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DESIGN CONSIDERATIONS FOR ENHANCED REDUCTIVE DECHLORINATION

Prepared for NAVFAC EXWC under Contract No. N62583-11-D-0515

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ACRONYMS AND ABBREVIATIONS

AFCEC	Air Force Civil Engineer Center
ARTT	Alternative Restoration Technology Team
BMP	Best Management Practice
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CH_4	methane
CLEAN	Comprehensive Long-Term Environmental Action, Navy
CO_2	carbon dioxide
COC	contaminant of concern
CQC	Construction Quality Control
CSM	conceptual site model
CVOCs	chlorinated volatile organic compounds
DB	Design-Build
DBB	Design-Bid-Build
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DoD	United States Department of Defense
DON	United States Department of Navy
DPT	direct push technology
ER	Environmental Restoration
ERD	enhanced reductive dechlorination
ESTCP	Environmental Security Technology Certification Program
FEAD	Facilities Engineering and Acquisition Division
FEC	Facilities Engineering Command
GHG	greenhouse gas
GSR	green and sustainable remediation
ITRC	Interstate Technology and Regulatory Council
MNA	monitored natural attenuation
NAPL	non-aqueous phase liquid
NAVFAC	Naval Facilities Engineering Command
ORP	oxidation-reduction potential
P&ID	Process and instrumentation diagram
PCE	perchloroethylene
PRB	permeable reactive barrier

PV	pore volume
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
QAO	Quality Assurance Officer
QAPP	Quality Assurance Project Plan
RAC	Remedial Action Contract
RAO	Remedial action objective
RCRA	Resource Conservation and Recovery Act
ROI	radius of influence
RPM	Remedial Project Manager
SERDP	Strategic Environmental Research and Development Program
SMART	specific, measureable, attainable, relevant, and time-bound
TCE	trichloroethylene
TTZ	target treatment zone
UFC	Unified Federal Criteria
UFGS	Unified Facilities Guide Specifications
U.S. EPA	United States Environmental Protection Agency
WBDG	Whole Building Design Guide
ZVI	zero valent iron

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1.0 PURPOSE

A recent survey of Naval Facilities Engineering Command (NAVFAC) Remedial Project Managers (RPMs) found that chlorinated solvents in groundwater remain a key issue at impacted sites and that enhanced reductive dechlorination (ERD) is a frequently selected remedy for treatment of these solvents. The results of the survey also suggested that technology transfer tools are needed to help to improve the design and performance of ERD at Navy sites.

The purpose of this document is to provide a framework for design submittals for ERD systems, including a summary of best practices for bioremediation design, tips for appropriate quality assurance and quality control (QA/QC) measures, and a listing of available standards and references. The goal is to assist in the development of improved and consistent design submittals within the U.S. Department of the Navy (DON) Environmental Restoration (ER) Program.

This document was developed by the Alternative Restoration Technology Team (ARTT). It incorporates lessons learned from Navy sites on the design, implementation, and performance of ERD for the remediation of chlorinated solvents in groundwater. The information provided here can be readily incorporated into a design format suitable to the scope of the project.

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2.0 ENHANCED REDUCTIVE DECHLORINATION

Under anaerobic conditions, many chlorinated solvents can be biodegraded via reductive dechlorination. Certain bacteria are known to respire specific chlorinated solvents, and grow in the process (e.g., degradation of trichloroethylene [TCE] by certain bacteria belonging to the genus *Dehalococcoides*). Respiratory dechlorination is referred to as *direct* dechlorination. Some chlorinated solvents can be degraded by anaerobic c*ometabolic* biodegradation reactions, in which the chlorinated solvent is biodegraded fortuitously while bacteria are degrading another compound. During this type of dechlorination, the chlorinated solvent is referred to as the secondary substrate, while the growth substrate is referred to as the primary substrate. Table 2-1 provides a list of chlorinated volatile organic compounds (CVOCs) commonly detected in groundwater and their respective susceptibility to degradation by direct and cometabolic anaerobic dechlorination.

ERD is a type of enhanced in situ bioremediation used to promote anaerobic biological dechlorination of chlorinated solvents in the subsurface, both by direct and cometabolic degradation processes. ERD involves the delivery of amendments (biostimulation) and, in some cases, specialized bacteria (bioaugmentation) into the subsurface to stimulate specific dechlorinating biodegradation reactions. Bioaugmentation may be required if indigenous microorganisms are not able to degrade the contaminants of concern (COCs) and is typically used in combination with biostimulation to provide optimal conditions. ERD amendments for biostimulation include electron donors, pH buffer/adjustments, and, in some cases, nutrients. Electron donors used in ERD applications are fermentable organic compounds and/or commercial product formulations that include or consist of alcohols, sugars, fatty acids, and/or vegetable oils.

Bioaugmentation for ERD applications involves the one-time injection of specialized dechlorinating bacterial cultures to seed the target treatment zone (TTZ) with requisite bacteria that grow in the presence of chlorinated solvents and electron donors. These bacterial cultures may contain *Dehalococcoides*, *Dehalobacter*, *Dehalogemonas* and/or other bacteria that degrade and respire specific chlorinated solvents. The decision of whether to bioaugment or not is site-specific, and often depends on the population density in the TTZ prior to ERD implementation. At sites where the population density of dechlorinating bacteria in groundwater is low ($< 10^3$ cells/L), bioaugmentation is typically required to achieve complete dechlorination to innocuous endproducts (e.g., ethene, ethane, carbon dioxide [CO_2]). At many sites dechlorinating bacteria occur naturally; however, bioaugmentation with exogenous dechlorinating cultures has been shown to accelerate the rate of ERD treatment even at sites where dechlorinating bacteria are indigenous (Stroo et al., 2013).

Table 2-1. Biodegradation Mechanisms for Selected CVOCs

Contaminant	Direct	Cometabolic
Chlorinated Ethenes		
tetrachloroethene	•	•
trichloroethene	•	•
cis-1,2-dichloroethene	•	•
trans-1,2-dichloroethene	•	•
1,1-dichloroethene	•	•
vinyl chloride	•	•
Chlorinated Ethanes		
1,1,1-trichloroethane	•	•
1,2-dichloroethane	•	•
1,1-dichloroethane	•	•
chloroethane	x	x
Chlorinated Methanes		
carbon tetrachloride	×	•
chloroform	•	•
methylene chloride	•	•
chloromethane	×	×

• Known to occur in natural and/or engineered systems; × Not known to occur; Modified from U.S. Environmental Protection Agency (U.S. EPA), 2000.

Many resources are available for the design and implementation of ERD, including, but not limited to, the following (see References section for more information):

- Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) - Bioaugmentation for Groundwater Remediation (Stroo et al., 2013);
- SERDP & ESTCP - In Situ Remediation of Chlorinated Solvents (Stroo and Ward, 2010);
- ESTCP (2005) - Technology White Paper on Chlorinated Solvent Bioaugmentation;
- U.S. EPA (2013) - Introduction to In Situ Bioremediation of Groundwater;
- U.S. EPA (2006) - Engineering Issue on In Situ and Ex Situ Biodegradation Technologies for Remediation of Contaminated Sites;
- U.S. EPA (2000) - Engineering Approaches to In Situ Biodegradation of Chlorinated Solvents;
- Air Force Civil Engineer Center (AFCEC) (2007) - Protocol for In Situ Bioremediation of Chlorinated Solvents Using Edible Oil;
- AFCEC et al. (2004) - Principles and Practices of Enhanced Anaerobic Bioremediation of Chlorinated Solvents;
- Interstate Technology and Regulatory Council (ITRC) (2008a) - Guidance on Enhanced Attenuation of Chlorinated Organics; and
- ITRC (2002) - A Systematic Approach for In Situ Bioremediation in Groundwater.

3.0 REMEDIAL DESIGN SUBMITTALS

Remedial design submittals are provided to RPMs for review and approval prior to remedy implementation. At some installations, the Facilities Engineering and Acquisition Division (FEAD) may also participate in reviewing design submittals.

Remedial design submittals should comprise the following components, at a minimum:

- **Basis of Design:** Conceptual site model (CSM), rationale for the design, calculations to support the design, and a description of the design (see Sections 4.0 and 5.0).
- **Drawings:** Detailed drawings to describe (prescriptive or performance-based) how to construct, operate, and maintain the system (see Section 6.0).
- **Specifications:** Details of performance-based specifications on how to construct, operate, and maintain the system (see Section 7.0).
- **QA/QC Plans:** Project-specific Construction Quality Control (CQC) Plan with QA/QC provisions for monitoring construction (if required by the contract and as necessary to convey design-specific requirements [see Section 5.5.2]).
- **Monitoring Plans:** Details of process and performance monitoring plans, including locations, monitoring parameters, sampling frequency, remedial action objectives (RAOs) and goals (see Section 5.5).
- **Schedule and Milestones:** Remedial designs are typically performed in several phases. The first phase is the conceptual design (10 to 15% design). The conceptual design provides basic information about the project and includes the conceptual site plan and other preliminary drawings. The second set of design submittals (35 to 50% design) should convey the complete design, but in a preliminary manner. All necessary drawings should be included, but are not finalized and might not include all of the details necessary for implementation of the design. However, although all of the details may not be included, many times for environmental projects, the level of detail included in the 35 to 50% design packages is sufficient for project execution. The 90 to 100% design consists of a very detailed design package, which could be required for design-bid projects (as opposed to design-build projects) or very complex projects and would include all of the necessary details required for execution. The final 100% design package consists of submittal and acceptance of all reviewed and previously approved drawings and design elements.
- **Cost Estimate:** In some cases, a construction cost estimate is included with +/- 10% accuracy for bidding purposes.

Because of the simple nature of in situ remediation systems, remedial design submittals can be streamlined. However, regardless of the streamlining effort, the submittals should contain the design components discussed above. Streamlining efforts could be performed in the following ways:

- **Work Plan Approach:** This approach involves combining all components of the design submittals into a work plan format and submitting the work plan for NAVFAC and base approval in a three-phase review process: draft review, draft-final review, and final submittal. In some cases, if required, the draft review, draft-final review, and final submittal could correspond to the 15% to 35% design, which is equivalent to the conceptual design, 50% to 60% design, which is equivalent to the preliminary design submittal, and the 90 to 100%, which is equivalent to the final design. For some contracts, it may be appropriate for a single contractor to develop the design from the concept through a more detailed level, which is a common element of a performance-based design contract. However, in other cases, it may be appropriate for one contractor to develop the conceptual design and a second contractor to finalize the design and implement it. For example, many times, the Comprehensive Long-Term Environmental Action, Navy (CLEAN) contractor prepares the conceptual design that is used to bid the project and the Remedial Action Contract (RAC) contractor refines and finalizes the design after project award.
- **Design-Build Approach:** This involves a design-build approach, which is less prescriptive, but contains appropriate performance-based language and combines design drawings and specifications. A design-build approach is appropriate when site uncertainties necessitate that the design evolve during the course of the contract even after construction has commenced. These uncertainties can include gaps in site characterization data or using a treatment train approach (for which accurate design of the secondary or tertiary remedy is not possible until the primary remedy has been implemented). The objective of the design-build approach is to avoid prescriptive requirements that limit the range of options available to the remediation contractor. The frequency and level of internal design reviews are at the discretion of the RPM within the limits set forth in the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), and other state orders or permits. If a design-build project is competitively bid, the award can be made based on a "Best Value" evaluation as opposed to "Lowest Price" to account for the fact that the proposed approaches could vary substantially due to site uncertainties. Evaluation criteria should include both technical understanding of the work and cost to perform the work. Technical understanding of the work may be demonstrated through various metrics including, but not necessarily limited to, experience with the proposed remedy, experience at the site or sites having similar conditions, and use of innovative technical approaches. As a result, it is necessary that proposal reviewers also have a detailed understanding of the site and the technologies that are proposed.

4.0 KEY CSM ELEMENTS

The CSM summarizes site conditions, the distribution, concentration, fate and transport of COCs, potential receptors and exposure pathways, and the land use data available for a given site. The CSM is a living model. It is developed based on data from the first investigation performed at the site and is continually updated throughout the lifecycle of the project to reflect new information as it becomes available. It must be reviewed, updated, and incorporated into each stage of the remedial design as the design progresses. In some cases, remedies fail because of an incomplete or improper CSM and/or failure to integrate the information presented in the CSM into the design of the remedy. The section below provides an overview of key CSM elements needed to adequately describe the site and common pitfalls in site characterization that can lead to suboptimal designs of ERD treatment systems.

4.1 Key CSM Elements and Potential Impacts to ERD Designs

It is important to have a thorough understanding of the CSM when designing and applying ERD treatment technologies. Because ERD involves the addition of various amendments to stimulate the microbially-mediated transformation of COCs, it is important to include information in the CSM about the aquifer microbiology and geochemistry (redox chemistry) that will affect the desired microbial reactions and potential for secondary water quality impacts. To ensure adequate distribution and contact of ERD amendments with the COCs, the CSM should include a detailed understanding of microbiological, geochemical and lithological characteristics of the site, flow and mass transport, transformation, and retardation characteristics of contaminants and the proposed ERD amendments. Failure to address these components in the design can have a negative effect on technology performance. Specifically, a CSM should take into consideration the site-specific factors listed in Table 4-1.

Several of these elements can have significant impact on ERD design and the introduction and distribution of ERD amendments in the subsurface. Some of the more common impacts are listed in Table 4-2.

Table 4-1. Key CSM Elements for ERD Applications

CSM Element	Description
Nature and extent of contamination	Determine horizontal and vertical distribution of COCs including presence of non-aqueous phase liquids (NAPLs) to establish TTZs for introducing ERD amendments. Chlorinated solvents may be present as dense non-aqueous phase liquids (DNAPLs) in the subsurface and either the known or suspected presence of DNAPL will impact the overall design approach.
Human and ecological health risks	Consider risks presented by COCs, as well as risks associated with the potential effects of introducing ERD amendments (e.g., methanogenesis is common during ERD) that can influence amendment concentrations and injection frequency.
Fate and transport	Determine how the fate and transport of COCs affect the delivery of ERD amendments to the subsurface (i.e., injection/recirculation locations, concentrations of amendments, flow rates, and the method of introduction into the aquifer).
Site-specific infrastructure and characteristics	Consider urban vs. rural environment, presence of buildings and utilities, proximity to nearby receptors, current and future land use, etc., which will influence overall strategy and the approach for delivering ERD amendments into the aquifer.

Table 4-1. Key CSM Elements for ERD Applications (continued)

CSM Element	Description
Hydrogeology	Understand lithology (lithologic units, heterogeneities, grain size, permeability, presence of bedrock, etc.), hydrogeology (gradients, confined or unconfined conditions, saturated thickness, conductivities, flux, groundwater flow direction, Darcy velocity, anisotropy, etc.), and mineralogy (e.g., could contribute to metal mobilization if more reducing conditions of ERD solubilize metals), which will influence the approach for delivering ERD amendments into the aquifer.
Hydrogeochemistry	Document distribution coefficients (K_d), pH, buffering, temperature, oxidation-reduction potential (ORP), terminal electron acceptor concentrations, and potential inhibitors for the desired microbiological reaction.
Microbiology	For ERD, determine microbial characteristics that are required for degrading the specific COCs (e.g., *Dehalococcoides* for chlorinated ethenes, specific genes for dechlorinating vinyl chloride [e.g., *vcrA*], and *Dehalobacter* for chlorinated methanes and ethanes), which will determine if bioaugmentation will be beneficial for the design.

Table 4-2. Impacts of Several Site-Specific Factors on ERD Design

CSM Element	Design Impact
Hydraulic conductivity and aquifer anisotropy	▪ ERD in porous media relies on groundwater advection (either natural or forced gradient) to deliver ERD amendments to TTZs. ▪ Groundwater and amendments follow the path of least resistance. Low conductivity regions may not be adequately treated or may require longer treatment timeframes. Additional treatment or specialized methods for introducing amendments into the aquifer may be required in those regions.
Lithology	▪ In low-permeability zones (silty or clayey deposits), fracturing or other enhancements (e.g., electrokinetics) may be required to facilitate amendment distribution. ▪ Heterogeneities will influence flow pathways and contact of ERD amendments with COCs.
Presence of NAPL or sorbed contaminants	▪ Affects the demand for and type of ERD amendments (e.g., a higher sustained dose of electron donors, and possibly pH buffer may be required in the presence of halogenated DNAPL). ▪ Contributes to substantial rebound if the supply of bioremediation amendments is only sufficient to treat the dissolved phase. ▪ Contributes to back-diffusion from the matrix, especially in low permeability areas. ▪ Mobility of the DNAPL will affect the type and extent of treatment.
COC mass estimate	▪ The performance and duration of an ERD remedy depends on the distribution and mass of COCs. ▪ Based on observation of NAPL, sorbed and dissolved phase COCs, an estimate of the total COC mass at a site should be developed for each compartment/phase (NAPL, sorbed, dissolved). ▪ An understanding of where the center of COC mass occurs at a site can be used to ensure that an ERD remedy is focused on the greatest mass. ▪ Development of a baseline COC mass estimate can be used as a reference to measure remedy performance and for comparison of mass estimates post-remedy implementation. ▪ An improved understanding of COC mass can be invaluable for setting realistic expectations for remediation timeframe and RAOs.
Horizontal extent of contamination	▪ Affects degree and configuration of treatment, which could include only the source area, a portion or all of the dissolved phase plume, or a combination of these areas.

Table 4-2. Impacts of Several Site-Specific Factors on ERD Design (continued)

CSM Element	Design Impact
Vertical extent of contamination	▪ The vertical extent of COC impacts needs to be defined to ensure that the TTZ for ERD addresses the majority of contaminant mass. ▪ Depth of contaminants will influence cost and design (i.e., direct push technology [DPT], recirculation wells, aboveground recirculation, etc.).
Subsurface utilities and conduits	▪ Potential pathway for groundwater and amendments potentially causing amendments to flow into undesirable locations (e.g., streams, sewers) rather than contacting the COCs. ▪ Potential pathway for volatile gases generated from biodegradation byproducts, which could result in vapor intrusion.
Presence of aboveground structures	▪ The presence of structures above a TTZ may necessitate consideration of horizontal or angled wells/DPT points to deliver ERD amendments underneath the structure. ▪ In rare instances, vapor recovery may be required to mitigate potential risks associated with gases generated as end products of ERD (methane [CH_4] and CO_2). In poorly designed ERD systems, excessive amounts of electron donor may be injected into shallow TTZs, and consequent accumulation of CH_4 may cause a potential explosion hazard at aboveground structures.
Competing biological and chemical reactions	▪ ERD is most effective under sulfate-reducing and methanogenic conditions where organic electron donors are fermented to hydrogen and acetate, which are used by the halorespiring microbes of the genus *Dehalococcoides*. However, sulfate reducers and methanogens also compete for the electron donor to produce hydrogen sulfide and methane (Duhamel and Edwards, 2007); these competing reactions should be considered in the design with respect to electron donor demand and potentially hazardous byproducts. (However, hydrogen sulfide does subsequently react with soluble metals such as iron forming iron sulfide precipitates and therefore removing it from solution). ▪ Methane generation is a hallmark of most ERD systems and is to be expected. Methanogenic bacteria are believed to play an important role in fermentation of electron donors, providing co-factors that support *Dehalococcoides* and other dechlorinating bacteria (Duhamel and Edwards, 2007). ▪ One objective in developing a well-designed ERD system is to avoid a high degree of methanogenesis because methanogens: 1) compete with dechlorinating bacteria and 2) methane generation in shallow TTZs may create an exceedance to the lower explosion limit for methane.
Potentially inhibiting conditions	▪ Baseline pH conditions outside the optimal ranges for dehalogenating cultures (typically 6 to 8) can inhibit specific ERD reactions; pH neutralization and buffering can be difficult to sustain for extended periods of time, but it is possible if a proper engineering design and monitoring protocols are followed. ▪ Hydrogen generated by electron donor fermentation reactions that are part of ERD can overwhelm the buffering capacity of the aquifer and may require additional amendments to control pH during implementation. ▪ In addition to affecting the biological activity of microorganisms, decreases in pH can solubilize toxic metals and create secondary environmental impacts. ▪ The optimal temperature for complete ERD is between 10 and 30 ^{o}C; below 10 ^{o}C, the degradation rate is slower (U.S. EPA, 2013). ▪ Under certain conditions, performance of ERD for treatment of chloroethenes can be inhibited by high concentrations of hydrogen sulfide, chloroform, 1,1,1-trichloroethane, and/or metals (U.S. EPA, 2000; 2013; Stroo et al., 2013).
Remedial Action Objectives/Timeframe	▪ Affects the type of ERD system that is designed (i.e., active, passive, or semi-passive). ▪ What mass, volume, concentration and type of amendments will be injected. ▪ Whether or not to bioaugment to potentially accelerate degradation of COCs.

Additional guidance on the design of ERD systems for treatment of chlorinated solvent DNAPLs is available in the following documents (see References section for more information):

- ITRC (2011b) - Integrated DNAPL Site Strategy;
- ITRC (2008b) - In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones;
- ITRC (2007) - In Situ Bioremediation of Chlorinated Ethene DNAPL Case Studies;
- NAVFAC (2012b) - Using Bioremediation in Dense Non-Aqueous Phase Liquid Source Zones Fact Sheet;
- NAVFAC (2012d) - Development of a Protocol and a Screening Tool for the Selection of DNAPL Source Area Remediation;
- NAVFAC (2007a) - Lessons Learned on Bioaugmentation of DNAPL Source Zone Areas;
- NAVFAC (2007b) - Biodegradation of DNAPLs through Bioaugmentation of Source Areas, Dover National Test Site, Dover, Delaware; and
- NAVFAC (2004) - Assessing the Feasibility of DNAPL Source Zone Remediation: A Review of Case Studies.

4.2 Remedial Action Objectives and Remedial Goals

The basis of design document should present the RAOs, remedial goals, and treatment goals for the planned ERD remedy. In addition, the basis of design document should present the interrelationship between the RAOs, remedial goals, and treatment goals, as well as the overall strategy/decision-making framework for site closure.

RAOs are site-specific goals that are formed based on the nature, extent, fate and transport of COCs, the impacted media, and potential exposure routes, receptors, and remediation goals identified in the CSM. The RAOs should provide a clear and concise description of what the remedial action should accomplish at a given site. RAOs should express how to protect human health and the environment rather than achieving a specific regulatory standard or requiring a particular remedial technology to be operated until RAOs are achieved. Remedial goals are developed to achieve the RAOs and may be based on regulatory standards and site-specific risk-based concentrations. As part of the process for establishing RAOs and remedial goals, it is recommended that functional objectives consistent with the SMART (specific, measureable, attainable, relevant, and time-bound) attributes presented by ITRC (2011b) be established. Selecting objectives that reflect SMART attributes can make subsequent decisions more valid and ERD approaches more successful. It is often appropriate to develop SMART functional objectives for different locations, phases, and alternative endpoints for an overall site cleanup.

Treatment goals (or performance objectives) are endpoints that must be achieved to ultimately meet remedial goals for the site. These endpoints are interim goals and typically apply to one particular part of the treatment train to identify when to discontinue the use of one technology once it is no longer operating cost-effectively. These endpoints should be realistic, achievable, and flexible enough to respond to situations where it becomes impracticable to meet a particular remedial goal due to site-specific constraints. One of the important treatment goals for ERD applications is to demonstrate that treatment agents (e.g., electron donor, electron acceptor, nutrients, and/or pH-control) have been delivered at sufficient concentrations throughout the TTZ. Another treatment goal is to ensure that presence of electron donor (and other bioremediation additives) and requisite bacteria (e.g., *Dehalococcoides*) are maintained over a period that is relevant for conditions at a given site (e.g., to treat contaminants that dissolve from NAPL, or desorb or back-diffuse from the aquifer matrix).

4.3 Key Issues of Concern for Regulators and other Stakeholders

Project stakeholders can include federal, state, and/or local regulatory agencies, as well as the public, especially those individuals that may be in close proximity to the respective site. Each group of stakeholders will have a number of concerns, which should be addressed early in the design process. The DON encourages regular communications between stakeholders to ensure concurrence on any issues that will impact the design and implementation of the treatment system. Although a wide range of concerns may present themselves during the initial stages of the project, many of which may be very site-specific, there are a number of concerns that are commonly expressed for ERD projects. These include:

- Project cost;
- Time required to complete the active portion of the remedy and time to achieve remedial goals and RAOs;
- Redistributing contamination, potentially into previously uncontaminated portions of the aquifer;
- Injection of microorganisms;
- Potential for reinjecting contaminated groundwater; and
- Creating byproducts or changes to geochemistry that can adversely impact the aquifer (e.g., methane and hydrogen sulfide generation; decrease in pH; precipitation of metals, which can clog the aquifer; mobilization of dissolved metals, which can create a long-term secondary water quality impact [e.g., mobilization of dissolved arsenic or manganese]).

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5.0 KEY DESIGN ELEMENTS

This section presents key elements and best practices for ERD design, including amendment selection, development of an amendment delivery plan, and planning for monitoring and QA/QC measures. This information will assist the practitioner and RPM in understanding key considerations when developing and/or reviewing the ERD design.

5.1 Consideration of Site Lithology/Geology and its Effect on ERD Approach

Early in the process of considering the feasibility of ERD, project stakeholders must consider the lithology/geology of the TTZ and feasible methods for delivering ERD amendments to the TTZ. The site geology affects the methods for injecting donors, as well as the types of donors that can be used. Soluble electron donors are a viable and proven option for ERD systems treating dissolved phase chlorinated solvents in porous media (e.g., sandy aquifers and moderately-to-highly fractured bedrock). The permeability of porous media generally makes it well suited to active ERD systems that rely upon forced gradients (e.g., pulsed or continuous pumping, recirculation, etc.). Flushing porous media with groundwater containing soluble electron donors also has been shown to enhance dissolution of chlorinated solvent DNAPL in source areas by promoting ERD reactions at the DNAPL-water interface (ITRC, 2007; 2008b). Flushing (recirculation or other design) also can be effective at distributing soluble electron donors and bioaugmentation cultures to the TTZ.

If the TTZ subject to ERD occurs within an aquitard, or other low-permeability deposit (silts, clays), low-solubility ("slow-release") electron donors are often more cost-effective than soluble electron donors because: 1) flushing (or other forced gradient delivery) often is not geologically feasible, and 2) low-solubility donors can be injected once every few years, providing a slow-release delivery that lasts significantly longer than would be possible with a soluble electron donor. Low-solubility electron donors (e.g., emulsified soybean oil) are often appropriate for permeable reactive barriers (PRBs) to cut off plume migration, and these donors can form a stationary bioactive zone to intercept migrating contamination.

As described in Section 5.3, a variety of soluble and low-solubility electron donors can be used for ERD applications. Site geology (lithology) and ERD treatment objectives both affect electron donor selection. These issues need to be considered prior to developing bench- and pilot-test designs.

5.2 Bench-Scale and Pilot Tests

At most sites, it is necessary to perform bench-scale and/or pilot tests to address uncertainties that could have a significant impact on the selection, design, cost, and application of the remedy. Design by process scale-up (i.e., bench-, pilot, and full-scale design) provides the best means to cost-effectively optimize treatment performance. Objectives of bench and pilot tests typically include evaluating the microbiology and reaction chemistry for site-specific conditions and determining factors that would impact the completeness and rate of biodegradation. Bench-scale tests are typically performed using samples of site groundwater and aquifer material (soil or bedrock, depending on the geology of the TTZ). Bench-scale tests can evaluate a large number of conditions and parameters and are less expensive than field pilot tests; however, results are not easily scalable for full-scale application so pilot testing is recommended for complex sites. The design parameters determined from these tests can include amendment selection, treatment rates by ERD, whether bioaugmentation is required or is beneficial and what microbial culture or community is optimal, estimate of amendment dose requirements, what COC concentrations and combinations are treatable, whether pH control is needed, the effect of site-specific properties such as natural electron donor demand, effect of DNAPL pools or residuals if present, effect of metals or other inhibitors if present, and the potential for byproduct formation. Pilot tests are typically small-scale field tests that include a set of injection wells, a pilot-scale treatment trailer/shed for amendments, or DPT injection points and monitoring wells. The results of pilot tests are more representative of what can be expected during the full-scale application since they are performed at the site under in situ conditions. The information gathered during the pilot test includes determination of optimum injection flow rates and pressure, radius of influence (ROI), geochemical impacts to the aquifer, and the potential for rebound. Depending on the type of design, pilot test system components (wells, amendment trailers, etc.) can be used over the longer term by incorporating them into the full-scale ERD treatment system.

5.3 ERD Amendment Selection

The selection and delivery of amendments are critical components of any ERD design. The type of amendments used in a design will depend on what the existing subsurface conditions are, what the desired transformation is, and the results of any bench-scale testing that is performed. For ERD, the selection of electron donor is related to the method of amendment delivery (e.g., soluble electron donor for recirculation versus long-lasting or solid for passive). Design considerations for common electron donors are provided in Table 5-1. Other amendments that could be included in the design are bioaugmentation cultures, buffering agents for pH control, and other nutrients to stimulate optimal degradation of COCs. Additional guidance on bioremediation amendments can be found in the references listed in Sections 2.0 and 4.1.

Table 5-1. Design Considerations for the Application of Electron Donors for ERD

Substrate Type	Electron Donor Substrates	Typical Delivery Techniques	Form of Application	Frequency of Injection
Soluble Substrates	Lactate, Butyrate	DPT injection, injection wells, or recirculation systems	Acids or salts diluted in water	Continuous to monthly
	Methanol, Ethanol	DPT injection, injection wells, or recirculation systems	Diluted in water	Continuous to monthly
	Sodium Benzoate	DPT injection, injection wells, or recirculation systems	Dissolved in water	Continuous to monthly
	Molasses, High-fructose corn syrup	Injection wells	Dissolved in water	Continuous to monthly
	Whey (soluble)	DPT injection or injection wells	Dissolved in water or slurry	Monthly to annually

Table 5-1. Design Considerations for the Application of Electron Donors for ERD (continued)

Substrate Type	Electron Donor Substrates	Typical Delivery Techniques	Form of Application	Frequency of Injection
Slow-Release Substrates	Polylactate ester	DPT injection	Neat injection	Annually to biennially; some proprietary formulations 3-4 years according to vendor claims. Depends on contaminant mass and distribution (NAPL, sorbed).
	Vegetable oil	DPT injection or injection wells	Neat oil injection with water push or high oil concentration (>20%) emulsions in water	One-time application (typical). Depends on contaminant mass and distribution (NAPL, sorbed).
	Vegetable oil emulsions	DPT injection or injection wells	Low oil concentration (<10%) microemulsions suspended in water	Every 2 to 3 years (typical)

Adapted from U.S. EPA, 2013; ITRC, 2008a; and AFCEC et al., 2004.

5.4 ERD Amendment Delivery

An amendment delivery plan is a critical component of every ERD design and must be included as part of the design document. The plan should include appropriate treatment milestones, contingencies for conceivable deviations based on uncertainties and unknowns present in the CSM, health and safety issues, and any regulatory issues. The strategy chosen for amendment delivery will depend on the RAOs and the timeframe for achieving remedial goals and is often different for source areas versus downgradient plumes. Since the ability to distribute treatment reagents is site-specific, it is preferred that the plan is based upon the results of a pilot test, modeling, and/or previous results at the site. At a minimum, the plan must include:

- Amendment dosing and longevity considerations, including the required amendment concentrations, volume of fluids to be introduced into the aquifer, and the anticipated number of injection events or frequency of injection.
- Treatment well/point spacing and layout, ensuring that the wells are placed appropriately to achieve adequate treatment within the TTZ. For in situ groundwater remediation, the TTZ may include the source zone, the dissolved phase plume, hot spot areas with elevated contaminant concentrations within the plume, and/or a downgradient boundary of the plume. The basis for determining well/point spacing and the ROI must be included (e.g., pilot test, modeling, or previous results at the site). Drawings depicting the extent of the plume, the extent of the TTZ, and the locations of injection and extraction wells/points also must be included. If the ERD treatment employs media placed in excavated pits or trenches or applications where soil mixing is performed rather than injection points or wells, then the layout of those areas should be depicted on drawings with the extent of the plume.

- Specifications for injection wells, pumps, tanks, and ancillary equipment that will be used during the injection/reagent delivery process. If permanent wells are used to inject ERD amendments, the plan should specify well construction requirements (diameters, materials; stainless steel wire-wrapped screens are recommended for forced gradient or active recirculation systems, as they are durable and well suited to rehabilitation in the event of fouling).
- A description and operational procedures for the method that will be used to introduce amendments into the aquifer, including target injection volumes and rates. If DPT is used to inject ERD amendments, the plan should specify approximate injection pressures and depth intervals, and general methodology (top down versus bottom up).
- A description of the monitoring program (sampling methods, parameters, and frequency) to evaluate the effectiveness of the ERD strategy.
- Appropriate endpoints and milestones for effective amendment delivery and distribution.

These items are discussed in further detail below.

5.4.1 Amendment Delivery Method

The ERD design must include a detailed description of the method that will be used to introduce and distribute amendments into the aquifer. There are four principal types of amendment delivery methods:

- **DPT Injection:** The amendments are injected directly into the subsurface in a specified volume of water from an external source, displacing groundwater corresponding to the volume of reagent injected. This is an example of a passive approach. DPT injection typically involves delivery of slow-release, low-solubility electron donors such as emulsified vegetable oil that are designed with a reactive longevity of a few years. This injection method is fast and relatively low-cost; however, it has depth limitations and cannot achieve the same treatment rates that are possible with active, forced-gradient (e.g., recirculatory) ERD systems.
- **Recirculation:** Groundwater is extracted from one or more extraction wells, amended with the reagents and then reinjected into a different series of injection wells. Alternatively, groundwater circulation wells may be used, which allows recirculation of groundwater without pumping the groundwater to the surface. This is sometimes referred to as an active approach and is most commonly used in ERD systems that are used to treat DNAPL source areas. The forced gradient flushing that is inherent in recirculatory systems facilitates dissolution of DNAPL, as well as distribution of amendments. For this reason, recirculation is most commonly used for ERD applications in chlorinated solvent source areas where high COC concentrations and/or DNAPLs have been detected. If horizontal wells are used (e.g., in the case of ERD systems underneath buildings or other structures), recirculation can also be a design option (e.g., injection in an overlying horizontal well, extraction in an underlying horizontal well, operated on a pulsed or continuous recirculation schedule). Recirculation in some cases is not practicable for ERD applications for treatment of large plumes; in those cases, a PRB can be more cost effective.

- **PRB:** A PRB is an in situ permeable treatment zone that is designed to intercept and remediate a contaminated groundwater plume. It is a hydraulically passive approach and is ideally designed to be more permeable than the surrounding aquifer media so that groundwater can easily flow through it. Several installation methods can be used including trenching and excavation, DPT injection, or short-term recirculation. Substrates used for PRBs are often solid (e.g., mulch and compost) or slow-release compounds (e.g., emulsified vegetable oil). The PRB must be designed with sufficient thickness to achieve a hydraulic residence time within the barrier that achieves ERD treatment goals. In order for a PRB to be effective, a component of advective groundwater flow is required so that the groundwater plume fluxes through the PRB. PRBs often are not appropriate for hydrogeologic settings where groundwater flow is negligible due to low hydraulic gradients or low hydraulic conductivities.
- **Pull-Push:** A set volume of groundwater is extracted, amended aboveground, and then reinjected into the subsurface through the same well and well screen from which it was extracted. This is a batch process and is typically used during pilot testing for one or more wells located in different areas of the site, when a small, localized area requires treatment, or when a source of water and/or hydraulic control is needed.

In aquitards, glacial clay till, or other low-permeability zones impacted by chlorinated solvents, implementation of ERD via DPT may be unsuccessful or have unacceptably long performance timeframes due to poor contact between injected amendments and COCs diffused into the geologic matrix. In unconsolidated low-permeability geologic deposits, enhanced fracturing techniques such as hydraulic and pneumatic fracturing can be used to improve delivery of ERD treatment agents to the TTZ. Hydraulic fracturing involves injection of a mixture of water, guar, and sand, and can be used to emplace sand-filled fractures in low-permeability deposits, which subsequently can be flooded with electron donors and dechlorinating bacteria for treatment of chlorinated solvents that diffuse out of the matrix into the fracture (Scheutz et al., 2010). Because of improved contact with the TTZ, hydraulic fracturing implemented via DPT often will achieve better performance than that implemented through a permanent polyvinyl chloride (PVC) well. Hydraulic fracturing also can be used to emplace reactive solids such as zero valent iron (ZVI) powder, which can be used in combination with ERD amendments. Pneumatic fracturing can be used in much the same way as hydraulic fracturing, except that it propagates fractures via high pressure gas injection (either N_2 or air). Pneumatic fracturing can be used to emplace sand-filled fractures that subsequently are used to receive ERD amendments, or emplace a mixture of ZVI powder and sand. In order to maintain pressure during fracturing, inflatable packers are often used to isolate the target injection interval. Pneumatic fracturing has been used with success to improve delivery of treatment agents to fractured bedrock, as well as aquitards and clay till.

Table 5-2 lists some considerations associated with each type of amendment delivery strategy. Additional guidance is available in NAVFAC's Best Practices for Injection and Distribution of Amendments (2013), SERDP/ESTCP's Delivery and Mixing in the Subsurface: Processes and Design Principles for In Situ Remediation (Kitanidis and McCarty, 2012), and ITRC's PRB Technology Update (2011a).

Table 5-2. Amendment Delivery Strategy Considerations

Consideration	DPT Injection	Enhanced Fracturing	Recirculation	PRB	Pull Push [(a)]
Ability to hydraulically control fluids	High degree of control of injection fluids, but ROI is smaller than recirculation	Applied in low-permeability formations, offers high degree of control of injection fluids	Maintains better hydraulic control of fluids than DPT injection and pull-push	Once installed, maintains better hydraulic control of fluids than DPT, but may not provide as much as recirculation	Maintains better hydraulic control of fluids than DPT, but may not provide as much as recirculation
Need for source of water	Requires that a source of water is available for mixing amendments; could be extracted groundwater	Requires that a source water is available for mixing amendments; could be extracted groundwater	Extracted groundwater typically is dosed with amendments and reinjected (without above-ground removal of COCs)	May require a source of water depending on what substrate and installation method are used	Extracted groundwater can be dosed with amendments and reinjected
Ease and speed of application	Relatively quick to apply	More complex than conventional DPT injection, but faster implementation than recirculation	More equipment intensive, typically requires more field time for application	More invasive construction if installed by trenching or excavation, but can be similar to DPT and recirculation if those methods used	Quick to apply in a single location. Can be time consuming to mobilize and demobilize to multiple locations
Limitations due to formation permeability	Difficult to apply in tight formation such as clays and silts. High injection pressures can be problematic and daylighting of fluids can occur.	Often is the default option for applying ERD in low-permeability formations due to optimize delivery of amendments	Effective when hydraulic conductivity is greater than 10^{-4} cm/s; should be avoided at lower permeability	Permeability within the PRB can decrease over time and reduce or prevent the desired preferential flow of groundwater through the PRB for treatment	Difficult to apply in tight formations such as clays and silts. High injection pressures can be problematic and daylighting of fluids can occur
Need for above ground treatment	Relatively little aboveground equipment is required	Hydraulic fracturing requires hoppers for mixing sand and guar; tanks and additional mixing equipment are required. Pneumatic fracturing may require large nitrogen gas tanks	Aboveground tanks and mixing equipment are required	Aboveground tanks and mixing equipment may be required during construction	Aboveground tanks and mixing equipment are required

Table 5-2. Amendment Delivery Strategy Considerations (continued)

Consideration	DPT Injection	Enhanced Fracturing	Recirculation	PRB	Pull Push [(a)]
Ability to achieve mixing of amendments and contact with COCs	Difficult to ensure adequate contact of amendments with contaminated groundwater	In low-permeability deposits, may offer best ability to achieve mixing of amendments and contact with COCs, with possible exception of electrokinetics	Aboveground mixing of amendments and contaminated groundwater is easily achieved.	Contact of amendments and contaminated groundwater depends on groundwater flow through PRB	Aboveground mixing of amendments and contaminated groundwater is easily achieved

(a) Typically used for pilot tests, when a small-localized area requires treatment, or when a source of water and/or hydraulic control is needed.

5.4.2 Amendment Dosing Amount and Longevity

The dosing of amendments must consider the volume, concentration, and frequency of introductions into the aquifer. Insufficient loading rates increase the probability that the amendments will not be adequately distributed and reduce the likelihood of achieving RAOs. Conversely, excess amendments can create undesirable changes in the aquifer such as plugging the formation with insoluble byproducts, uncontrolled fermentation reactions that reduce the aquifer pH to a level that is not optimal for ERD, exceedances of secondary groundwater quality criteria, potentially mobilizing metals, and unnecessarily increasing the cost and environmental footprint of the remedy.

The first step in determining appropriate amendment dosing is to calculate the target treatment volume, which is based on the area of the TTZ, the saturated zone thickness, and the porosity of the aquifer material. The design must then consider many site- and application-specific factors such as contaminant mass and phase distribution (dissolved/sorbed/DNAPL); aquifer properties including total organic carbon, hydraulic conductivity, anisotropy; chemical and physical properties of the amendments and aquifer material including viscosity, density, solubility, sorption coefficients; natural demand for the amendments; degradation kinetics; and the practitioner's experience applying ERD at other sites. In general, it is recommended that bench-scale tests be performed to test proposed dosages, evaluate degradation kinetics and byproducts, and determine any other amendment- or bioaugmentation-specific parameters that may be required. Results of these tests are used to determine the optimal amendment concentrations and the volume to be injected expressed as percentage of the pore volume (PV) in the TTZ that will be treated. This can range from a fraction of a PV to greater than 100%, depending on the amendment and the amendment delivery strategy (Table 5-3).

Table 5-3. General Guidance for Determining Amendment Dosing

Guidance and Considerations for Amendment Dosing and Longevity
▪ Perform bench-scale tests using site groundwater and aquifer material ▪ Consider potential impacts of overdosing (health and safety concerns [e.g., methane generation], fouling, groundwater chemistry changes [e.g., metals mobilization, low pH], formation of adverse byproducts or degradation intermediates [e.g., VC], impacts to distribution, etc.) ▪ Determine the number of PV that will be injected or recirculated for ERD amendments. ▪ Evaluate tradeoffs between concentration of amendments, injection flow rate, and number and frequency of injections. For example: o A low concentration and possible continuous flow rate may be appropriate for soluble compounds, especially if the groundwater velocity is high. o Multiple injection events may allow time between events for amendments to passively diffuse into the aquifer matrix and also allow back-diffusion from the aquifer matrix to occur. ▪ Consider compatibility of equipment, materials, subsurface infrastructure, and site activities with the types of amendments and concentrations that will be used. ▪ Consider how interactions between amendments and aquifer material may impact distribution when multiple amendments are used simultaneously or in sequence. For example: o Electron donor should be added and the aquifer should be anoxic and with near neutral pH (6.5 - 8) prior to bioaugmenting with *Dehalococcoides*. o Minimize storage time for amendments. Consider conditions in which they are stored (i.e., exposure to heat, sunlight, moisture, etc.).

5.4.3 Treatment Well/Point Spacing

The ERD design must specify the layout and spacing of the injection wells, points, or PRB. If recirculation is performed, the locations of the extraction wells also must be included. The basis for the assumed ROI must be provided in the design. The ROI may be estimated using a number of methods; however, the best approach is to perform a pilot test and/or injection test in a localized area to ensure that a suitable ROI can be obtained. Site-specific considerations that impact the ROI and should be considered during the design include:

- Bioremediation reaction kinetics;
- Amendment concentration;
- Soil retardation factors;
- Injection flow rate;
- PV of the TTZ; and
- Direct injection versus recirculation approaches (see Section 5.4.1).

A number of available design tools and models may be used to aid in the design process. Capture modeling using industry standard flow and transport models (e.g., MODFLOW and MT3DMS) may be performed to provide a basis for determining an extraction and injection well spacing that will be adequate for distribution of the amendments. The practitioner also may want to consider using a reactive transport model, which accounts for aquifer changes as the amendment reacts with the COCs and aquifer materials, such as RT3D. Spreadsheet-based analytical models such as REMChlor are also useful for simulating the transient effects of groundwater source and plume remediation in one dimension. The output from these models can help to determine expected flow and distribution to determine an appropriate well or injection point configuration. If modeling tools are utilized, a sensitivity analysis should also be performed, and the results should be included in the design.

As part of the process for designing the layout of injection points, the locations of subsurface utilities must be considered so that injection points/wells are placed at a safe distance from subsurface water, sewer, electrical, and telecommunications lines. The presence of subsurface utilities can pose a risk to worker safety for any invasive subsurface investigation or remedy implementation. Accordingly, utilities should be cleared during the design process, prior to performing any drilling activities, by reviewing any existing subsurface utility maps, completing a geophysical survey, and air knifing or soft-digging to a depth of 5 feet for each boring location. A second reason to avoid utilities is that if injected ERD amendments intercept the annulus of a subsurface utility during injection, they may propagate in an uncontrolled manner along the length of the subsurface utility.

5.4.4 Application Tooling and Techniques

Application of liquid ERD amendments typically is performed either through permanent wells or using DPT points. In some cases, trenches may be used for injection or recirculation. The use of either method is highly project- and site-specific. In some cases, it could be appropriate to use a combination of fixed wells and temporary DPT points. Several advantages and limitations for each are provided in Table 5-4.

Table 5-4. Comparison of DPT Injection Points and Permanent Wells for Reagent Application

Injection Method	Advantages	Limitations
DPT Injection	▪ Lower installation cost than permanent wells ▪ Well-suited for unconsolidated materials ▪ Injection locations can be easily changed or added during application based on real time observations ▪ Easier access inside buildings and sites with aboveground structures or overhead lines	▪ May result in greater cost if multiple injection events are required ▪ Not feasible in consolidated materials or bedrock ▪ Limited ROI in low permeability material ▪ Typically limited to a depth of about 100 feet below ground surface ▪ Smearing of formation material across the injection screen could clog the screen and hinder the introduction of fluids
Permanent Wells	▪ May result in lower overall cost if multiple injection events are required ▪ Greater depths can be achieved ▪ Proper design can: 1) help minimize fouling due to bacterial growth and precipitation of inorganic minerals; 2) specify well-screen materials that are well-suited to rehabilitation (e.g., with strong chemicals or brushing) to eliminate fouling.	▪ Higher installation cost than DPT injection ▪ Additional wells may be required if real time observations dictate contamination in other areas or ROI is limited, etc. ▪ Fouling can be problematic if multiple injections over an extended time are required

At a minimum, the ERD design must include the following information:

- The type of injection (and extraction) methods to be used and the rationale for choosing them;
- Locations of all the injection wells and points and the design basis for selecting them; and
- Design details and drawings depicting screened/injection intervals.

There are a variety of ways to apply each of the injection strategies described in Section 5.4.1, ranging from continuous gravity feed of fluids into wells to high pressure applications using specialized injection equipment. A wide range of proprietary injection tooling and application methods have been developed and may be applied; however, unless absolutely necessary, the design should not reference specific vendor names or proprietary methods and tools. Rather, the design should document specific parameters that the tooling should achieve. Specifications should include parameters such as length of injection tip and injection interval, desired injection flow rate, injection pressure, material compatibility, etc.

5.4.5 Specifications for Pumps, Tanks, and Ancillary Equipment

Specifications for aboveground equipment used to introduce, mix, and monitor the introduction of bioremediation amendments into the aquifer should be included in the ERD design (see Section 7.0). Aboveground equipment associated with ERD systems typically includes pumps, tanks, and in-line mixers. This equipment might be on site for the duration of treatment as with an active recirculation system or only during DPT injection for installation of a passive system. A variety of flow and pressure measuring devices also are used to monitor application of the amendments into the aquifer. It is not the intent of this document to identify specific types of equipment for an ERD application since the optimum equipment is application-specific and, to some extent, is dependent on the experience and preference of the design engineer. However, a number of factors must be considered when selecting equipment and designing the ERD application. Some of the more important factors are:

- Equipment is chemically compatible with the amendments that will be used;
- Pumps are sized properly to handle anticipated flow rates and pressure drops;
- Tanks and mixing systems are sized to ensure adequate residence time and mixing;
- Secondary containment is provided for all liquid handling equipment;
- Health and safety equipment including eyewash stations, safety showers, and fire extinguishers is specified appropriately based on the amendments that will be present on site; and
- Green and sustainable remediation (GSR) practices are incorporated into the design as applicable (see Section 5.7).

5.4.6 Operation Procedures and Specifications

The procedures used to introduce ERD amendments into the aquifer must be included in the design and injection plan. Typical information includes the following:

- Procedures for introducing amendments. Parameters such as design pressures, flow rates, and other key operational parameters;
- Procedures to ascertain and mitigate - potential surfacing of amendments, unintended migration of amendments to underground utilities, and unintended migration of amendments to fractures intended by injection;
- If multiple injection events are required using permanent injection wells (not DPT injection points), procedures for addressing fouling of well screens should be included;
- Procedures to ensure the health and safety of workers and the surrounding community;
- Monitoring requirements, procedures, and required equipment (see Section 5.5); and
- QA/QC procedures (see Section 5.5.2).

5.4.7 Establishing Endpoints and Milestones for Amendment Delivery

In some cases, remedial actions are perceived to fail because of unrealistic expectations and a lack of appropriate endpoints and metrics to gauge remedial progress. Key milestones and endpoints for ERD systems include when to: discontinue active injection/recirculation; replenish passive ERD systems; transition to confirmation monitoring or monitored natural attenuation (MNA), and when to close the site. ERD can be used to take a site to closure when the remedy is being used to address dissolved phase plumes; however, for source area applications, it might not be practicable for ERD alone to reach remediation goals/endpoints within a reasonable timeframe. For ERD applications in source areas, often it can be appropriate to set an ERD treatment goal of 90% treatment (e.g., by mass or groundwater concentration), with MNA treating the remaining 10% down to final cleanup goals. In cases where ERD – MNA treatment trains are used, this approach needs to be incorporated into pre- or post-ROD agreements. Regardless of whether MNA is included as part of an ERD remedy, the remediation endpoints should be specified in the ROD.

Endpoints may be based on achieving a specific response in the aquifer that results from applying ERD or completing a specific portion of the process or plan. A performance-based endpoint might be defined as achieving a specific COC concentration in the aquifer; however, achieving such an endpoint can be problematic if the endpoint is unrealistic for the technology. Endpoints based on completion of part of the implementation through process monitoring would trigger performance monitoring to assess the remedy effectiveness and whether the system should be optimized or the remedy could be transitioned. Examples of completion endpoints might be related to the distribution and concentration of electron donor, bioaugmentation culture, or amendment of specified amounts into the subsurface. It is beneficial to involve all of the project stakeholders during the design process to select and agree upon appropriate endpoints for amendment delivery. Table 5-5 provides several example endpoints that could be applied for an ERD remedy.

Table 5-5. Examples of Endpoints, Milestones, and Metrics for ERD Operations

Category	Endpoint	Example Milestones	Measureable Metrics
Example Endpoints, Milestones, and Metrics Based on Performance	Reduce dissolved concentrations of COCs in groundwater by a reasonable percentage.	Achieve a pre-determined percentage reduction in concentrations in order to achieve RAOs	Changes in concentration measured in monitoring wells throughout TTZ
	Achieve an average *Dehalococcoides* culture density of greater than 10^6 gene copies per liter in the TTZ	Achieve 30, 60, 90 and 100% of target concentration	*Dehalococcoides* concentrations in monitoring wells
	Achieve a 90% reduction in mass within or mass flux from the TTZ	Achieve 30, 60, and 90% reduction in mass within or mass flux from TTZ	COC concentrations, groundwater flow velocity, initial/final mass estimates
Example Endpoints, Milestones, and Metrics Based on Completion of Application	Perform recirculation of groundwater until three PV (100,000 gallons) have been exchanged	Exchange 25, 50 75, and 100% of total	Volumetric flow rate
	Inject 1,200 gallons of emulsified vegetable oil and bioremediation culture into each of 20 DPT points	Complete injections per design into 5, 10, 15, and 20 points	Mass (volume and concentration) of electron donor injected into each point

5.5 Monitoring Plan

A performance monitoring program must be developed as part of the design and injection plan. It provides the framework for evaluating compliance with performance objectives, metrics to evaluate the efficacy of the injections, and necessary data to optimize the strategy for future injection events. Specifically, the performance monitoring program should prescribe the following:

- The measurements that will be performed;
- The metrics by which the measurements will be evaluated;
- Specific criteria that define the endpoint for ERD;
- Applicable milestones (e.g., mass or concentration removal targets, transition from active to passive treatment, transition from ERD remediation to MNA or confirmation monitoring);
- Contingency triggers (i.e., additional injections, revised dosing strategy, alternate technology [treatment trains]) in the event that milestones are not being achieved;
- How the monitoring program should be optimized when milestones are achieved, and how the number of monitoring points, sampling frequency, and/or analytical parameters will be reduced at such milestones.

The performance monitoring plan should include two distinct categories of monitoring: process monitoring and performance monitoring. Process monitoring includes monitoring those parameters that provide information on the state of the remedial action during implementation, whereas performance monitoring provides information on the efficacy of the remedy to achieve remedial goals for ERD. Design guidance for both types of monitoring is provided in the remainder of this section. Additional information can be found in the DON Guidance for Planning and Optimizing Monitoring Strategies (NAVFAC, 2010a).

5.5.1 Process and Performance Monitoring

Process and performance monitoring involves observing and measuring parameters that provide information about the state of the remedial action during implementation. For application of ERD, this consists of confirming that the amendments are introduced and distributed into the aquifer according to the design and that the desired microbial activity and COC degradation is occurring without undesirable side effects. Changes in the physical parameters such as pressures, temperatures, flow rates, and groundwater levels in injection and monitoring wells are measured during application of the amendments. In addition to COC concentrations, chemical changes in the aquifer such as dissolved oxygen (DO), ORP, pH, and conductivity are measured to evaluate the distribution of amendments and the need to perform additional injections. For ERD, the growth of *Dehalococcoides* population density in groundwater samples is often monitored. For installation of passive ERD systems, process monitoring should be comprised of field methods and analyses when possible to allow for fast real-time measurements and results to allow the field team to make changes that will optimize the introduction and distribution of the amendments. Typical process and performance monitoring measurements and their intended purpose are presented in Tables 5-6 and 5-7, respectively. A checklist presented in Table 5-8 provides further considerations and performance monitoring recommendations.

Table 5-6. Common Process Monitoring during ERD Injection

Injection Method(s)	Measurement	Method	Primary Purpose
All	**Groundwater levels**	Water level indicator	▪ Mounding and/or changes in levels during injection helps assess distribution of amendments and may indicate the need to reduce the flow rate or discontinue injection. This can also serve as an early warning for development of preferential pathways/surfacing for ERD amendments ▪ Calibrate models ▪ Evaluate changes to the flow direction and gradient resulting from injection, creating the potential for spreading contamination. Also, stimulated microbial activity can create conditions that cause the formation of insoluble byproducts, which can impact groundwater flow
	Pressures	Gauges or transducers	▪ Confirm injections are proceeding as designed ▪ Pressure increases may indicate well/formation plugging; may also indicate strain on piping/pumps and potential worker safety risk. ▪ A decrease in pressure combined with an increase in flow may indicate that the formation was fractured during injection

Table 5-6. Common Process Monitoring during ERD Injection (continued)

Injection Method(s)	Measurement	Method	Primary Purpose
			▪ Application of high pressure can fracture aquifer material
	Flow rates and volumes	Digital meters, rotameters, etc.	▪ Confirm design loading of amendment is achieved ▪ Decrease in flow rate combined with an increase in pressure may indicate plugging of injection well or formation, or fouling of any filters (bag or spun nylon) for particulate removal from recirculated groundwater, prior to injection. ▪ An increase in flow combined with a decrease in pressure may indicate that the formation was fractured during injection
	Visual observations	Visual	▪ Surfacing of amendments inside and outside the TTZ ▪ Presence of amendments or groundwater in utility corridors
Recirculation / active ERD systems	**Vapors in treatment system/trailer**	Photoionization detector, explosimeter, and other gas detectors	▪ Protect health and safety of site workers; periodic survey for fugitive emissions of methane and/or hydrogen sulfide within an around above-ground treatment trailers/containers
	Dissolved or total iron	Field or laboratory analysis	▪ Monitor abundance of dissolved iron for reaction with hydrogen sulfide and for predicting degree of iron fouling that will need to be managed
DPT and Enhanced Fracturing	**Radius of influence**	Visual, field and laboratory analysis of groundwater samples	▪ In monitoring wells, monitor distribution of ERD amendments at a range of distances (or depths) from injection points to confirm ROI ▪ Collect soil cores (lesser frequency than groundwater samples) to confirm placement of injected ERD amendments
Enhanced Fracturing	**Ground heave**	Tiltmeter or elevation survey	▪ Heave of ground surface can be used to monitor ROI during enhanced fracturing ▪ Too much ground heave / lift may damage pavement or undermine building foundations. Monitoring of heave can be used to avoid or minimize such damage.

Table 5-7. Common Performance Monitoring during ERD

Measurement	Method	Primary Purpose
Visual observations	Visual	▪ Bubbles may be generated and noted in groundwater if substantial gases are produced by increased microbial activity ▪ Presence of amendments or groundwater in utility corridors
Groundwater quality parameters (temperature, pH, ORP, DO, conductivity)	Field analysis - thermocouple and meter, groundwater quality meter	▪ Indirect indicator of amendment distribution and microbial activity. Bioremediation amendments should decrease the ORP and DO for anaerobic ERD, pH can be decreased by reductive dechlorination processes ▪ Monitor to assess whether subsurface conditions are optimal for microbial activity (e.g., near neutral pH)
Total or dissolved organic carbon	Laboratory analysis	▪ Provides assessment of electron donor supply and distribution
COCs (chlorinated solvents)	Laboratory analysis	▪ Provides direct measurement of effect of ERD treatment on COCs and will show decreases in parent compounds such as perchloroethylene (PCE) or TCE, temporary increases in intermediate daughter products such as cDCE and VC
Dissolved hydrocarbon gases	Laboratory analysis	▪ Ethane and ethene are the ultimate reductive dechlorination daughter products for chloroethenes; increases in their concentration are a direct indication of complete dechlorination ▪ Methanogenesis typically is the process that consumes the majority of electron donor. Methane monitoring provides a measure of electron donor wastage. ▪ Elevated methane is usually unavoidable under reducing conditions, but high concentrations can be inhibitory to reductive dechlorination and may pose a health and safety concern if present in shallow soils; provides an indication that too much donor has been injected (overdosing).
Anions	Laboratory analysis	▪ Decreasing sulfate concentrations indicate that the aquifer is sufficiently anoxic for reductive dechlorination to occur ▪ Chloride is released into groundwater during reductive dechlorination and can be used as an indicator of the effectiveness of the ERD treatment
Specific dechlorinating bacteria	Laboratory analysis	▪ *Dehalococcoides* bacteria containing the *vcrA* or *bvcA* gene are the only bacteria known to dechlorinate PCE and TCE to ethene/ethane. ▪ *Dehalococcoides* cell or gene copy counts in groundwater samples provide a measure of the performance of ERD systems. ▪ An absence of *Dehalococcoides*, or low concentrations, may suggest the need for bioaugmentation to improve ERD performance
Alkalinity	Laboratory analysis	▪ Provides measurement of buffering capacity against pH change, can increase with increased biological activity
Dissolved or total metals	Laboratory analysis	▪ Regular measurement of dissolved iron provides a measure of redox conditions within the TTZ, along with the extent that iron reduction processes are consuming donor. ▪ Evaluate mobilization of metals of concern in response to ERD (e.g., Mn^{2+}, As^{3+})
Soil gas and well vapors	Photoionization detector, explosimeter, and other gas detectors	▪ Health and safety concerns, in particular methane production under reducing conditions ▪ Monitor for potential of vapor intrusion by vinyl chloride and methane into buildings near TTZs

Table 5-8. Performance Monitoring Checklist

Consideration	Monitoring Recommendations
Are there any nearby receptors?	Installation and monitoring of sentinel wells should be performed to ensure that COCs are not approaching receptors
Is migration of metals or byproducts a concern?	Analyze concentrations within the TTZ, sentinel wells, and point of compliance wells. Total and dissolved concentrations in groundwater and total metals in soil should be analyzed to help assess if metal mobilization has occurred
Is rebound a concern?	Multiple post-ERD monitoring events will be required to confirm the long-term effectiveness of treatment
How do local regulatory requirements impact the monitoring program?	Regulatory requirements may dictate the frequency that post-ERD monitoring is performed. Analyses of parameters other than COCs and byproducts that could impact primary or secondary groundwater standards may be required

5.5.2 Quality Assurance and Quality Control

QA/QC must be built into every project. The primary document pertaining to the installation of an ERD remedy is the CQC Plan. The purpose of the CQC Plan is to identify the definable features of work and to establish appropriate procedures to ensure that the work performed meets the design specifications and conforms to the requirements of the contract and applicable regulations. The CQC Plan describes an effective program for monitoring project contract compliance on and off site using the "three phases of control" methodology, which incorporates preparatory and initial inspection and planning with follow-on inspection to assess the outcome. Specifically, the plan must:

- Include a description of the project and relevant background information;
- Define data quality objectives;
- Identify the project QC organization and define each individual's respective authority, responsibilities, and qualifications;
- Define project communication, documentation, and record-keeping procedures;
- Establish QC procedures, including the necessary supervision and testing to ensure that all work meets applicable specifications, drawings, and plans; and
- Identify how deficiencies will be managed.

In most cases, the contractor performing the installation of the system is responsible for the development of and implementation of the CQC Plan.

In addition to the CQC Plan, Quality Assurance Project Plans (QAPPs) should also be developed. The QAPP should comply with the *Uniform Federal Policy for Quality Assurance Project Plans Manual* (U.S. EPA, 2005), as well as the NAVFAC UFP-SAP Tier 1 and Tier 2 Sampling and Analysis Plan Template (NAVFAC, 2011). The QAPP is primarily focused on QA/QC associated with the collection of data. It provides requirements and guidelines to federal agencies for implementing acceptable environmental quality systems to ensure that: environmental data are of known and documented quality and suitable for their intended uses;

and environmental data collection and technology programs meet stated requirements. The level of detail and format required for individual QAPPs depends on the complexity of the project. The Facilities Engineering Command (FEC) Quality Assurance Officer (QAO) may have additional requirements with respect to QAPP preparation, review, and submittal.

5.6 Optimization

The goal of optimization is to achieve response complete and site closeout faster and more efficiently with reduced costs, reduced environmental footprint, and with better performing remedies. Cleanup objectives should be met in a timely, cost-effective manner while minimizing negative environmental impacts. The DON Policy for Optimizing Remedial and Removal Actions at all DON ER Program Sites (DON, 2012) requires optimization and GSR evaluations during planning and implementation. Opportunities for optimization should be considered and implemented throughout all phases of remediation, including: site characterization; remedy screening, evaluation, and selection; remedial design and construction; remedial action operation, maintenance, and monitoring; and long-term management. During remedial design, optimization should be incorporated during the development or refinement of the CSM, establishment of realistic RAOs and remedial goals, selection of TTZs, and development of exit strategies. Key principles for incorporating optimization are described in the DON Guidance for Optimizing Remedy Evaluation, Selection, and Design (NAVFAC, 2010b); concepts for remedial design are summarized in Table 5-9.

Table 5-9. Remedial Design Optimization Concepts

Guidance and Considerations for EISB Remedial Design Optimization
• A comprehensive CSM should be developed and updated as new information is gathered so that it can be used as an engineering management tool from the initial site characterization through remedial action operation and long-term management. Regular analysis of the CSM to refocus remedy selection, design, and implementation will lead to a more cost-effective site cleanup.
• RAOs should focus on the protection of human health and the environment and avoid being overly prescriptive so that there will be more flexibility for the development of remedial goals and remedial alternatives for evaluation.
• The selection of the TTZs has a significant impact on the life-cycle cost for a remedial action and the amount of time required to achieve remedy completion. Targeting hot spots or source zones can be a cost-effective strategy if there is an adequate CSM and the remedial action is designed and implemented appropriately.
• The remedy should be designed for the entire life cycle of the cleanup and not just the initial conditions. Multiple remedial technologies should be considered to address each TTZ at a site to develop a more effective approach. Sequential implementation of multiple remedial alternatives is known as a "treatment train." Multiple technologies can also be applied concurrently in different areas (e.g., PRB at downgradient edge of source area with MNA for the downgradient plume).
• Performance objectives should be continually evaluated during operation to determine if planned transitions need to be made (e.g., switching from one phase of a treatment train to the next) or if modifications to the remedy or even the performance objective itself are required in order to meet remedial goals and ultimately RAOs.
• The development and documentation of exit strategies for each component of the remedy and the remedy as a

Table 5-9. Remedial Design Optimization Concepts (continued)

Guidance and Considerations for EISB Remedial Design Optimization
• whole to achieve completion and site closure should begin during the remedy evaluation phase with refinement continuing through remedial design. The exit strategy should include decision logic for system optimization, rebound evaluation and contingencies, and transition or termination of remedial actions based on performance monitoring results as compared to performance objectives.
• Opportunities to incorporate GSR practices and reduce the footprint of remedial actions should be evaluated throughout the ER process. GSR is discussed further in the next section.
• The cost-effectiveness of leasing equipment rather than purchasing, designing mobile remediation systems, using passive remediation systems where appropriate, and operating intermittently when contaminant transport is diffusion-controlled should be considered during remedial design.
• The performance monitoring program should be designed to collect data of the appropriate type, quantity, and quality to support decision making during implementation. Flexibility should be included in work plan and SAP documents so that monitoring programs can be optimized based on decision criteria as treatment progresses. Optimization can be applied to the monitoring locations, frequency, analytical parameters, and/or sample collection methods.

If, despite optimization, an ERD remedy design in a complex DNAPL source area or large-scale application fails to meet performance expectations, RPMs may convene a Tiger Team review of the remedial program at the site to identify improvements to the remedial program. Typically, Tiger Teams are assembled in coordination with EXWCs, and are used to solve remediation design and strategy issues at complex sites.

The DON Guidance for Planning and Optimizing Monitoring Strategies (NAVFAC, 2010a) and DON Guidance for Optimizing Remedial Action Operation (NAVFAC, 2012a) contain additional information to support optimization for remedial action projects. ITRC has also produced Guidelines for Remediation Process Optimization (2004). Other resources including case studies are available at the NAVFAC Optimization Workgroup Web site.

5.7 Sustainability

A sustainable ERD design starts with adequate site characterization and the development of a good CSM so that the TTZs are well defined. During remedy evaluation, a full GSR evaluation should be completed to support remedy selection. DON has identified eight metrics for GSR evaluations: energy consumption; greenhouse gas (GHG) emissions; criteria air pollutant emissions; water impacts; ecological impacts; resource consumption; worker safety; and community impacts. The use of SiteWise™, a tool that was developed by the U.S. Army Corps of Engineers, DON, and Battelle to quantify the effects of remedial actions, is now required by the DON during remedy evaluation and selection. Other methods and tools that are available for GSR evaluation can be used in conjunction with SiteWise™ as needed.

Remedy selection is a key point where the opportunity to reduce the environmental footprint is the greatest. During remedial design, there is ample opportunity to incorporate environmental footprint reduction methods for use during construction, operation, and monitoring of the remedial system. Life-cycle impacts of the remedial design should be considered as more sustainable designs might have a higher impact during construction, but lower impact during operation and overall. Design inefficiencies that increase the environmental footprint may result from designing the system for initial site conditions only without taking into consideration changes as concentrations decrease, over-designing equipment rather than carefully designing equipment for the intended purpose, or installing lower cost, but less-efficient equipment.

A list of best management practices (BMPs) for improving the sustainability of ERD projects during the design phase through construction and implementation is provided in Table 5-10. Many resources are available on the topic of GSR, in particular, the DON Guidance on GSR (NAVFAC, 2012c), U.S. EPA's Green Remediation BMPs for Bioremediation (2010) and the U.S. EPA's Green Remediation Primer (2008).

Table 5-10. BMPs for Improving the Sustainability of ERD

GSR BMPs for ERD
Materials Management & Waste Reduction • Use additional characterization (e.g., three-dimensional imaging) to minimize the area in which treatment is be applied • Consider using more aggressive/active treatment for hot spots and source areas and less aggressive/passive treatment for dissolved phase plumes or transitioning to a less aggressive treatment such as MNA after a specified performance goal is achieved • Because a large component of the ERD environmental footprint is typically related to the manufacturing of the amendments such as emulsified vegetable oil, optimize the injection program to efficiently use amendments during treatment; this could be done by reducing the number of injection points and/or the quantity of reagents injected. Consider mixing the amendment to meet the daily dosing requirement only, thereby avoiding generation and handling of wastes in the event that the injection operation ceases unexpectedly. • Reuse existing wells for injections and monitoring to the extent practical to avoid wasting resources • Use existing buildings instead of new construction, where feasible, for housing active ERD equipment • Consider using one wellhead to serve more than one well during the injection • Consider additional design and pilot testing to optimize the manner in which injections are performed • Consider using innovative bioremediation amendments from non-traditional sources to reduce the consumption of virgin natural resources and beneficially use waste products, especially if available from local sources. • Request electronic submittals of project documents instead of hard copies as much as possible to minimize use of materials as well as fuel for shipping • Recycle routine waste and recycle or salvage scrap material during construction and demolition • Consider using "green" concrete, which contains a percentage of repurposed fly-ash, where needed on-site
Energy Use • Consider low flow active or passive treatment systems instead of high flow active groundwater recirculation systems to minimize energy use • Use high-efficiency or premium-efficiency motors for systems that operate continuously • Use variable frequency drives instead of fixed-speed drives for pumps, compressors, etc. to improve energy efficiency • Consider pulsed operation instead of continuous injection • Consider operating high-demand equipment at off-peak times • If high-pressure injection is not necessary for proper distribution of amendments in certain geologic units, consider using gravity feed • Use energy efficient lighting for site trailers and buildings
Transportation • Consider reducing transportation use by reducing the number of trips for mobilization, operation and monitoring and scheduling simultaneous tasks • Employ local contractors and subcontractors to minimize travel requirements • Use remote sensing or telemetry to operate, monitor, and manage the system to the extent practical to

Table 5-10. BMPs for Improving the Sustainability of ERD (continued)

GSR BMPs for ERD
reduce transportation to the site • Hold virtual meetings to avoid unnecessary travel • Use rail transportation, if available, instead of trucks for shipping equipment and/or supplies that are needed in large amounts to reduce carbon dioxide emissions
Alternative Fuel • Consider use of green fuel for heavy equipment (e.g., biodiesel or ultra-low sulfur diesel for drill rigs, trucks) and other electric or hybrid transportation for smaller vehicles • Consider using renewable energy such as solar (photovoltaics), wind power, or microturbines for ERD equipment, especially for sites in remote locations where the cost of bringing in electric power lines would be high • Consider purchasing green power from an energy provider
Air Emissions • Reduce the atmospheric release of toxic or priority pollutants during recirculation of contaminated groundwater • Minimize the use of heavy equipment that requires large amounts of fuel • Implement idle control on chemical delivery trucks, field trucks, etc. • Implement emission control measures such as after-treatment technologies for diesel engines on DPT drill rigs, trucks (e.g., diesel oxidation catalysts, diesel particulate filters, selective catalytic reductions, diesel multistage filters)
Equipment Use • Size equipment properly for intended use • Maintain equipment so that it will perform efficiently • Use DPT instead of rotary methods for constructing wells where feasible to eliminate the need for disposal of cuttings and the use of drilling fluids • Consider installing dedicated pumps for groundwater monitoring wells that will be sampled repeatedly to increase sampling efficiency, eliminate the need for decontamination of pumps in between sample locations (thus reducing wastewater generation, deionized or distilled water and detergent use, and the need for equipment blank samples)
Monitoring Program • Periodically re-evaluate and optimize the monitoring program as treatment progresses and the plume size and concentration decreases; optimization could include reducing sample analyses, sample frequency, and/or the number of sample locations • Consider using passive sampling devices for groundwater monitoring to use less energy and generate less waste
Water Resources • Minimize the use of fresh water consumption during injection of amendments • Include beneficial reuse of extracted groundwater as makeup water for additional injections to minimize fresh water consumption • Protect nearby and downstream surface water; avoid the improper addition of nutrients in the vicinity of aquatic environments where it could quickly cause algal blooms
Land Management & Ecosystem Protection • Use minimally invasive ERD designs, where feasible • Minimize soil compaction and soil and habitat disturbance during system construction by establishing well defined work areas • Consider using native vegetation for site restoration to reduce maintenance requirements (water, fertilizer, pesticides) while adding habitat and food for local wildlife • Consider phytoremediation for shallow groundwater to provide habitat and food for local wildlife
Worker Safety • Comply with all applicable health and safety requirements and plans, use proper protective equipment, with a goal of zero incidents
Community • Minimize noise and lighting disturbance during ERD system construction and operation • Engage stakeholders and communicate openly and transparently

6.0 DRAWINGS

All design submittals for ERD should, at a minimum, include the following drawings:

- **Site layout drawing:** Depicting existing infrastructure, nearby receptors, and the proposed treatment area.
- **Target treatment area schematic:** Depicting the horizontal and vertical extent of the plume and portions that will be impacted by the remedy.
- **Injection well or DPT injection point location map:** This can be a combination of two-dimensional and three-dimensional drawings depicting the locations of the injection and extraction wells in relationship to the COCs present in the TTZ. The locations of the monitoring wells can also be included.
- **Well and/or injection point design:** Including all pertinent construction and design details.
- **Process and instrumentation diagram (P&ID) for aboveground portion of injection and treatment equipment:** This drawing is of particular importance with recirculation systems since they typically require multiple aboveground tanks, mixing equipment, pumps, etc.
- **Monitoring location map:** To illustrate wells that will be used to collect samples for process and performance monitoring. If practical, locations of wells also may be included on the injection location map described above.

Many times, ERD projects require conceptual level drawings, which can be prepared using a variety of graphic design software. However, design-build contracts, for which Unified Federal Criteria (UFC) specifications may be required, must follow the requirements documented in the UFC Design Procedures (Department of Defense [DoD], 2011), which is explained in further detail in Section 7.0. Drawings should be provided in both the native format and the format required for submittal of the design document (i.e., PDF). All drawings that are not final should be stamped “Preliminary, not for Construction”, until the final design submittal. Depending on the nature of the drawing, a Professional Engineer or a Professional Geologist, registered in the state where the ERD project will be conducted, may be required to sign and seal the drawings depending on the requirements of the state or local regulatory jurisdiction.

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7.0 SPECIFICATIONS AND STANDARDS

This section provides an overview of key design requirements for projects involving review by RPMs and, in some cases (depending on the installation), the FEAD. FEAD adheres to the UFC system, so the RPM should confirm the applicable format if the project involves FEAD oversight. The most important message is to ensure that the technical content requirements are met regardless of the selected format.

The UFC system is prescribed in the latest edition of MIL-STD-3007 (DoD, 2006) and provides planning design, construction, sustainment, restoration, and modernization criteria, and applies to the military departments, the defense agencies, and the DoD field activities. It provides policy and standards for the design, development, and revision of project documents, drawings, and specifications for NAVFAC facilities. It applies to both Design-Bid-Build (DBB) and Design-Build (DB) projects. UFCs are living documents and will be periodically reviewed, updated, and made available to users as part of the Services' responsibility for providing technical criteria for military construction.

NAVFAC UFC documents are maintained at the WBDG Whole Building Design Guide® Web site at http://dod.wbdg.org. Of the numerous UFCs available, one in particular is directly applicable to ERD projects and is normally reviewed by the FEAD. The criterion is FC 1-300-09N (DoD, 2014), which provides policy and standards for the design, development, and revision of project documents, including drawings, specifications, and requests for proposal, for facilities under the cognizance of NAVFAC. It applies to projects for all NAVFAC activities and their contractors that are preparing construction contract drawings, specifications, and requests for proposal for shore facilities, and is applicable to both DBB and DB projects. Specifically, FC 1-300-09N provides standardized design guidance pertaining to:

- Requirements for requests for proposal for design-build projects;
- Basis of design;
- Design calculations;
- Construction drawings;
- Unified Facilities Guide Specifications (UFGS) and other specifications;
- Cost estimates;
- Contracting requirements;
- Electronic design deliverable requirements, which also includes drawing requirements and specifications; and
- Design review and submittal requirements.

NAVFAC, U.S. Army Corps of Engineers, and National Aeronautics and Space Administration (NASA) use a software package, SpecsIntact, to facilitate preparation of government facility construction projects using UFGS. SpecsIntact is available on the NASA Web site. As mentioned above, contractors may be required to use this system to develop specifications for DBB or DB projects and could be requested to do so for other types of contracts at the discretion of the Navy RPM and/or FEAD. UFGS are published only in electronic format and are intended to be used with SpecsIntact software. UFGS are divided into a Procurement and Contracting Requirements Group and five Specification Groups consisting of General Requirements, Facilities Construction, Facilities Services, Site and Infrastructure, and Process Equipment. Examples of UFGS that are applicable to ERD projects and available through SpecsIntact are provided in Table 7-1. Table 7-1 is not a comprehensive list; other specifications may apply to various aspects of the ERD design.

Table 7-1. UFGS Relevant to ERD Design

Division	Name	Title	Revision Date
General	UFGS 01 35 45.00 10	Chemical Data Quality Control	04/06
	UFGS 01 50 00	Temporary Construction Facilities and Controls	08/09
	UFGS 01 78 23	Operation and Maintenance Data	07/06
	UFGS 01 74 19	Construction and Demolition Waste Management	01/07
Existing Conditions	UFGS 02 32 00	Subsurface Drilling, Sampling, and Testing	05/10
	UFGS 02 61 13	Excavation and Handling of Contaminated Material	02/10
	UFGS 02 81 00	Transportation and Disposal of Hazardous Materials	02/10
Plumbing	UFGS 22 10 00.00 10	Vertical, Axial-Flow and Mixed-Flow Impeller Pumps	07/07
	UFGS 22 11 23.00 10	Submersible, Axial-Flow and Mixed-Flow Pumps	07/07
Utilities	UFGS 33 24 13	Groundwater Monitoring Wells	08/08
	UFGS 33 24 00.00 20	Extraction Wells	04/06
Process Interconnections	UFGS 40 95 00	Process Control	10/07
Process Gas and Liquid Handling, Purification and Storage Equipment	UFGS 43 11 00	Fans/Blowers/Pumps; Off-Gas	04/08
	UFGS 43 15 00.00 20	Low Pressure Compressed Air Piping	04/06
	UFGS 43 21 13	Pumps: Water, Centrifugal	01/08
	UFGS 43 32 69	Chemical Feed Systems	04/06
	UFGS 43 41 16 16 40	Vertical Atmospheric Tanks and Vessels	02/11
	UFGS 46 61 00	Filtration Equipment	02/11

Some activities have modified UFGS for their region. These specifications contain local requirements, which are not necessarily imposed across all NAVFAC installations, and are available on the WBDG Web site. In addition, a number of standards available from various organizations relate to design, application, and monitoring of ERD remedies. For instance, the American Society of Testing Materials had developed many standards pertaining to drilling, sampling various media, and for performing a wide-variety of analyses.

In some instances, it may not be necessary to adhere to the UFC system for design and construction of ERD remediation projects. At many sites, the design of ERD remediation systems lacks the complexity and public safety concerns that are inherent in other construction projects (e.g., construction of a building, bridge, etc.). Furthermore, it may not be necessary to develop the design to the 90 to 100% level. As discussed in Section 3.0, a 35 to 50% design may be satisfactory for ERD remediation systems. However, it is important that all project stakeholders agree to the content and the level of detail that will be provided in the design. As applicable or required, appropriate specifications may be included as part of the design package.

8.0 SCHEDULE

A schedule for implementing the remedy must be included as part of the design. Table 8-1 lists milestones for a hypothetical ERD project for which an active recirculation approach is used. Both design and implementation milestones should be included. The amount of time required to complete each phase of the remedy is both site- and project-specific. In particular, consideration must be given to the amount of time required for regulatory review of project documents and the number of versions of documents that will be required. Both can vary from project to project and from state to state. In addition, time must be allotted between direct injections or biobarrier/PRB replenishment and after the final injection to monitor changes in groundwater chemistry and rebound of COCs.

Table 8-1. Typical Schedule Milestones for ERD Design and Implementation

Example Milestones
Submittal and Acceptance of Draft, Draft Final, and Final Work Plans or 30%, 60%, 90%, and 100% Designs
Completion of Site Preparatory Activities
Completion of Construction/Installation of ERD System
Completion of Operation and Maintenance and Process Monitoring Events (e.g., weekly, monthly)
Completion of Groundwater Performance Monitoring Events (e.g., monthly, quarterly, semi-annual, and/or annual)
Completion of Progress Reports (e.g., annual)
Submittal and Acceptance of Draft, Draft Final, and Final Remedial Action Completion Report

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