pH amendments at IDOT construction sites are typically only allowed following excavation. Challenges during in situ pH amendments may arise due to heterogenous soil conditions.

### **Complexing and Chelating Agents**

Complexing agents are chemicals that form soluble metal complexes by donating a single pair of electrons to the metal ion. Chelating agents are chemicals that form soluble metal chelate complexes by donating multiple electron pairs to the metal ion. Either of these chemicals may be used to desorb metal contaminants from soil and suspend them into solution for extraction or reaction in the aqueous phase. Selection of a complexing or chelating agent should target chemicals that form strong complexes over the treatment's operational pH regime and exhibit high specificity for the contaminant of concern (COC), low affinity for sorption to soil surfaces, and relatively negligible toxicity. Chelating agents are typically preferred for use in remediation due to the increased stability of their metal complexes. In fact, a review by Leštan et al. (2008) found the chelating agent EDTA to be the most frequently cited enhancement for the extraction of metal contaminants from soils due to its low cost, high efficacy, and availability. Chelate complexes such as Pb(II)-EDTA remain highly stable and water soluble over wide pH ranges, thus increasing their mobility for extraction (Kim, 1996). Also, chelating agents may be used to enhance the metal catalysts used for in situ chemical treatments. For instance, Fe(III)-EDTA is highly stable and remains soluble over a wider pH range than conventional soluble iron catalysts for CHP, thus allowing for deeper penetration of the catalyst into contaminated soil matrices (Kakarla et al., 2002; Watts et al., 2005). Despite the nontoxic nature of EDTA, its recapture and treatment are often required due to its persistence in soils. Conversely, natural organic

compounds like oxalic, acetic, citric, fulvic, and humic acid readily biodegrade, requiring no recapture and treatment when used in situ (Nogueira et al., 2007; Cameselle & Pena, 2016; Merdoud et al., 2016; Bahemmat et al., 2016). Similar to the use of acids and bases, chelating agents are only allowed at IDOT construction sites following excavation.

## **TREATMENT ALTERNATIVES**

Soil remediation relies upon treatment alternatives which serve to meet remedial requirements through reduction in site toxicity or prevention of contaminant migration and exposure. Remediation may be achieved through containment, transformation, or extraction of the contaminants depending on site characteristics, budget, and time available. Inorganic contaminants are typically addressed via containment or extraction, while organic contaminants are most often treated with transformation technologies. PAHs and metals are often co-present in ROW soils at levels resulting in regulatory violation; therefore, this section describes accelerated on-site and in situ treatment alternatives applicable to the remediation of ROW soils contaminated with PAHs and/or metals. The treatments are grouped according to their mode of action and may incidentally apply to extraneous contaminants such as VOCs and nonmetal inorganics. These treatment alternatives may be used individually or supplementary to one another and are amenable to the distribution systems in “Soil Amendment Distribution Systems” and enhancements in “Treatment Enhancements.”

### **Containment**

Containment methods meet remedial requirements by reducing the potential for contaminant migration and exposure, usually without achieving a reduction in site toxicity (a.k.a., treatment). These methods are highly effective for relatively immobile contaminants that are stable, insoluble, and nonvolatile. Containment methods are often the fastest and least expensive strategies to implement and may be used as either temporary or permanent measures. Temporary containment is typically used to address emergency contaminant releases or to sequester newfound contaminants until treatment is practicable. Implementing permanent containment in place of treatment typically faces regulatory barriers yet may be necessary for sites that risk potential hazards associated with treatment, entail inhibitory treatment costs, or require unavailable treatment technologies (FRTR, 2007). Despite requiring long-term monitoring and institutional controls, permanent containment is typically more economical than excavation and off-site disposal (FRTR, 2007). In situ containment methods typically use solidification, stabilization, or sequestration technologies with institutional controls.

#### *Institutional Controls*

Institutional controls are non-engineered administrative or legal actions taken to reduce the potential for contaminant exposure or to protect the integrity of an ongoing treatment (EPA, 2012a). These methods may be used to restrict access to contaminated lands and their resources or to provide information intended to modify human behavior at and around the site. Simple institutional controls such as fences and signage are a common element of most treatment alternatives; however, extreme controls exist such as property acquisition or imposing land-use restrictions on neighboring properties (EPA, 2012a). Typical examples of institutional controls are provided in Table 17. Institutional controls may be harder to implement for ROWs than for individual properties.

**Table 17. Types of Institutional Controls**

Category	Example
<b>Proprietary Controls</b>	Negative easements and restrictive covenants that prohibit activities that compromise treatment integrity or restrict future resource use that may result in harm to human health or the environment.
<b>Governmental Controls</b>	Zoning, building codes, groundwater-use regulations, fishing bans, etc.
<b>Enforcement and Permit Tools</b>	Administrative orders, permits, Federal Facility Agreements, or Consent Decrees which limit or require specific site activities.
<b>Informational Devices</b>	Signage, registries, advisories, or other methods of disseminating risk. These controls are not typically enforceable yet may relieve liability.

EPA (2012a)

### *In Situ Soil Capping and Engineered Barriers*

In situ soil capping entails installation of an impermeable medium above contaminated soils to physically isolate contaminants, preventing their migration and exposure (EPA, 2012b). Soil capping is used to address soils contaminated with relatively immobile contaminants including both PAHs and metals at sites where the source has been mitigated (“Sediment Capping,” n.d.). Conventional soil caps are constructed as single layers of earthen material, asphalt, or concrete for trace contamination, or as multilayer landfill configurations with enhanced drainage and ventilation as outlined in Table 18. In addition to the cap, institutional controls are mandatory to prevent deterioration of the cap via future land-use activities, and long-term monitoring with routine inspections are typically required for up to 30+ years to assess containment integrity (EPA, 2012a, 2012b; EPA, 2011). As most IDOT construction sites include excavation, the capping and engineered barriers will be most useful after completion of the construction.

**Table 18. Conventional Soil Cap Composition**

Layer	Function	Material	RCRA Subtitle C	RCRA Subtitle D
<b>Cover</b>	Prevent erosion, protect from freeze-thaw damage	Vegetated topsoil or gravel	24 in.	6 in.
<b>Drainage</b>	Remove rejected infiltration	Sand, gravel, or geonet	12 in.	-
<b>Synthetic Barrier</b>	Prevent infiltration and vapor release	Geosynthetics	20–40 mil	-
<b>Earthen Barrier</b>	Prevent infiltration and vapor release	Compacted clay	24 in.	18 in.
<b>Gas Ventilation</b>	Allow passage of gas vapors for collection and removal	Sand, gravel, or geosynthetics	12 in.	-

“Landfill Capping RCRA C, D”, n.d.

Conventional soil capping is typically the least expensive and fastest treatment alternative to implement, estimated to cost approximately \$175,000–225,000 per acre and requiring < 1–4 months for installation (FRTR, 2007; “Sediment Capping,” n.d.). Soil caps are often paired with vertical engineered barriers (VEBs) such as slurry or sheet pile walls to prevent horizontal infiltration and contaminant migration (EPA, 2012c). VEBs are estimated to cost approximately \$5–7 per square foot

and are easily constructed at depths 60–100 feet below ground surface (BGS) and may be installed at greater depths using clam shell bucket excavation for roughly three times the cost (FRTR, 2007). Horizontal engineered barriers (HEBs) may additionally be required for sites overlying sensitive groundwater supplies and are typically implemented via directional drilling with forced grout injection below the contaminated soil. On average, HEBs cost \$50–150/ft of directional drilling in addition to \$50–75/ft of pressure grouting (FRTR, 2007). As a standalone treatment, in situ soil capping has only been used to address contaminated soils at five Superfund sites between 1982 and 2014 (EPA, 2017). Representative case studies for field-scale in situ soil capping are summarized in Table 19.

<b>Advantages</b>	<b>Disadvantages</b>
<ul style="list-style-type: none"> <li>• Highly cost-effective</li> <li>• Minimal site disturbance</li> <li>• Rapid implementation times</li> <li>• Readily implementable</li> <li>• Simple and widely applicable</li> </ul>	<ul style="list-style-type: none"> <li>• Barrier addition requires excavation</li> <li>• Construction and equipment intensive</li> <li>• Long-term monitoring requirements</li> <li>• May only postpone need for treatment</li> <li>• Potential regulatory barriers</li> </ul>

**Table 19. Representative Case Studies for Field-Scale Soil Capping**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$)
			Initial	Final			
Waterway: US <sup>(a)</sup>	Sediment 5,250 ft <sup>2</sup>	Zn, Hg, PAHs	410, 0.59, 17	n/a	-	-	11,500,000
Demonstrations: US <sup>(b)</sup>	Soil 83,958 ft <sup>2</sup>	Precipitation	n/a	n/a	99.9	5 Years	See Caption

\*Dashes indicate unavailable information.

<sup>(a)</sup> EPA (2008): 3/8 in. high-density polyethylene and 4–6 ft sand cap with vertical sheet pile walls

<sup>(b)</sup> DOE (2000): Water flux through six 13,993 ft<sup>2</sup> caps was evaluated to establish relative cost-efficacies:

<sup>(b.1)</sup> RCRA Subtitle C: Cost \$14.64/ft<sup>2</sup>; Equal in function to (5) and (6) for greater cost.

24 in. topsoil, 12 in. sand, 40 mil geomembrane, 24 in. compacted bentonite clay

<sup>(b.2)</sup> RCRA Subtitle D: Cost \$4.77/ft<sup>2</sup>; Ineffective over first year of testing, effective once saturated.

6 in. topsoil, 18 in. compacted native soil

<sup>(b.3)</sup> Geosynthetic Clay Liner: Cost \$8.36/ft<sup>2</sup>; Construction damage resulted in poor performance.

24 in. topsoil, geotextile filter fabric, 12 in. sand, 40 mil geomembrane, geosynthetic clay liner

<sup>(b.4)</sup> Capillary Barrier Cover: Cost \$8.61/ft<sup>2</sup>; Poor function prior to vegetation growth.

12 in. topsoil, 6 in. sand, 9 in. gravel, 18 in. compacted bentonite clay, 6 in. sand

<sup>(b.5)</sup> Anisotropic Barrier Cover: Cost \$6.99/ft<sup>2</sup>; Function improved after first year.

6 in. topsoil, 24 in. native soil, 6 in. fine sand, 6 in. pea gravel

<sup>(b.6)</sup> Evapotranspiration Soil Cover: Cost \$6.86/ft<sup>2</sup>; Estimated to save \$7.6 million compared to (1)

6 in. vegetated topsoil, 30 in. compacted native soil

Reactive soil capping is an innovative approach in which cap materials are specifically selected to enhance contaminant containment and/or degradation either chemically or biologically in addition to physical sequestration. Multilayer soil caps are widely amenable to various active layers such as (1) activated carbon, organoclays, bauxite, or apatite for contaminant sequestration; (2) clay aggregate

composites for permeability control; (3) zero valent iron for contaminant dehalogenation; (4) biopolymers as a binding agent for metals and organics; and (5) siderite or oxygen/hydrogen release compounds for pH control (“Reactive Capping,” n.d.). Reactive soil caps are often thinner than conventional caps making them ideal for space-limited sites; however, they require an additional 2 to 4 months for installation and require additional monitoring efforts due to their newness as a treatment technology (“Reactive Capping,” n.d.). Case studies on over 200 innovative soil caps are available from the EPA’s alternative landfill database (EPA, 2011; “Alternative Landfill Cover Project Profiles,” n.d.).

### *In Situ Solidification/Stabilization*

In situ solidification/stabilization (S/S) utilizes soil amendments to immobilize and encapsulate contaminants in place. Solidification uses physical binding agents to conglomerate loose particles into a solid matrix whereas stabilization uses chemical binding agents to react with contaminants, forming immobile water-insoluble compounds (EPA, 2012d). S/S is typically used to address soils contaminated with relatively immobile contaminants, including both PAHs and metals, at sites where the source has been mitigated (ITRC, 2011). Inorganic binders such as Portland cement, fly ash, lime, soluble silicates, and sulfur-based binders are commonly selected to address metal contaminants and are generally less expensive and easier to apply than organic binders (“Solidification & Stabilization In Situ,” n.d.). At sites where PAHs are present, organic binders such as asphalt, epoxide, granulated activated carbon (GAC), organophilic clays, polyesters, and polyethylene are added prior to solidification by inorganic binders (“Solidification & Stabilization In Situ,” n.d.). S/S is highly convenient for use at ROW sites, as it often paired with a soil cap (asphalt roadway) to preserve containment integrity (ITRC, 2011). Further, the structural integrity of soils treated with S/S typically increases resultant from reaction between the cement and soil particles (Estabragh et al., 2015). Drawbacks of this approach include the need for work at the construction site after the treatment is complete, for instance to replace a utility line or culvert.

<b>Advantages</b>	<b>Disadvantages</b>
<ul style="list-style-type: none"> <li>• Highly cost-effective</li> <li>• Rapid implementation times</li> <li>• Readily implementable and cost-effective</li> <li>• Simple and widely applicable</li> </ul>	<ul style="list-style-type: none"> <li>• Limited by rocky or dense soil matrices</li> <li>• Long-term monitoring requirements</li> <li>• May only postpone need for treatment</li> <li>• Soil undergoes significant volume increase</li> </ul>

Binding agents are typically distributed by mechanical soil mixing with an auger and caisson. Shallow mixing techniques are limited to maximum depths of about 10 ft BGS yet are highly effective, costing approximately \$40–60/yd<sup>3</sup> at an average rate of 40–80 tons per hour (“Solidification & Stabilization In Situ,” n.d.; EPA, 2007a; FRTR, 2007). S/S applications are feasible to depths of 100 ft BGS but can become cost prohibitive below 60 ft BGS, costing \$150–250 per cubic yard at an average rate of 20–50 tons per hour (“Solidification & Stabilization In Situ,” n.d.; EPA, 2007a; FRTR, 2007). In situ S/S has been used to address contaminated soils at 170 Superfund sites, in addition to 290 ex situ applications between 1982 and 2014 (EPA, 2017). Assessment of 29 completed S/S projects by the EPA found total costs to range from \$75,000 to \$16 million, averaging \$264/yd<sup>3</sup>, or \$194/yd<sup>3</sup> excluding two outliers which cost \$1,200/yd<sup>3</sup> each (EPA, 2000a). Further findings from the same study include (1) inorganic binders were used to address 94% of sites with cement being the most

commonly applied amendment; (2) the average operational time per 1,000yd<sup>3</sup> was 1.1 months; and (3) 90% of in situ S/S applications were used to address metal contaminants, the most common being lead, chromium, arsenic, cadmium, and copper, whereas only 6% of S/S uses were for organic contamination alone (EPA, 2000a). An extensive review of in situ S/S including 40 case studies is available online as “Stabilization and Solidification of Contaminated Soil and Waste: A Manual of Practice” (Bates & Hills, 2015). Representative case studies for field-scale in situ S/S are summarized in Table 20.

In situ vitrification (ISV) is an innovative approach to S/S used as an alternative to binding agents at especially recalcitrant sites. ISV heats soils to extreme temperatures (2,900–3,650°F) via high-intensity electrical currents to fuse soil matrices into a vitrified crystalline mass (FRTR, 2007). During this process, organic contaminants are destroyed by pyrolysis and inorganics are incorporated within the vitrification product, which is chemically stable and leach resistant. ISV is more expensive and complex, but it is less prone to containment failure than binding agents. As shown by Long and Zhang (1998) even relatively immobile heavy metals such as lead may mobilize post-S/S-treatment using binding agents, whereas stabilization by heating is increasingly robust (Long & Zhang, 1998). ISV is typically cost prohibitive at most sites, on average costing \$25,000–30,000 for treatability testing in addition to \$200,000–300,000 for equipment mobilization and demobilization, and operational costs of \$365–425 per ton of soil (“Solidification & Stabilization In Situ,” n.d.; FRTR, 2007).

**Table 20. Representative Case Studies for Field-Scale In Situ Solidification/Stabilization**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Burn/Detonation: US <sup>(a)</sup>	Soil 3,000yd <sup>3</sup>	Pb	1,942–2,402 (> 1.5)	< 24 (0.0065–0.46)	> 99	-	22
Arms Ranges: US <sup>(b)</sup>	Sand/Stone 5,380yd <sup>3</sup>	Pb	< 12,200 (734)	< 366 (< 0.5)	97	6 months	151
Wood Treatment: US <sup>(c)</sup>	Sediment 2,450yd <sup>3</sup>	PAHs	500	-	-	3 months	229

\*Parentheses indicate toxicity characteristic leaching procedure (TCLP) (mg/L); dashes indicate unavailable information.

<sup>(a)</sup> DOD (2006): PIMSTM using Apatite II™; process rate of 600yd<sup>3</sup>/day

<sup>(b)</sup> EPA (2000b): MAECTITE®; cost and duration include an additional 17,788yd<sup>3</sup> treated ex situ

<sup>(c)</sup> EPA (2003): Cement-based grout and proprietary chemicals; total cost of \$561,154

## Transformation

Transformation alternatives meet remedial requirements by destroying contaminants or altering their chemical structure into less toxic, less mobile, and/or less stable forms (FRTR, 2007). Conversely, transformation can be used to increase the mobility of contaminants for extraction by coupled processes. As such, transformation alternatives may be used as standalone treatments or to enhance either containment or extraction. Chemical transformation reagents are commonly applied to destroy highly concentrated organic contaminants or to manipulate the speciation of multivalent metals. Biological transformation alternatives have been excluded from review due to their prohibitively long treatment durations.

## *Chemical Transformation*

Chemical transformation methods use the distribution of chemical reduction/oxidation reagents throughout the soil to rapidly destroy or transform contaminants. In this way, contaminants are reduced or oxidized to beneficially alter their chemical structure. These relatively rapid treatments are often cost-effective for addressing highly concentrated contaminants that are recalcitrant towards containment, extraction, or biological methods. With respect to the remediation of PAH contaminated soils, transformation methods are typically the fastest, most cost-effective, and least disruptive to the environment, relative to similarly effective treatment alternatives (de Boer & Wagelmans, 2016). Standalone in situ chemical treatments have been used to address contaminated soils at 38 Superfund sites, in addition to 40 ex situ applications between 1982 and 2014 (EPA, 2017). The costs typically vary between \$100–500/yd<sup>3</sup> of contaminated soil, and durations can vary anywhere from days to months depending on the site complexities and the nature of the contaminants (EPRI et al., 2007; FRTR, 2007).

### In Situ Chemical Reduction

In situ chemical reduction (ISCR) is typically used to address sites contaminated with hexavalent chromium and chlorinated solvents but may be used to transform any multivalent metals or halogenated contaminants (EPA, 2012e). The most commonly used reducing agents are zero valent iron (ZVI) for organics and polysulfide solutions or foams for metals; however, numerous other reductants are feasible including (1) scrap iron and iron minerals such as magnetite, green rust, ferruginous clays, goethite, mackinawite, and pyrite; (2) sodium dithionite; (3) bimetallic materials; and (4) vegetable oil (DOD, 2018; EPA, 2012e). ZVI is typically distributed in the form of granular, microscale, or nanoscale powders that have been blended with clays to emulsify NAPLs (Shackelford et al., 2005). Finer ZVI particle size can be used to increase soil matrix penetration and treatment efficacy in exchange for a greater reagent cost (Wadley et al., 2005; DOD, 2018). Implementation of ISCR for soils utilizes either source zone targeted injection (SZTI), mechanical soil mixing via auger and caisson, or a permeable reactive barrier (PRB) coupled with forced advection by hydraulic, pneumatic, or electrokinetic systems (DOD, 2018). ISCR is often coupled with S/S to encapsulate contaminants in their reduced state, helping to prevent contaminant rebound and leaching. Requiring anywhere from months to years for operation, soil mixing and direct-push injection systems offer the fastest ISCR implementation times (EPA, 2012e). Representative case studies for field-scale ISCR are summarized in Table 21.

<b>Advantages</b>	<b>Disadvantages</b>
<ul style="list-style-type: none"><li>• Can destroy or immobilize contaminants</li><li>• Low generation of waste material</li><li>• Minimal site disturbance</li><li>• Rapid implementation times</li><li>• Readily implementable and cost-effective</li></ul>	<ul style="list-style-type: none"><li>• Does not lower total concentration of metals</li><li>• Long-term monitoring requirements</li><li>• Metal transformations are prone to rebound</li><li>• Regulatory barriers on underground injection or the transportation of chemicals</li><li>• Lower efficacy for large scale contamination</li></ul>



**Table 21. Representative Case Studies for Field-Scale In Situ Chemical Reduction**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Chrome Plating: US <sup>(a)</sup>	Silt/Sand/Clay 20,962yd <sup>3</sup>	Cr	620–7,500	< 5	> 99	7 Months	124
Embankment: US <sup>(b)</sup>	Sand/Silt/Gravel 1,025yd <sup>3</sup>	Total Cr Cr(VI)	< 129,000 < 31,000	92–67,000 0–5,600	48–99 82–100	-	117
Unidentified: US <sup>(c)</sup>	Sand/Silt/Clay 19,444yd <sup>3</sup>	Cr(VI)	32 (300)	- (< 0.05)	> 99 in Sand	-	-

\*Parentheses indicate TCLP (mg/L); dashes indicate unavailable information.

<sup>(a)</sup> EPA (2005): ECOBOND®; total cost \$2,419,500; followed by grout S/S for soil strengthening

<sup>(b)</sup> EPA (2004): Calcium polysulfide, 18% solution; total cost \$119,719

<sup>(c)</sup> Perkins and Chui (2008): Calcium polysulfide, 0.1 to 6.1 percent solution by weight

**In Situ Chemical Oxidation**

In situ chemical oxidation (ISCO) is typically used for the treatment of groundwater, but it may also be applied to soils for the destruction of PAHs and most other organic contaminants (EPA, 1998a; ITRC, 2005; Medina et al., 2007). The most commonly used oxidants are hydrogen peroxide, persulfate, ozone, and permanganate (Ceulemans & Labeeuw, 2013). Additional well-established oxidants include percarbonate, dual-oxidant systems such as perozone, and surfactant-enhanced oxidant mixtures (ITRC, 2005; EthicalChem, 2014a, 2014b). Oxidants should be carefully selected for each site based on their contaminant, soil, and regulatory compatibility to avoid worsening site conditions. For example, permanganate is inadvisable for use in Illinois due to restrictive manganese regulations (e.g., MAC: 630–636 mg/kg) and its common inclusion of heavy metal impurities, despite demonstrating the highest compatibility with PAHs (ITRC, 2005). Catalyzed H<sub>2</sub>O<sub>2</sub> propagations (CHP) systems are the fastest acting and most powerful, capable of destroying contaminants in as little as hours, yet these systems are highly limited by soil composition (ITRC, 2005; Usman et al., 2016). Activated persulfate systems are slower acting, typically requiring weeks to meet remedial goals, but are applicable to most soil compositions due to reagent longevity (ITRC, 2005). Table 22 outlines different features of hydrogen peroxide, activated persulfate, and ozone, as each can degrade PAHs but with different advantages depending on soil composition and time available. Representative case studies for field-scale ISCO are summarized in Table 23.

**Table 22. Summary Table for Select ISCO Reagents**

	Hydrogen Peroxide	Activated Persulfate	Ozone
<b>Reagent Parameter</b>			
Form	Liquid	Solid/liquid	Gas
Oxidation potential (V)	1.8–2.8	2.1–2.6	2.1
Activators	Iron, minerals	Iron, pH, H <sub>2</sub> O <sub>2</sub> , heat	None
Cost	Low	Moderate to high	Low (high capital cost)
<b>Operational Parameter</b>			
Soil pH	Acidic to neutral	Acidic to basic	Acidic to slightly basic
Soil organic matter	Low	Low to moderate	Low
Soil permeability	Moderate to high	Low to high	High

	<b>Hydrogen Peroxide</b>	<b>Activated Persulfate</b>	<b>Ozone</b>
Contaminant conc.	Low to high	Low to high	Low to moderate
Loss/day	High	Low	Moderate
Treatment duration	Days to weeks	Weeks to months	Weeks to months
Potential detriments	(1) Byproducts (2) Gas evolution (3) Heat generation (4) Metal solubilization	(1) Byproducts (2) Metal solubilization (3) Typically slow	(1) Corrosivity (2) Gas evolution (3) Heat generation (4) Toxic gas release
Efficacy for PAHs	Moderate: exhibits enhanced desorption and NAPL dissolution	Moderate: high stability results in enhanced contact	Moderate: reacts with both aqueous and NAPL contaminants

ITRC (2005), EPA (2006), Ceulemans and Labeeuw (2013)

### Advantages

- Can desorb contaminants from soils
- Can dissolve contaminant NAPLs
- Extensively demonstrated at the field scale
- Highly compatible with other treatments
- Low generation of waste material
- Rapid implementation times
- Readily implementable and cost-effective
- Widely applicable to organic contaminants

### Disadvantages

- Can damage underground utilities
- Limited by soils high in oxidant scavenging compounds and natural organic matter
- Long-term monitoring requirements
- Prone to contaminant rebound
- Regulatory barriers on underground injection or the transportation of chemicals
- Lower efficacy for large scale contamination

**Table 23. Representative Case Studies for Field-Scale In Situ Chemical Oxidation**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Federal Facility: US <sup>(a)</sup>	Sand/Silt/Clay 5,926yd <sup>3</sup>	PAHs	-	-	“Complete”	-	83.5
Fuel Oil Terminal: US <sup>(b)</sup>	Sand/Silt 6,000yd <sup>3</sup>	PAHs	32.5	Non-detect	> 90	60 Days	24
Wood Treatment: US <sup>(c)</sup>	Silty Sand/Clay -	PAHs	5,680	114–398	93 -> 98	1 Year	-
Wood Treatment: US <sup>(d)</sup>	Sand/Silty Clay -	PAHs	1000 (14)	< 30 -	> 97	2 Months	-
MGP: US <sup>(e)</sup>	Sand/Silt/Clay 2,500ft <sup>2</sup>	PAHs	(7.93)	-	38	90 Days	-
Petroleum UST: US <sup>(f)</sup>	Sand/Silt/Clay -	PAHs	0.2	Non-detect	> 99	8 Days	-
Industrial Facility US <sup>(g)</sup>	Soil 2-acres	PAHs	1,800	9	99.5	1–3 Months	-
MGP: US <sup>(h)</sup>	Silt/Clay 2-acres	Total Petroleum Hydrocarbons (TPH) PAHs	6,100–6,400 2,542–3,379	1,800–2,100 755–978	68–75 55–63	2 Weeks	-

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Urban Harbor: Australia <sup>(i)</sup>	Soil -	Total Petroleum Hydrocarbons (TPH) PAHs	-	-	> 97 73	8 Weeks	-
Manufacturing: US <sup>(i)</sup>	Soil 0.73-acres	PAHs	[26,389]	[1,319]	95	5 Months	-

\*Parentheses indicate TCLP (mg/L); brackets indicate mass NAPL removed (lb); dashes indicate unavailable information.

(a) Pohlmann (2012): Permanganate; total cost \$495,000

(b) ITRC (2005): Ozone; total cost \$144,000

(c) ITRC (2005): Ozone

(d) EPA (2007b): Peroxone 3.3:1 molar ratio (17.5% hydrogen peroxide and 2,500 ppmv ozone)

(e) Dey et al. (2006): Ozone

(f) Haslow et al. (2005): Thermally activated persulfate; total cost \$15,000

(g) EPA (1998a); ITRC (2005): Ozone; total cost \$300,000

(h) XDD (2007): Alkaline and iron-chelate (Fe(II)-EDTA) activated persulfate with VeruSOL<sup>®</sup> surfactant/cosolvent; 63% leachability reduction; 90% destruction projected for second application.

(i) EthicalChem (2014a): Hydrogen peroxide, activated persulfate, and VeruSOL<sup>®</sup>

(j) EthicalChem (2014b): Alkaline-activated Klozur<sup>®</sup> persulfate, sodium hydroxide, and VeruSOL<sup>®</sup>

## Extraction

Extraction alternatives meet remedial requirements by leveraging the physicochemical properties of contaminants to remove them from soil. These methods may be used to completely extract contaminants from soil in situ or on-site or to lower off-site disposal costs by concentrating contaminants into a different media to reduce waste volumes. Extraction alternatives are typically used to address inorganic contaminants when containment is unacceptable or contaminant mixtures where treatment of one compound risks deleterious mobilization of another. Extraction technologies that target PAHs and/or metals will typically remove extraneous contaminants such as VOCs and nonmetal inorganics as well.

### *In Situ Soil Flushing*

In situ soil flushing uses water injected into the soil to solubilize contaminants for extraction. Solubilized contaminants are flushed into the underlying groundwater which is extracted downgradient by pumping for off-site disposal or on-site treatment and recirculation when possible. Soil flushing is typically used to address soils contaminated with water-soluble contaminants or LNAPLs, and overlying groundwater that is also contaminated (EPA, 1996a; ITRC, 2003b). Water-soluble contaminants may be extracted using only water over long periods for low cost; however, enhancements such as those in the “Treatment Enhancements” section are necessary to accelerate or facilitate the extraction of PAHs and metals that sorb strongly to soil and exhibit negligible water solubility (Reddy et al., 2011). Enhancing agents must be recovered and treated prior to recirculation of the process fluid, and care should be taken to avoid introducing chemicals which will worsen site conditions by increasing toxicity, decreasing soil permeability, or resulting in other undesirable reactivity (Lee et al., 2006, 2007). Coupling chemical transformation alternatives with soil flushing can greatly accelerate treatment times and reduce necessary ex situ treatment of the process fluids. Soil

flushing is inadvisable at sites overlying uncontaminated groundwater as downward contaminant dispersal is intrinsic to its function.

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Adaptable to numerous enhancements and coupled technologies for compatibility with most contaminants</li> <li>• Metals may be separated from waste streams for collection and reuse</li> <li>• Simple, effective, and inexpensive for coarse soils with water-soluble contaminants</li> <li>• Small surface footprint</li> </ul>	<ul style="list-style-type: none"> <li>• Deep water tables or the need for synthetic enhancing agents greatly increases cost</li> <li>• Enhancing agents may worsen site characteristics and/or contamination</li> <li>• High potential for contaminant dispersal</li> <li>• High waste generation</li> <li>• Ineffective in soils that are highly heterogenous, low-permeability, or high in organic matter</li> <li>• Regulatory acceptance is limited</li> </ul>

In situ soil flushing has been used to address contaminated soils at 40 Superfund sites between 1982 and 2014 (EPA, 2017). Soil flushing is estimated to cost between \$18–250 per cubic yard of contaminated soil and require several months to years for operation depending on enhancements pursued (FRTR, 2007; ITRC, 2009). Representative case studies for field-scale in situ soil flushing are summarized in Table 24.

**Table 24. Representative Case Studies for Field-Scale In Situ Soil Flushing**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Industrial Facility: US <sup>(a)</sup>	Sand/Silty Sand 0.73-acre	PAHs	[53,600]	[< 5,360]	> 90	5 Months	-

\*Brackets indicate mass NAPL removed (lb); dashes indicate unavailable information

<sup>(a)</sup> Panter (2012): Enhanced with citrus-based surfactant and sodium persulfate solution.

### *On-Site Physical Separation and Soil Washing*

On-site physical separation and soil washing can be coupled to address all types of soil contamination including organics, inorganics, and debris. Physical separation is conventionally performed ex situ as a waste minimization process but may also be implemented as an accelerated on-site remedy through use of mobile installations (CL:AIRE, 2007). Physical separation is the most frequently selected soil-treatment alternative in the United States, having been used to address contaminated soils at 382 Superfund sites from 1982 to 2014 (EPA, 2017). This treatment minimizes waste media by leveraging the fact that most soil contaminants bind to the fine soil fraction (EPA, 1996b). Following excavation, the fine soil fraction is separated from coarse particles and large debris by means of mechanical screening, sieving, hydrocyclones, and/or gravity settling. The coarse particles and debris are then quickly treated via attrition scrubbing to remove any remaining adherent particles and contaminants. The coarse soil fraction may then be reused as fill material, whereas the fine soil fraction is typically disposed of as a concentrated volume of non-special, special, and hazardous waste or treated for reuse via soil washing. Consequently, physical separation always precludes soil washing.

Like physical separation, soil washing is conventionally applied ex situ, having been used to address contaminated soils at 33 Superfund sites between 1982 and 2014 (EPA, 2017). Soil washing is performed in batch reactors as an ex situ variant of in situ soil flushing, during which soils are dissolved or suspended in chemical solutions tailored to the site-specific contaminants (Chu, 2003). As such, soil washing avoids risks associated with in situ chemical amendments, enabling the use of harsh chemical approaches typically barred from underground injection (Chu & Chan, 2003). Furthermore, relative to in situ flushing, batch-processing simplifies the recycling of nonbiodegradable enhancing agents and both reagent expenditure and treatment duration are minimized via washing only the fine soil fraction. A common approach to accelerating workflow is to immediately backfill the coarse fraction as soil washing pursues, allowing for construction to continue and the later treated fines to be disposed of as nonhazardous waste (EPA, 2013). However, it may be challenging to implement on-site due to space restrictions in construction ROWs.

<b>Advantages</b>	<b>Disadvantages</b>
<ul style="list-style-type: none"> <li>• Adaptable to numerous enhancements for compatibility with most contaminants</li> <li>• Coarse soil fractions are rapidly treated</li> <li>• Considered short-medium term, process rates of up to 45 tons/hr. are commercially attainable</li> <li>• Effective for sites requiring separation of construction debris from complex media</li> <li>• Metals can be collected from waste streams</li> </ul>	<ul style="list-style-type: none"> <li>• Equipment and labor intensive</li> <li>• Large surface footprint</li> <li>• Limited availability of mobile installations</li> <li>• Potential for high waste generation</li> <li>• Requires excavation</li> </ul>

Conventional ex situ soil washing is estimated to cost between \$53–142 per cubic yard of soil and require several months to years for operation (FRTR, 2007). Using mobile installations, daily throughput rates of 10–500yd<sup>3</sup> and 20–200yd<sup>3</sup> are attainable for physical separation and soil washing respectively (“Physical Separation,” n.d.; “Chemical Extraction,” n.d.). As such, the duration and cost are dependent upon the availability of commercial installations. Representative case studies for field-scale soil washing are summarized in Table 25.

**Table 25. Representative Case Studies for Field-Scale On-Site Soil Washing**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/ton)
			Initial	Final			
Gasworks: UK <sup>(a)</sup>	Soil 130,795yd <sup>3</sup>	PAH TPH	3,000 2,000–5,000	< 500 < 500	> 83 > 75	-	-
Industrial: Germany <sup>(b)</sup>	Soil -	TPH, PAH, Pb, Cd, Cr, Cu, Ni, Zn	150, 30, 802, 4, 69, 196, 30, 1,287	80, 7, 129, 1, 3, 34, 7, 277	47, 76, 84, 70, 96, 82, 78, 79	-	-
Unidentified: US <sup>(c)</sup>	Soil -	Cr, Cu, Ni	837, 1,120, 422	159, 259, 83	81, 77, 80	-	-
Arms Range: USA <sup>(d)</sup>	Soil 263 tons	Pb, Cu, Zn, Sb	1,000, 1,000, 1,000, 1,000	70, 70, 230, 300	93, 93, 77, 70	4 Months	-
Arms Range:	Soil	Pb, Cu,	500, 500,	20, 15,	96, 97,	4 Months	1,400

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/ton)
			Initial	Final			
USA <sup>(e)</sup>	835 tons	Zn, Sb	500, 500	55, 200	89, 60		170 <sup>P</sup>
Waste Facility: US <sup>(f)</sup>	Soil/Sludge 19,200 tons	Cr, Cu, Ni	660, 860, 330	172, 350, 98	74, 59, 70	4 Months	401

\*Dashes indicate unavailable information; superscript "P" indicates projection for scale-up

<sup>(a,b,c)</sup> CL:AIRE (2007): Soil volume fully treated (a) 80–85%; (b) > 90%; (c) > 90%

<sup>(d)</sup> DOD (1997): Physical Separation and Acetic Acid; 2.8 tons/hr

<sup>(e)</sup> DOD (1997): Physical Separation and Hydrochloric Acid; 6.3 tons/hr; projection for 10,000 tons

<sup>(f)</sup> EPA (1995): Total cost \$7,700,000; 25 tons/hr.

### *In Situ Thermal Treatment*

Also referred to as in situ thermal desorption, low-temperature soil heating (< 212°F), or thermally enhanced soil vapor extraction (SVE), in situ thermal treatments are frequently used to address organic contaminants including PAHs ("Heating In Situ," n.d.). Low-temperature thermal systems stimulate contaminant desorption while dewatering soils and volatilizing contaminants for extraction by SVE wells (EPA, 2012g). The in situ addition of heat accelerates extraction by increasing soil permeability via drying and fracturing, decreasing the viscosity of soil pore fluid, lowering contaminant boiling points, and increasing contaminant vapor pressure, diffusivity, and volatility (FRTR, 2007). Additionally, mechanisms such as thermal oxidation, biotic decomposition, and steam stripping enable this technology to address contaminants with boiling points higher than 212°F, extending its applicability to high-molecular-weight PAHs (HMW-PAHs) ("Heating In Situ," n.d.). Well-established in situ thermal technologies include electrical resistance heating (ERH), radio frequency heating (RFH), microwave frequency heating (MFH), and the injection of hot air or steam (FRTR, 2007; EPA, 2012f). ERH, RFH, and MFH are electrical heating methods best suited for saturated fine-grained soils. These systems use subsurface electrodes to distribute energy in the form of either alternating current or radiation to heat soils via the thermal conductivity of soil moisture. Therefore, the efficacy of these systems decreases over time as pore fluid evaporates. Conversely, hot air and steam injection are best suited for unsaturated coarse-grained soils. All thermal systems are most effective for large sites and rely on coupled SVE for off-gas collection and treatment.

SVE typically utilizes vacuum wells at depths of 5 ft or greater to extract contaminants from soil based on their volatility (EPA, 2012g). Shallow contamination is easily removed via horizontal venting along the surface; however, SVE has been successful as low as 300 ft below ground surface with the addition of vertical extraction vents (FRTR, 2007). Unenhanced, SVE works best for VOCs within unsaturated coarse-grained soils over a medium-long term duration, requiring approximately nine months on average to address 20,000 tons of contaminated soil (FRTR, 2007). Although SVE is typically ineffective for contaminants with a Henry's Law constant of less than 100 atmospheres per mole fraction and vapor pressures less than 0.1 mm Hg to 1.0 mm Hg at ambient temperatures (EPA, 1997a), the addition of heat overcomes these drawbacks by accelerating extraction and extending applicability to fine-grained saturated soils and semi-volatile organics. In both unenhanced SVE and thermal treatments, extracted vapors and fugitive emissions must be captured and treated above grade through secondary processes, most commonly activated carbon treatment, significantly increasing costs and waste generation (EPA, 2012h). Risks associated with thermal enhancement are

minimal but may include potential pressure accumulation and explosivity, damage to soil structural integrity, and inefficacy due to buried metal objects in the case of electrical heating.

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Complete contaminant removal is attainable</li> <li>• Highly effective for organic contaminants</li> <li>• Simple and well established</li> <li>• Widely commercially available</li> </ul>	<ul style="list-style-type: none"> <li>• Heat addition can damage soil structural integrity and kill soil bacteria</li> <li>• High waste generation</li> <li>• Limited to organic contaminants</li> <li>• High cost and carbon footprint (energy intensive)</li> </ul>

In situ SVE is the most frequently selected in situ soil treatment technology in the United States, having been used for contaminated soils at 301 Superfund sites in addition to 30 ex situ applications between 1982 and 2014 (EPA, 2017). Additionally, in situ thermal treatment has been used to treat contaminated soils at 93 Superfund sites and 117 ex situ applications during the same time period (EPA, 2017). The costs of applying (1) steam injection range from \$46/yd<sup>3</sup> to \$166/yd<sup>3</sup>; (2) hot air injection range from \$75/yd<sup>3</sup> to \$100/yd<sup>3</sup>; (3) RFH range from \$195/yd<sup>3</sup> to \$336/yd<sup>3</sup>; and (4) ERH are typically \$100/yd<sup>3</sup> or greater (EPA, 1997a). Representative case studies for field-scale in situ thermal treatment are summarized in Table 26.

**Table 26. Representative Case Studies for Field-Scale In Situ Thermal Treatment**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Wood Treatment: US <sup>(a)</sup>	Sand/Silt/Debris 16,480yd <sup>3</sup>	PAHs	2,306	-	-	26 Months	382
Wood Treatment: US <sup>(b)</sup>	Sand/Silt 39,722yd <sup>3</sup>	PAHs	100	[4,629]	-	4 Months	-
Sand Dunes: US <sup>(c)</sup>	Sand 2,698yd <sup>3</sup>	TPH PAHs	(22mg/L) -	(6.6mg/L) Non-detect	- -	8 Months	-

\*Brackets indicate mass NAPL removed (lb); parentheses indicate TCLP (mg/L); dashes indicate unavailable information

<sup>(a)</sup> EPA (2006a), Baker (2007): In situ conductive heating

<sup>(b)</sup> EPA (2006): Electrical resistance heating

<sup>(c)</sup> Udell et al. (2006): Hot water (3 months) and steam injection (5 months)

### *On-Site Thermal Treatment*

Also referred to as thermal desorption or incineration, on-site thermal treatments use mobile thermal desorption systems or furnaces to heat soils to extreme temperatures (212–3000°F) for the extraction and/or destruction of organic contaminants (EPA, 2012i, 2012j; “Incineration,” n.d.). On-site thermal treatments are typically used to address semi-volatile organic compounds (SVOCs) with high boiling points such as HMW-PAHs at sites where in situ treatment is ineffective or cumbersome; however, incineration is also applicable to volatile and semi-volatile heavy metals including lead, cadmium, mercury, and arsenic, making it highly effective for addressing mixed wastes (“Incineration,” n.d.; Long et al., 1999). On-site thermal treatments require off-gas collection and treatment in addition to disposal of combustion byproducts as hazardous wastes, together contributing to significant cost increases (EPA, 2012j).

### Advantages

- Complete destruction of organic contaminants
- Nearly guaranteed efficacy
- Rapid for most soils and contaminants
- Widely applicable

### Disadvantages

- Damage to soil structural integrity
- Energy intensive; highest costing alternative
- High site disturbance; requires excavation
- Inorganic waste products require S/S
- Physical separation required prior to treatment

On-site incineration and thermal desorption have been used to address contaminated soils at 85 and 60 Superfund sites, respectively, from 1982 to 2014 (EPA, 2017). Additionally, 228 Superfund sites have been remediated via ex situ thermal treatments over the same period (EPA, 2017). Solids residence time within incinerators ranges from 30–90 minutes for complete destruction to occur, allowing for mobile system throughput rates of 30–200yd<sup>3</sup> per day (“Incineration,” n.d.). The cost of on-site incineration is estimated to range from approximately \$700–1,200/yd<sup>3</sup> or greater than \$300/ton, prohibiting its application at most sites (FRTR, 2007). Conversely, mobile thermal desorption systems can process 7–50 tons of soil per hour, typically costing between \$40–240/yd<sup>3</sup> and requiring just over four months to remediate a 20,000-ton site (FRTR, 2007). Representative case studies for field-scale on-site thermal treatment are summarized in Table 27.

**Table 27. Representative Case Studies for Field-Scale On-Site Thermal Treatment**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/ton)
			Initial	Final			
Wood Treatment: US <sup>(a)</sup>	Sludge/Soil 102,000 tons	PAHs	< 38,000	0	> 99.99	9 Months	265
Industrial Facility: US <sup>(b)</sup>	Sludge/Soil 4,660 tons	Sb, Pb, Cr	3,000, 2,041, 40	0, 0, 0	> 99.99	9 Months	410
Chemical Plant: US <sup>(c)</sup>	Soil 210,000 tons	PAHs	5,600	0	> 99.99	2 Years	< 633
Military Base: US <sup>(d)</sup>	Soil 104,336 tons	HMW-PAHs	2.2	0.13	94	4 Months	34
Coal Tar Plant: US <sup>(e)</sup>	Soil 3,700 tons	HMW-PAHs	250–126,020	< 20	> 75	3 Months	251
Wood Treatment: US <sup>(f)</sup>	Silty Clay/Sand 170,300 tons	As, Cr, PAHs	-,-,-	< 94, > 88, > 100	> 99.99	10 Months	58

\*Dashes indicate unavailable information

<sup>(a)</sup> EPA (1993): Incineration; total cost \$27,000,000; 2,770yd<sup>3</sup> sludge, 850yd<sup>3</sup> sediment, 21,000yd<sup>3</sup> soil. 1,425°F rotary kiln and 2,091°F secondary combustion chamber (SCC); throughput of 18 tons/hr.

<sup>(b)</sup> EPA (1998b): Incineration; total cost \$5,300,000, \$1,000/ton, thermal treatment unit cost of \$410/ton; 1,500°F rotary kiln and 1,900°F SCC; residence time of 45 minutes; throughput of 2.3 tons/hr.

<sup>(c)</sup> EPA (1998c): Incineration; total cost \$133,000,000; additional 1,500yd<sup>3</sup> of sediment were treated; 1,233°F rotary kiln and 1,950°F SCC. throughput of 25 tons/hr.

<sup>(d)</sup> EPA (1998d): Thermal Desorption; total cost \$3,532,270; 700–750°F thermal desorber and >1600°F thermal oxidizer; throughput of 50–150 tons/hr.

<sup>(e)</sup> EPA (2002a): Thermal Desorption; total cost \$1,087,732; 350–450°F thermal desorber and >1400°F thermal oxidizer. Residence time of 15–20 minutes; throughput of 20–22 tons/hr.

<sup>(f)</sup> EPA (2002b): Thermal Desorption; 113,000yd<sup>3</sup> treated; total cost \$10,963,573; 445°F thermal desorber and 1,557°F thermal oxidizer; residence time of 20 minutes; throughput of 43.3 tons/hr.



### *In Situ Electrokinetic and Electrochemical Treatments*

In situ electrokinetic treatments can be used to address sites contaminated with metals and/or PAHs (Page & Page, 2002). Electrokinetic treatments impose a low-intensity direct current electrical field throughout the soil by gridded placement of alternately charged electrodes, typically for the extraction of inorganic contaminants (Reddy & Cameselle, 2009). Electrochemical treatments augment electrokinetic treatments by the injection of electrolytic solutions and/or enhancing agents to increase the efficacy of inorganic extraction and/or the removal or destruction of organic contaminants (Reddy & Cameselle, 2009). The electrical field is carried by ions adsorbed to soil contents and suspended in solution to induce fluid transport throughout fine-grained soils via the electrokinetic mechanisms: (1) electroosmosis, the transport of pore fluid from anode to cathode; (2) electromigration, the transport of ions and their complexes to the oppositely charged electrode; and (3) electrophoresis, the transport of charged colloids to the oppositely charged electrode (Acar & Alshwabkeh, 1993). These systems overcome issues of low permeability by generating an advective plug flow throughout soil capillaries via an electrical gradient as opposed to a hydraulic gradient, allowing for operation in clays, silts, sediments, and other media resistant towards conventional hydraulic distribution systems (Reddy & Cameselle, 2009). Electroosmotic flow may be used to solubilize and transport contaminants, distribute chemical reagents that enhance contaminant desorption or transformation, or to pass contaminants through treatment zones such as permeable reactive barriers. Concurrently, the electromigrative flux desorbs and transports inorganic contaminants to the electrodes where they may be extracted by methods such as electroplating, precipitation, or ion-exchange filters (Acar & Hamed, 1991).

Electrochemical systems are typically used to address low-permeability soils contaminated with metals but are widely amenable to chemical enhancement, allowing for the added in situ desorption and destruction of most organic contaminants. As such, these systems are the only viable in situ treatment alternative for highly heterogeneous soils of low permeability, which contain mixtures of organic and inorganic contaminants.

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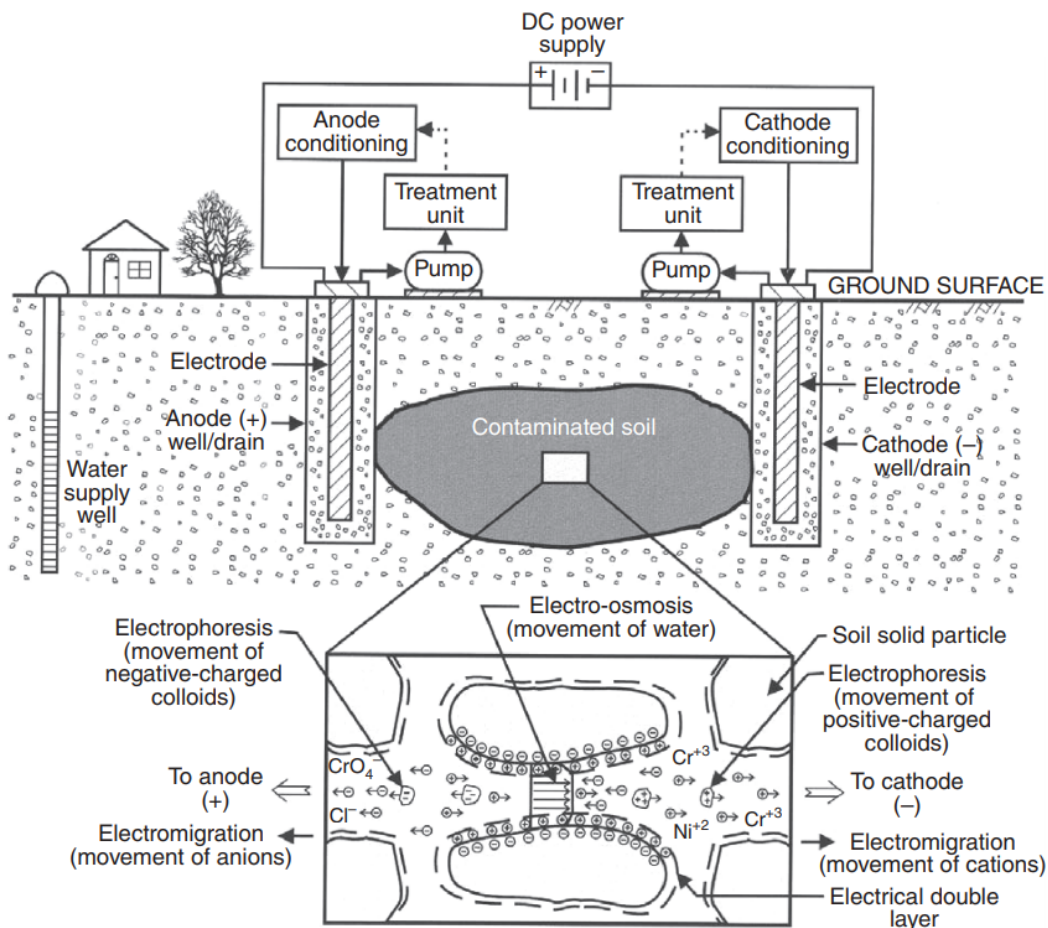
#### **Advantages**

- Adaptable to numerous enhancements for compatibility with most contaminants
- Can address organics and inorganics
- Functional in fine-grained soils
- Functional in saturated and unsaturated soil
- Good hydrological control
- Stimulates contaminant desorption

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#### **Disadvantages**

- High capital and operational costs
- Highly complex
- Hindered by buried metal objects
- System is in developmental stage
- System optimization requires the most comprehensive site characterization



**Figure 2. Schematic. Field-scale in situ electrochemical remediation with a diagram of electrokinetic transport mechanisms between clay particles.**

***As taken directly from Reddy and Cameselle (2009) with permission from John Wiley and Sons, Wiley Books: License Number 4703211191972.***

Based on field-scale technology demonstrations, unenhanced electrokinetic treatments, also known as electrokinetic separation, are estimated to cost approximately \$90 per cubic yard on average and require several weeks to months for operation (FRTR, 2007). Electrochemical remediation typically operates faster at greater expense, costing \$90–300/yd<sup>3</sup> for the extraction of inorganic contaminants, and \$75–200/yd<sup>3</sup> for the treatment of organic contaminants, both costing \$150/yd<sup>3</sup> on average and equating to \$90 per ton of saturated loamy soil (Athmer, 2009). A cost breakdown for electrokinetic/electrochemical treatments is shown as Table 28. Both in situ electrokinetic and electrochemical systems are emerging technologies which were not used to address contaminated soils at any Superfund sites during the 1982 to 2014 period, but they have been used for groundwater at two sites (EPA, 2017). Representative case studies for field-scale in situ electrokinetic separation are summarized in Table 29. Because electrochemical treatment alternatives use the electrokinetic distribution of chemical oxidants and/or additional enhanced flushing agents (Thepsithar & Roberts, 2006), comparison between Table 29 and those in previous sections in this chapter can be made to approximate costs of enhanced electrokinetic alternatives.

**Table 28. Typical Cost Breakdown for Electrokinetic or Electrochemical Remediation**

Component	Range (%)	Average (%)
Electricity	7–25	15
Site preparation	5–25	10
Installation (labor, equipment, materials)	10–60	40
Operation, excluding electricity (labor, expendables)	15–50	25
Waste management, permits, oversight	5–20	10

Athmer (2009)

**Table 29. Representative Case Studies for Field-Scale In Situ Electrokinetic Separation**

Site	Media	Contaminants	Concentration (mg/kg)		Efficiency (%)	Duration	Cost (\$/yd <sup>3</sup> )
			Initial	Final			
Timber Plant: US <sup>(a)</sup>	Clay 250 yd <sup>3</sup>	As	250	30	88	-	-
Temp. Landfill: US <sup>(a)</sup>	Sand/Clay 7,200 yd <sup>3</sup>	Cd	> 180	< 40	> 78	-	-
Military Base: US <sup>(a)</sup>	Clay 2518 yd <sup>3</sup>	Cd, Cr, Cu, Ni, Pb, Zn	660, 7,300, 770, 860, 730, 2,600	47, 755, 98, 80, 108, 289	93, 90, 87, 91, 85, 89	-	-
Paint Factory: US <sup>(a)</sup>	Peat/Clay 300 yd <sup>3</sup>	Cu, Pb	1,220, 3,780	200, 280	84 92	-	-
Metals Plant: US <sup>(a)</sup>	Clay 50 yd <sup>3</sup>	Zn	1,400	600	57	-	-
Military Base: US <sup>(b)</sup>	Soil 84 yd <sup>3</sup>	Cr, Cd	180–1,100 5–20	40–242 1.5–6	78 70	-	-
Paint Factory: Netherlands <sup>(c)</sup>	Clay/Peat 400 yd <sup>3</sup>	Pb Cu	300-> 5,000 500–1,000	90–1,500 100–200	70 80	43 Days	300
Metals Plant: Netherlands <sup>(d)</sup>	Soil 300 yd <sup>3</sup>	Zn	< 7,010 Avg. 2,410	< 5,300 Avg. 1,620	33	8 Weeks	533
Timber Plant: Netherlands <sup>(e)</sup>	Heavy clay 327 yd <sup>3</sup>	As	400–500	> 30	> 92	65 Days	489
Temp. Landfill: Netherlands <sup>(f)</sup>	Soil/sludge 2,500 yd <sup>3</sup>	Cd	2–3,400	< 1–40	99	2 Years	384
Temp. Depot: Netherlands <sup>(g)</sup>	Clay/peat 3,400 yd <sup>3</sup>	Cd, Pb, Cu, Ni, Cr, Zn	660, 730, 770, 860, 7,300, 2,600	-, -, -, -, 47,-	-, -, -, -, > 99, -	580 Days	305

\*Dashes indicate unavailable information.

<sup>(a)</sup> Adapted from Ottosen et al. (2009) and Onnittan et al. (2009).<sup>(b)</sup> Gent et al. (2004): 24,978 kWh applied, 153 kWh/yd<sup>3</sup>; electricity cost only \$2,064, \$12.6/yd<sup>3</sup>.<sup>(c)</sup> Lageman (1993), EPA (1997): 50 kWh/yd<sup>3</sup>, 42 kWh/ton, 65 kWh/yd<sup>3</sup>; total cost \$120,000.<sup>(d)</sup> Lageman (1993), EPA (1997): 145 kWh/ton; projected 24 weeks at 290 kWh/ton; total cost \$160,000.<sup>(e)</sup> Lageman (1993), EPA (1997): Treatment unsuccessful in one-quarter of site due to buried metal debris led to excavation and increased costs; total cost \$160,000.<sup>(f)</sup> Lageman (1993), EPA (1997): 5 kWh/mg Cd; 2 years; previously undetected cadmium concretions increased duration from initially predicted 300 days; total cost \$960,000.<sup>(g)</sup> Lageman (1993), EPA (1997): 5 ft electrode spacing; total cost \$1,040,000.

As discussed previously, treatment duration and costs vary widely due to the large variability in site characteristics (e.g., soil volume, soil type, depth of contamination) and nature, type, and severity of contamination (e.g., inorganic compounds, marginal, or high levels of contaminants). Table 30 presents a summary of the relevant treatment technologies and the corresponding typical treatment durations and costs per cubic yard of treated soil. Also included in the table is the cost of excavating, transporting, and disposing of the contaminated soil at a landfill in Illinois. Although this is not an on-site or in situ option, nor is the soil treated, from a cost perspective the information allows for a meaningful comparison to the feasible technologies. In situ chemical oxidation and electrokinetic remediation present two of the most rapid treatment options. Similarly, these two treatment technologies are in the low to moderate price range. Although the high range of the costs exceed that of landfilling, numerous technologies discussed are relatively competitive with landfilling when the low range of the costs are considered, with the exception of soil washing and in situ thermal treatment. Actual costs will be dictated on a site-specific basis. In addition, several technologies offer the opportunity to reuse the soil on-site as construction fill, which leads to additional cost savings.

**Table 30. Summary of Treatment Technology Durations and Costs**

<b>Technology</b>	<b>Approximate Duration</b>	<b>Average Cost (\$/yd<sup>3</sup>)</b>
In Situ Solidification/Stabilization	Months	\$25–230
In Situ Chemical Reduction	Months	\$115–150
In Situ Chemical Oxidation	Weeks-months	\$24–100
On-Site Soil Washing	Months	\$600–2000
In Situ Thermal Treatment	Months-years	\$350–400
On-Site Thermal Treatment	Months-years	\$55–1000
Electrokinetic Remediation	Weeks-months	\$150–500
<b>Cost of Landfilling</b>		\$65–90

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