Design Considerations for In Situ Chemical Oxidation

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TECHNICAL MEMORANDUM

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DESIGN CONSIDERATIONS FOR IN SITU CHEMICAL OXIDATION

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

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ACRONYMS AND ABBREVIATIONS

ARAR	applicable or relevant and appropriate requirement
ARTT	Alternative Restoration Technology Team
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing Materials
BMP	best management practice
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CLEAN	Comprehensive Long-Term Environmental Action Navy
CO_2	carbon dioxide
COC	contaminant of concern
CORT3D	Chemical Oxidation Reactive Transport in 3-D
CQC	contractor quality control
CSI	Construction Specifications Institute
CSM	conceptual site model
DB	Design-Build
DBB	Design-Bid-Build
DMF	diesel multistage filter
DO	dissolved oxygen
DOC	diesel oxidation catalyst
DON	United States Department of the Navy
DPF	diesel particulate filter
DPT	direct push technology
EDTA	ethylenediaminetetraacetic acid
ESTCP	Environmental Security Technology Certification Program
f_{oc}	fraction organic carbon
FEAD	Facilities Engineering and Acquisition Division
FEC	Facilities Engineering Command
GSR	green and sustainable remediation
ISCO	in situ chemical oxidation
ITRC	Interstate Technology and Regulatory Council
K_{oc}	organic carbon-water partition coefficient
K_d	distribution coefficient
MCL	maximum contaminant level
NAPL	non-aqueous phase liquid
NASA	National Aeronautics and Space Administration

NAVFAC	Naval Facilities Engineering Command
NOD	natural oxidant demand
NOM	natural organic material
ORP	oxidation-reduction potential
PG	professional geologist
PE	professional engineer
PV	pore volume
QA/QC	quality assurance/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
RG	remedial goal
ROI	radius of influence
RPM	Remedial Project Manager
SCR	selective catalytic reduction
SMART	specific, measureable, attainable, relevant, and time-bound
SOD	soil oxidant demand
TOC	total organic carbon
TOD	total oxidant demand
TTZ	target treatment zone
UFC	Uniform Federal Criteria
U.S. EPA	United States Environmental Protection Agency
WBDG	Whole Building Design Guide

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1.0 PURPOSE

Most in situ remediation systems including in situ chemical oxidation (ISCO) are less mature than ex situ remediation systems (e.g., pump and treat) and other conventional environmental systems (e.g., wastewater treatment systems); therefore, design information, formats, and standards for in situ remediation systems are generally not as readily available or as consistent. The lack of available standards causes the design submittals for in situ remediation systems to vary widely from one project to another.

The purpose of this document is to provide a framework for design submittals of ISCO systems. The document provides a summary of best practices for ISCO 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 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 ISCO. 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 REMEDIAL 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
- **Drawings**: Detailed drawings to describe (prescriptive or performance-based) how to construct, operate, and maintain the system
- **Specifications**: Details of performance-based specifications on how to construct, operate, and maintain the system
- **QA/QC Plans**: Project-specific Contractor 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 4])
- **Monitoring Plans:** Details of process and performance monitoring plans, including locations, monitoring parameters, sampling frequency (see Section 4.4).
- **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 (see Section 5.0). 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 package is sufficient for project execution. The 90 to 100% design consists of a very detailed design package, which could be required for 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 Naval Facilities Engineering Command (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 Remedial Project Manager (RPM) within the limits set forth in Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), and other state orders or permits. If a design-build contract 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 price. 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.

3.0 KEY CSM ELEMENTS

The CSM summarizes site conditions, the distribution, concentration, and fate and transport of contaminants of concern (COCs), potential receptors and exposure pathways, and 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. This section 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 ISCO treatment systems.

3.1 Key CSM Elements and Potential Impacts to ISCO Designs

It is important to have a thorough understanding of the CSM when designing and applying ISCO treatment technologies. A detailed understanding of geochemical and lithologic characteristics of the site, flow and mass transport, and transformation and retardation of contaminants and the proposed oxidants is required to ensure adequate distribution and contact of the oxidant with the COCs. Failure to address these components in the design can have a negative impact on technology performance. Specifically, a CSM should take into consideration the site-specific factors listed in Table 1.

Several of these elements can have a significant impact on ISCO design and successful introduction and distribution of ISCO reagents into the subsurface (see Table 2).

Table 1. Key CSM Elements for ISCO Applications

CSM Element	Description
Nature and extent of contamination	Several factors help to determine the horizontal and vertical locations to introduce oxidants as follows: • Age and origin of COCs, COC physical and chemical properties (e.g., organic carbon-water partition coefficient [Koc], solubility) • Mass of COCs, horizontal and vertical distribution of COCs, and heterogeneity of COC distribution • Presence and distribution of non-aqueous phase liquids (NAPLs) – smear zone vs. clay lens
Human and ecological health risks	• Risks presented by COCs, as well as risks associated with the introduction and persistence of the oxidants (which can influence treatment endpoints, number of applications required, etc.)
Fate and transport of the COCs	• Determine how it impacts the location of injections, concentrations of oxidants, flowrates, and method of introduction into the aquifer
Site-specific infrastructure and characteristics	Several factors influence injection locations and overall strategy as follows: • Consider urban vs. rural environment • Presence of buildings and utilities • Proximity to nearby receptors • Current and future land use

Table 1. Key CSM Elements for ISCO Applications (Continued)

CSM Element	Description
Hydrogeology	Several factors determine the approach that will be used to introduce the oxidants into the aquifer as follows: • Lithology (lithologic units, heterogeneities, grain size, permeability, presence of bedrock, etc.) • Hydrogeology (gradients, confined or unconfined conditions, saturated thickness, conductivities, flux, Darcy velocity, groundwater flow velocity, anisotropy, etc.), • Mineralogy (e.g., could contribute to temporary metals mobilization)
Hydrogeochemistry	• Document dissolved oxygen (DO), oxidation reduction potential (ORP), pH, and buffering capacity. • Determine soil organic matter to estimate the fraction of organic carbon (foc) and distribution coefficients (K_d). • Geochemistry in background (uncontaminated) and contaminated areas should be determined.

Table 2. Impacts of Several Site-Specific Factors on Oxidant Distribution

CSM Element	Design Impact
Hydraulic conductivity and aquifer anisotropy	• Groundwater and oxidant flow follows the path of least resistance. Low conductivity regions may not be adequately treated. Additional or targeted injections may be required in those regions
Lithology	• Fracturing or other enhancements may be required in low permeability aquifers to facilitate oxidant distribution • Heterogeneities will influence reagent flow pathways and contact with COCs
Presence of NAPL, smeared, or sorbed contaminants	• Impacts oxidant demand • Contributes to substantial rebound if only dissolved phase is treated • Contributes to back diffusion (especially from low permeability areas) • Mobility will impact type and extent of treatment
Horizontal extent of contamination	• Impacts degree of treatment, which could include only the source area, a portion or all of the dissolved phase plume, or a combination of both
Vertical extent of contamination	• COCs distributed across regions having low hydraulic conductivities will be more difficult to treat requiring injection strategies that isolate these low permeability zones and/or increase fluid distribution (e.g., hydraulic or pneumatic fracturing) • Depth of contamination will influence cost and design (i.e., direct push, recirculation wells, aboveground recirculation, etc.)
Subsurface utilities and conduits	• Potential pathway for groundwater and reagents, may cause reagents to flow into undesirable locations (e.g., streams, sewers) rather than contacting the COCs • Potential direct impact to subsurface utilities. Important to check compatibility with utility corridors • Potential pathway for volatile gases generated, either from degradation byproducts or exothermic reactions, which could result in vapor intrusion
Presence of aboveground structures	• Vapor recovery may be required to mitigate risks associated with vapor intrusion when gas is generated (e.g., application of hydrogen peroxide) or heat evolution is a concern • Aboveground structures may pose access issues for ISCO injections

3.2 Remedial Action Objectives and Remedial Performance Goals

The basis of design document should present the remedial action objectives (RAOs), remedial goals (RGs), and treatment endpoints for the planned ISCO remedy. In addition, the basis of design document should present the interrelationship between the RAOs, RGs, and treatment endpoints, 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 RGs identified in the CSM. Cleanup levels, also referred to as RGs, are established based on a review of applicable or relevant and appropriate requirements (ARARs). These typically are numeric values that must be attained to achieve the RAOs at a site, such as drinking water maximum contaminant levels (MCLs). However, more recently, alternative RGs such as reducing mass flux from a source area also are being considered as part of cleanup RGs. As part of the process for establishing RAOs and RGs, it is recommended that functional objectives consistent with the SMART (specific, measureable, attainable, relevant, and time-bound) attributes presented by Interstate Technology and Regulatory Council (ITRC, 2011) be established. Selecting objectives that reflect SMART attributes can make subsequent decisions more valid and ISCO approaches more successful.

Treatment endpoints (or performance objectives) are interim goals that must be met to ultimately achieve RGs and RAOs for the site. Treatment endpoints 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. They should be realistic, achievable, and flexible to easily allow transition from one portion of the remedy to the next. Multiple steps are typically needed to achieve the ultimate RGs for a site. This may require a series of treatment endpoints for different locations, phases, and alternative endpoints for an overall site cleanup. The most important goal for ISCO is establishing criteria that demonstrate the amendments have been delivered and distributed sufficiently into the aquifer. This endpoint should be realistic and achievable, and should specify when to discontinue an application.

3.3 Key Issues of Concern for Regulators and Other Stakeholders

Project stakeholders can include Federal, state and/or local regulatory agencies, and the public, especially those that may be in close proximity to the site where cleanup will be performed. Each group of stakeholders will have a number of concerns, which should be addressed early on 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 an ISCO project. 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

- Potential for reinjecting contaminated groundwater
- Creating byproducts or changes to geochemistry, typically within the treatment zone, which can adversely impact the aquifer (e.g., manganese dioxide precipitates, which can clog the aquifer; introduction and/or mobilization of metals; formation of trihalomethanes, and other potential byproducts that could be incompatible with site infrastructure or activities)
- Potential for vapor intrusion during application
- Potential impacts to sensitive receptors (e.g., nearby waterways)

4.0 KEY DESIGN ELEMENTS

This section discusses key design elements related to oxidant selection, the development of an injection plan, and monitoring plan with QA/QC measures. This information will assist the practitioner and RPM in understanding key considerations when developing and/or reviewing the ISCO design.

4.1 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, and application of the remedy. Objectives of these tests typically include selection of the optimal oxidant and reagents, evaluating reaction chemistry and loading for site-specific conditions and determining factors that would impact the distribution and contact of the reagents with COCs.

Bench-scale tests can evaluate a large number of conditions and parameters and tend to be less expensive than pilot tests; however, results do not provide insight into design parameters such as achievable radius of influence (ROI) and field injection rates for full-scale application. The design parameters determined from these tests include oxidant and activator selection, estimate of oxidant and activator dosage, impacts of site-specific properties such as natural oxidant demand (NOD), presence of NAPL and metals, and the potential for formation of byproducts or geochemical impacts to the aquifer (e.g., heat and gas generation, pH changes, etc.).

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. However, they are more costly and time consuming to implement. The information gathered during the pilot test includes determination of achievable injection flowrates and pressure, oxidant distribution/ROI, and geochemical impacts to the aquifer.

4.2 Oxidant Selection

Common ISCO reagents include hydrogen peroxide, potassium permanganate, sodium permanganate, and sodium persulfate. A number of guidance documents are available to aid the practitioner in selecting an appropriate oxidant for a site-specific application and to design a treatment system to introduce and optimize its distribution into the aquifer. Some useful guidance documents include:

- In Situ Chemical Oxidation for Groundwater Remediation (Siegrist et al., 2011)
- Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater (ITRC, 2005)
- Design Tool for Planning Permanganate Injection Systems (Borden et al., 2010)
- In Situ Chemical Oxidation – Engineering Issue (U.S. Environmental Protection Agency [U.S. EPA], 2006)

In addition, specific oxidant manufacturers will be able to provide recommended best practices for applying their oxidants. Various technology-specific considerations for application of ISCO reagents must be addressed in the design. As described in Section 4.1, bench-scale testing may be performed to address common issues and data needs. Several of these frequently encountered challenges associated with the introduction and distribution of the common oxidants are highlighted in Table 3.

Table 3. Design Considerations for the Application of ISCO Reagents

ISCO Reagent	Injection/Distribution Design Considerations and Challenges
Hydrogen Peroxide	• Reaction is exothermic and generates gases • Vapor intrusion can occur into nearby buildings due to heat and vapor produced during reaction with organic matter and COCs, which can volatilize and transport COCs • Surfacing of reagents is common due to the formation of a large volume of gas • Reagent is short-lived, which limits ability to distribute via diffusion processes. However, stabilization agents such as phosphate and citrate are sometimes added to provide more stability to the reaction • May require injection and distribution of additional reagents to activate or stabilize (iron and acid or chelating agent[1]), which must also be distributed into the aquifer • The presence of naturally-occurring carbonate or bicarbonate has been noted to reduce oxidation rates, which could impact distribution • Injection and monitoring well materials must be compatible with the heat that may be generated by the exothermic reaction.
Permanganate	• Long lasting in the aquifer; hence, both advection and diffusion processes contribute to distribution • Can be used in reactive barriers to intersect plume and prevent further down-gradient migration • Deep purple color, which can be observed in nearby surface water bodies and groundwater supply wells if the permanganate distribution is not adequately controlled • Manganese dioxide, an insoluble precipitate, which can reduce the permeability of the aquifer, is formed as a byproduct of the reaction • Lower oxidation potential versus peroxide and persulfate so not applicable to some COCs. • Potential for long-term persistence if a site is overdosed with permanganate. It can persist for extended periods of time (years at some sites)
Persulfate	• Compatibility of injection equipment with persulfate should be considered • May require injection and distribution of additional reagents to activate (strong bases, iron catalyst, chelating agent, hydrogen or calcium peroxide) • Long lasting in the aquifer if dosed greater than demand; hence, both advection and diffusion processes contribute to distribution • Can be used in reactive barriers to intersect plume and prevent further down-gradient migration

[1]Chelating agents are chemicals that form soluble, complex molecules with certain metal ions. In this case, carboxyl groups of inorganic acids such as citric acid and ethylenediaminetetraacetic acid (EDTA) are used to bind ferrous iron to maintain its solubility.

4.3 Injection Plan

An injection plan is a critical component of every ISCO design and must be included as part of the design document. The plan provides the design details necessary to ensure contact between the ISCO reagents and the COCs. Since the ability of distributing the treatment reagents is site-specific, it is preferred that the injection plan is based on the results of a bench and pilot test, modeling, and/or previous results at the site. At a minimum, the plan must include:

- **Oxidant Dosing Amount and Longevity**. Oxidant dosing and longevity considerations, including the anticipated number of injection events, required oxidant concentration, and volume of fluids to be introduced into the aquifer;
- **Injection Method**. Selected injection approach based upon lithological and other site-specific considerations including recirculation, direct injection, push/pull, or soil mixing;
- **Treatment Well/Point Spacing**. Treatment well/point type, spacing, layout, and design specifications including target treatment interval and installation methods (drilling technique and construction materials). Ensure that the wells/points are placed appropriately to achieve adequate treatment within the target treatment zone (TTZ). The basis for determining well/point spacing and the ROI must be included (e.g., pilot test, modeling, or previous results at site), and should include the mass and volume introduced into each location. Drawings depicting the extent of the plume, the extent of the TTZ, and the locations of injection and extraction wells/points that may be used also must be included;
- **Application Tooling and Techniques**. A wide range of proprietary injection tooling and application methods have been developed and may be applied; however, the design should not reference specific proprietary methods and tools. Rather, the design should document specific parameters that the tooling should achieve;
- **Specifications for Pumps, Tanks, and Ancillary Equipment**. Specifications for pumps, tanks, and ancillary equipment that will be used during the injection process;
- **Operation Procedures and Specifications**. A description and operational procedures for the method that will be used to introduce the oxidants into the aquifer including the number of anticipated injection days, hours of operation, injection volume, estimated injection flow rate, number of points injected into simultaneously, number of pore volumes (PV) injected, and anticipated ROI.
- **Establishing Endpoints and Milestones for Delivery**. Appropriate treatment endpoints and milestones for effective oxidant delivery, distribution and treatment.

The plan should also include regulatory issues, health and safety issues, and schedule milestones and contingencies for conceivable deviations based on uncertainties and unknowns present in the CSM. In addition to the injection plan, a monitoring plan should be developed to evaluate the effectiveness of the injection strategy (see Section 4.4.) Each of these items is discussed in further detail below.

4.3.1 Oxidant Dosing Amount and Longevity

The dosing of reagents and substrates must consider the mass of COCs, the injection volume, concentration, and number and frequency of applications into the aquifer. Insufficient oxidant mass and volume of injection decrease the likelihood that the oxidant will be adequately distributed and RAOs achieved. Conversely, excess oxidants can result in significant wastage from autodecomposition and can create undesirable changes in the aquifer such as plugging of the formation with insoluble reaction byproducts, long-term aquifer pH changes, 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 oxidant dosing is to estimate the COC mass and non-target demand of the TTZ within the TTZ. The PV within the TTZ is also calculated 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-specific factors such as total organic carbon (TOC), hydraulic conductivity, anisotropy, lithology, and COC architecture. Application-specific factors to consider include the chemical and physical properties of the reagents and aquifer material including viscosity, density, solubility, sorption coefficients, NOD, reaction kinetics of the system, residence time, and the practitioner's experience applying oxidants at other sites. In general, it is recommended that bench-scale tests be performed to test proposed dosages, evaluate reaction kinetics and byproducts, and determine any other reagent-specific parameters that may be required (e.g., type and concentrations of activating or stabilization agents). Results of the bench tests are used to determine the optimal oxidant concentration and the volume to be injected expressed as percentage of PV in the TTZ that will be treated. The injection volume can range from a fraction of a PV to greater than 100% depending on the required loading, oxidant type and injection design. A list of considerations for determining oxidant dosing is provided in Table 4.

4.3.2 Injection Method

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

- **Direct injection**: The reagents 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.
- **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
- **Pull-Push**: A set volume of groundwater is extracted, amended with reagents aboveground and then reinjected into the subsurface through the same well and well screen from which it was extracted. This is a batch process that can be used to test one or more wells located in different areas of the site
- **Soil Mixing**: Soil mixing involves the use of large augers or galleries and trenches for introduction of oxidant. It has significant advantage in low permeability soils such as

clays where injection methods may not work. It may however need post-ISCO soil stabilization depending on the future land use and mixing depth

These methods assume that the oxidant will be injected in liquid form. However, in some cases, it may be desired to introduce oxidant in a solid or slurry form (e.g., potassium permanganate). In this case, alternate techniques such as soil mixing using large augers or introduction through galleries and trenches may be used. Hydraulic or pneumatic fracturing also may be considered to facilitate introduction and distribution of the solid material. Another emerging application technique is the use of slow-release permanganate-paraffin candles (Christenson et al., 2012). Table 5 lists some considerations associated with each type of injection strategy. More guidance is available in NAVFAC's Best Practices for Injection and Distribution of Amendments (2013).

Table 4. General Guidance for Determining Reagent Dosing

Guidance and Considerations for Reagent Dosing and Longevity
• Estimate COC mass in TTZ • Perform bench- and pilot-scale tests using site groundwater and aquifer material. Determine oxidant dosage, persistence, demand [soil oxidant demand (SOD) and total oxidant demand (TOD)], and appropriate activators and concentrations if needed. Determine the percent or number of PVs that will be injected or recirculated with ISCO reagents. A pilot test can be performed to determine optimum number of PVs, as well as reagent concentrations and flowrates to achieve the desired loading and distribution of the reagents. • Evaluate tradeoffs between concentration of reagents, injection volume, and number and frequency of injections. For instance: o Highly reactive oxidants may need to be introduced at a greater flowrate (and/or concentration) in order to minimize the likelihood of consumption to an unacceptable level due to non-target reactions. Use of stabilizing agents can be considered to slow down the reactivity of the reagent in the subsurface o At high oxidant concentrations, density-driven transport may impact distribution (e.g., the oxidant solution may sink) o A low concentration of oxidant and possibly continuous flowrate may be appropriate for soluble compounds, especially if the groundwater velocity is high. Recirculation may be considered to facilitate distribution and mixing and reduce the likelihood of displacing the plume. o Reaction rates may be dependent on the concentration of the reactant; hence, a greater concentration may result in greater consumption of the reactant with non-target compounds, contributing to higher project cost o Multiple applications are often preferred over single large PV applications. Multiple injection events may allow time between events for oxidants to passively diffuse into the aquifer matrix and also allow back diffusion from the aquifer matrix to occur. Multiple injections also allow for monitoring between events and refining the target area and oxidant dosing to satisfy the TOD. • Consider how interactions between oxidants and aquifer material may impact distribution when multiple reagents are used simultaneously or when a treatment train approach is used that requires using different reagents for each phase of application. For instance: o Greater concentrations of oxidant may result in greater consumption of natural organic material (NOM); o Application of an oxidant during ISCO will create an oxidizing environment that must be taken into consideration when determining the dosage of electron donor for enhanced in situ bioremediation as part of a treatment train approach. Also, application of persulfate can increase the sulfate concentration

Table 4. General Guidance for Determining Reagent Dosing (Continued)

Guidance and Considerations for Reagent Dosing and Longevity
in the aquifer, which can potentially inhibit degradation of cis-dichloroethene and vinyl chloride. • Consider potential impacts of overdosing, which can include health and safety concerns, fouling, long-term groundwater chemistry changes, formation of adverse byproducts, impacts to reagent distribution, oxidant wastage, etc.

Table 5. Injection Strategy Considerations

Consideration	Direct Injection	Recirculation	Pull Push[(a)]	Soil Mixing
Ability to hydraulically control fluids	Has greater potential for “displacing” primarily dissolved contaminants from treatment area compared to recirculation and pull-push	Maintains better hydraulic control of fluids than direct injection and pull-push	Maintains better hydraulic control of fluids than direct injection, but may not provide as good hydraulic control as recirculation	Good hydraulic control
Need for source of water	Requires a source of water for mixing reagents	Extracted water can be amended with reagents and reinjected	Extracted water can be amended with reagents and reinjected	Solid reagent may be mixed directly into soil negating the use of external water
Ease and speed of application	Relatively quick to apply	More equipment intensive, typically requiring a longer time to apply	Quick to apply in a single location. Can be time consuming to mobilize/demobilize to multiple locations	Relatively quick to apply, but equipment intensive. Application becomes more challenging at greater depths
Limitations due to formation permeability	Difficult to apply in tight formations such as clays and silts. High injection pressures can be problematic and surfacing of fluids can occur	Better effectiveness when hydraulic conductivity is greater than 10^{-4} cm/s	Difficult to apply in tight formations such as clays and silts. High injection pressures can be problematic and surfacing of fluids can occur	Works well in low permeability soils, in which other injection methods may not work. Post application stabilization may be required based on anticipated land use
Need for aboveground treatment	Less aboveground equipment required than other methods	Aboveground tanks and mixing equipment required	Aboveground tanks and mixing equipment required	Large aboveground mixing equipment is required
Ability to achieve mixing of reagents and contact with COCs	Difficult to ensure adequate contact and mixing of reagents with contaminated groundwater. Direct injection combined with hydraulic or pneumatic fracturing may facilitate introduction and distribution of solids and slurries	Aboveground mixing and treatment of dissolved COCs easily achieved	Aboveground mixing and treatment of dissolved COCs easily achieved	Very good contact and mixing is achieved using dual-axis type blenders

(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.

4.3.3 Treatment Well/Point Spacing

The design must specify the layout and spacing of the injection wells or points. 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 in a localized area to ensure that a suitable ROI can be obtained. The design ROI might be different from the actual ROI due to various site-specific factors. Distribution of reagent will be greater when a higher percentage of PV is injected into the subsurface. Groundwater flow also can increase distribution if the oxidant persists in the aquifer for an extended period. Site-specific considerations that impact the ROI and should be considered during the design include:

- Oxidant stability/half-life
- Soil conductivity and conductivity variability
- Oxidant reaction kinetics
- Oxidant concentration
- Injection volume and flowrate
- Target injection PV within the TTZ
- Passive diffusion of oxidant (i.e., the amount that the oxidant will distribute in groundwater after completing active injection into the aquifer)
- Direct injection versus recirculation approaches (see Section 4.3.2)

A number of design tools and models are available for the practitioner to use to aid 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/or injection well spacing that will be adequate for distribution of the reagents. The practitioner also may want to consider using a reactive transport model, which accounts for aquifer changes as the oxidant reacts with the COCs and aquifer materials, such as the Chemical Oxidation Reactive Transport in 3-D (CORT3D; *Environmental Security Technology Certification Program* [ESTCP], 2010). CDISCO, a spreadsheet-based numerical model for simulating one-dimensional radial transport and consumption of permanganate, is a useful tool for evaluating various aquifer and injection parameters on ROI (ESTCP, 2010). The output from these models helps to determine expected flow and distribution to determine an appropriate ROI and injection point spacing. If modeling tools are utilized, a sensitivity analysis should also be performed and the results should be included in the design.

4.3.4 Application Tooling and Techniques

Application of the oxidants and any required activators are typically performed through permanent wells or using direct push technology (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 6.

Table 6. Comparison of DPT Injection Points and Permanent Wells for Introducing Reagents into the Aquifer

	Advantages	Limitations
Direct Push Injection	• Generally lower cost than permanent wells • Well-suited for consolidated materials • Injection locations can be easily changed or added during application based on real time observations • Injection points can be offset from one injection event to the next • Drill cuttings are eliminated	• May result in greater cost if multiple applications are required • 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 • More prone to daylighting due to failure around the rods
Wells	• May result in lower overall cost if multiple injection events are required • Greater depths can be achieved • If properly designed and installed, there is less potential for reduced injection flowrates due to formation material	• Generally greater cost than DPT • Additional wells may be required if real time observations dictate contamination in other areas or ROI is limited • Screen length is a concern, sometimes requiring the installation of nested wells • Fouling and well failure can be problematic if multiple injections over an extended time are required

At a minimum the ISCO design must include the following information:

- The type of injection (and extraction) methods used and the rationale for choosing the methods
- Locations of all of the injection/extraction wells and points and the design basis for the locations selection
- Well/point design details and drawings depicting screened/injection interval

There are a variety of ways to apply each of the injection strategies described in Section 4.3.2, 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 flowrate, injection pressure, material compatibility, etc.

4.3.5 Specifications for Pumps, Tanks, and Ancillary Equipment

Specifications for aboveground equipment used to introduce, mix, and monitor the introduction of oxidant into the aquifer should be included in the ISCO design (see Section 6). Aboveground equipment associated with ISCO systems typically includes pumps, tanks, piping and in-line mixers. A variety of flow and pressure measuring devices also are used to monitor the application of the reagents into the aquifer. It is not the intent of this document to identify specific types of equipment for an ISCO application since the optimum equipment is application-specific and, to an 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 ISCO application. Some of the more important ones are:

- All wetted parts of equipment are chemically compatible with the oxidants and any activating agents that will be used
- Pumps are sized properly to handle anticipated pressures and flowrates
- Injection hoses must be rated for the maximum expected injection pressures
- Tanks and mixing systems are sized to ensure adequate reagent mixing and storage capacity
- Secondary containment is provided for all liquid handling equipment and storage
- Health and safety equipment such as eyewash stations, safety showers, and fire extinguishers, is specified appropriately based on the oxidants and activators that will be present on site
- GSR practices are incorporated into the design, as applicable

Useful design information can be found in a number of sources, including:

- Perry's Chemical Engineering Handbook (8th edition)
- Environmental Engineers' Handbook (2nd edition)
- American Society of Testing Materials (ASTM)[2]
- Vendor's literature and Web sites

4.3.6 Operation Procedures and Specifications

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

- Procedures for handling and storage of reagents
- Procedures for introducing the reagents. Parameters including injection volumes, concentrations, pressures, and flowrates should be included
- Procedures to identify and mitigate potential surfacing of reagents
- Procedures for addressing fouling of well screens if multiple injection events are required
- Procedures to ensure the health and safety of workers and the surrounding community
- Monitoring requirements, procedures, and required equipment (see Section 4.4)

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[2]ASTM provides a wide-range of specifications for pumps and other types of equipment. Chelating agents are chemicals that form soluble, complex molecules with certain metals.

- QA/QC procedures (see Section 4.4.3).

4.3.7 Establishing Endpoints and Milestones for Delivery

At times, remedial actions are perceived to fail because of unrealistic expectations and a lack of appropriate endpoints and metrics to gauge remedial progress. Two key endpoints for ISCO are: 1) when to discontinue a particular application and 2) determining when it is appropriate to discontinue all applications and transition to an alternative technology or site closure. Treatment endpoints may be based on completing a specific portion of the process or on achieving a specific response in the aquifer that results from applying the oxidants. A treatment endpoint may be defined as achieving a specific concentration reduction for COCs in the aquifer. However, achieving such an endpoint can be problematic if the level is too aggressive. It is beneficial to involve all of the project stakeholders during the design process to select and agree upon appropriate endpoints for the remedy. Table 7 provides several examples of each type of endpoint that could be applied for an ISCO remedy.

Table 7. Examples of Endpoints, Milestones, and Metrics

	Endpoint	Example Milestones	Measurable Metrics
Example Endpoints, Milestones, and Metrics for Discontinuing an Application	Achieve an average reagent concentration of 50 mg/L in the TTZ	Achieve 30, 60, 90, and 100% of target concentration	Changes in concentration measured in monitoring wells throughout TTZ
	Inject 1,000 lbs of persulfate into each of 20 points	Complete injection of 1,000 lbs of persulfate into 5, 10, 15, and 20 points	Mass of persulfate injected into each point
	Perform recirculation of groundwater until three PVs have been exchanged	Exchange 25, 50, 75, and 100% of total	Volumetric flowrate
Example Endpoints, Milestones, and Metrics for Transition from ISCO to a less Aggressive Technology	Transition ISCO to enhanced in situ bioremediation after three rounds of injections have been achieved[(1)]	Complete injection rounds 1, 2, and 3	Number of injections
	Achieve a 90% reduction in mass flux from the treatment zone	Achieve 30, 60, and 90% reduction	COC concentrations, groundwater flow velocity
	Reduce concentration of COCs in groundwater by a defined (reasonable) percentage	Achieve a specified percentage reduction in COC concentrations[(2)]	Changes in concentrations in monitoring wells

(1) Additional milestones, such as those listed above (i.e., achieve a specified PV recirculated or mass injected) also must be used in conjunction with this particular endpoint.
(2) There is substantial uncertainty built into this endpoint since it is not known at what concentration the asymptotic level will be achieved. Note that the asymptotic concentration may not be sufficiently low to achieve RAOs or remedial goals for the site.

4.4 Monitoring Plan

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

- The measurements that will be performed
- The metrics by which the measurements will be evaluated
- Applicable milestones
- Contingency triggers (i.e., additional injections, alternate technology) in the event that milestones are not being achieved.

The 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 (i.e., achieve interim treatment endpoint for each application), whereas performance monitoring provides information on the efficacy of the remedy to achieve remedial goals for ISCO. Design guidance for both types of monitoring is provided in the remainder of this section.

4.4.1 Process Monitoring

Process monitoring involves observing and measuring parameters that provide information on the state of the remedial action during implementation. Typical process monitoring techniques and their intended purpose are presented in Table 8.

For ISCO application, this consists of confirming that the oxidant is introduced and distributed into the aquifer according to the design[3]. Changes in physical parameters such as pressures, temperatures, flowrates, and groundwater levels in injection and monitoring wells are measured during application of the oxidant and activating agents.

Chemical changes in the aquifer such as changes in DO, ORP, pH, and conductivity are measured to evaluate the distribution of oxidants and the need to perform additional injections. In addition, colorimetric field test kits may be used to measure the concentration of the oxidant in the subsurface.

When possible, process monitoring should be comprised of field methods and analyses 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 oxidants.

[3] It also is desirable to confirm that the oxidant remains activated at the design distance. For potassium permanganate, the concentration merely needs to remain above the target design level to ensure reaction with COCs (in the presence of NOM). For catalyzed persulfate or hydrogen peroxide, measurements of the concentration of activator or indicator parameter in groundwater are useful. Specific monitoring requirements are application-specific depending on the nature of the oxidant and activator (e.g., monitor change in pH for base-catalyzed persulfate or total and dissolved iron for application of iron-activated persulfate).

Table 8. Common Process Monitoring during ISCO

Measurement	Method	Primary Purpose
Groundwater levels	Water level indicator	• Mounding and/or changes in levels during injection helps assess distribution of oxidants and may indicate need to reduce flow or discontinue injection • Used to calibrate models • Evaluate change to flow direction and gradient. Reaction of some oxidants, such as permanganate, can form insoluble byproducts (i.e., manganese dioxide), which can impact groundwater flow when high concentrations or mass of oxidant are used
Pressures	Gauges or transducers	• Confirm injections are proceeding as designed • Pressure increases may indicate well/formation plugging • A decrease in pressure combined with an increase in flow may indicate that the formation was fractured during injection • Application of high pressure can fracture aquifer material
Flow rates and volumes	Digital meters, rotameters, etc.	• Confirm design loading of oxidant is achieved • Decrease in flowrate may indicate plugging of injection well or formation • An increase in flow combined with a decrease in pressure may indicate that the formation was fractured during injection
Oxidant and activator concentrations	Colorimetric kits	• Ensure adherence to design specifications • Determine concentrations in monitoring wells to evaluate distribution, residuals, and update fate and transport/capture models
Visual observations	Visual	• Change in color may result from application of permanganate (purple) • Bubbles may be generated and noted in groundwater if substantial oxygen and carbon dioxide is produced (i.e., application of peroxide). • Surfacing of reagents inside and outside the TTZ • Presence of reagents or groundwater in utility corridors
Groundwater temperature	Thermocouples and meters	• Particularly important when applying reagents that react exothermically (e.g., hydrogen peroxide). Application should be discontinued if groundwater temperature cannot be controlled within design specifications
Groundwater quality (DO, ORP, pH, conductivity)	Groundwater quality meter	• Indirect indicator of oxidant distribution. Oxidants can increase ORP and possibly DO. Persulfate increases conductivity. pH can be decreased by both oxidants. Alkaline-activated persulfate will increase pH • Post-ISCO measurements will facilitate design and transition to a less aggressive polishing treatment after completing ISCO
Total organic carbon	Hand-held spectrophotometer	• Provides a line of evidence to assess distribution of oxidant and changes due to oxidation of organic matter
Metal concentration	Colorimetric kits, hand-held spectrophotometer	• Evaluate mobilization of metals during application
Soil gas and well vapors	Photoionization detector, explosimeter and other gas detectors	• Health and safety concerns. In particular, application of hydrogen peroxide can generate a substantial volume of gas, which can volatilize COCs and transport them to ground surface • Monitor for potential vapor intrusion

4.4.2 Performance Monitoring

Performance monitoring includes monitoring parameters that provide information on the potential success of the remedial action to achieve treatment goals for the ISCO phase of remediation and remedial goals for the overall project.

Performance monitoring is accomplished through sampling and analysis of groundwater and sometimes soil for the COCs within and possibly downgradient of the target area to estimate treatment effectiveness and mass removal efficiency. At most sites, the parameters that are measured during process monitoring are also measured at regular intervals to evaluate the aquifer return to baseline conditions. Performance monitoring is very important for evaluating if and when additional injections are required and will help to optimize dosing and injection spacing should additional injections be necessary.

Performance monitoring of ISCO systems will consist of similar measurements to the process monitoring measurements that are shown in Table 8. However, in addition, performance monitoring typically includes a variety of laboratory analyses to confirm the reduction in concentrations of COCs. Samples sent to laboratories generally include groundwater and sometimes soil. Typically, COCs and possible byproducts of the application, such as an increased level of metals are analyzed. Analysis of the concentrations of reagents that may persist for an extended period after injection also should be performed. If samples are collected at a time when oxidant is present, the residual oxidant may be quenched using a preservative such as ascorbic acid (Ko et al., 2012). Table 9 shows a list of considerations that highlight common performance monitoring considerations that should be incorporated into the design of an ISCO system.

Performance monitoring should consist of a baseline event, which is performed within one month prior to applying the ISCO reagents. Post-ISCO performance monitoring typically is conducted at several time points after the ISCO application. The results are compared to the results of the baseline event to understand how the application has impacted the site and to gauge progress toward achieving remedial goals. Post-application performance monitoring typically is performed quarterly beginning one month after completing the first application and may be decreased to semi-annual or annually over time. It should be noted that monitoring frequency is very site-specific and will be impacted by the longevity of the oxidant used[4], concentration of oxidants and activators, groundwater flow velocity, degree of change of groundwater chemistry between monitoring events, regulatory requirements, and RGs.

The specific media that will be monitored also is important. Historically, the majority of applications have monitored changes in concentrations of various parameters in groundwater. Although this may be adequate for dilute plumes or plumes containing COCs that have limited affinity for soil (e.g., vinyl chloride), in the source area or areas where concentrations of COCs are high, concentrations of COCs in groundwater may take substantial time to equilibrate with concentrations in soil. As a result, groundwater data may not accurately reflect treatment

[4] In some instances, it may not be necessary to begin post application performance monitoring until the majority of the oxidant is consumed since groundwater chemistry including COCs remaining, pH, ORP, and dissolved metals may continue to change in the presence of the oxidant.

efficacy. In these instances, the collection and analysis of soil samples should be considered. At a minimum samples should be analyzed for changes in COCs and TOC. As with groundwater samples, baseline sampling and analysis must be performed, against which post-treatment results are compared.

Table 9. Performance Monitoring Considerations

Considerations	Monitoring Recommendations
Are there any nearby receptors?	Installation and monitoring of sentinel wells and vapor monitoring points should be performed to ensure that oxidants, byproducts, and COCs are not approaching receptors
Is migration of metals or byproducts a concern?	Analyze concentrations within the TTZ, sentinel wells, point of compliance wells, and vapor monitoring points. Total and dissolved concentrations in groundwater and total metals in soil should be analyzed to help assess if mobilization of metals or byproducts has occurred within and/or outside of the treatment zone
Is rebound a concern?	Multiple post-ISCO events will be required to establish a trend in concentrations of COCs in TTZ
How do local regulatory requirements impact the monitoring program?	Regulatory requirements may dictate the frequency which post-ISCO monitoring is performed. Analyses of parameters other than COCs and byproducts that could impact primary or secondary groundwater standards may be required
Will an alternate technology be utilized after completing ISCO?	All monitoring parameters that impact a potential alternate technology after ISCO treatment should be monitored. Application of ISCO can substantially change groundwater chemistry, impact the microbial community, and create byproducts that could impact other remedial technologies

4.4.3 Quality Assurance and Quality Control

QA/QC must be built into every project. The primary document pertaining to the installation of the ISCO 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
- Identify how deficiencies will be managed

In most cases, the contractor performing the installation of the system is responsible for the development 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.

4.5 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 Environmental Restoration Program Sites (DON, 2012) requires optimization and green and sustainable remediation (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 RGs, 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, 2010a); concepts for remedial design are summarized in Table 10.

The DON Guidance for Planning and Optimizing Monitoring Strategies (NAVFAC, 2010b) 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.

4.6 Sustainability

A sustainable ISCO 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 emissions; criteria air pollutant emissions;

water impacts; ecological impacts; resource consumption; worker safety; and community impacts. The use of SiteWise™ is now required by the DON during remedy evaluation and selection to quantify the effects of remedial actions. 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 overall impact during operation. 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.

Table 10. Remedial Design Optimization Concepts

Guidance and Considerations for ISCO 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 RGs 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 lifecycle 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., ISCO in the source zone and monitored natural attenuation 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 to meet RGs and ultimately RAOs
• The development and documentation of exit strategies for each component of the remedy and the remedy as a 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 environmental restoration process
• The cost-effectiveness of leasing equipment rather than purchasing and designing mobile remediation systems
• 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 sampling and analysis plan 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

A list of best management practices (BMPs) for improving the sustainability of ISCO projects during the design phase through construction and implementation is provided in Table 11. In addition, many resources are available on the topic of GSR, in particular, the DON Guidance on Green and Sustainable Remediation (NAVFAC, 2012b), and U.S. EPA's Green Remediation Primer (2008).

Table 11. BMPs for Improving the Sustainability of ISCO

Green and Sustainable Remediation BMPs for ISCO
Materials Management & Waste Reduction • Consider using one wellhead to serve more than one well during the injection periods; allows for portable injection wellheads to be used at each well location when needed • Consider additional characterization (high resolution and/or three-dimensional imaging) to optimize the TTZ in which injections are performed • Consider pilot-testing and optimizing the design such as more aggressive treatment for hot spots and source areas and less aggressive treatment for the plume area. Consider transitioning to a less intensive treatment such as monitored natural attenuation after a performance metric is achieved • Consider the appropriate amount of oxidant needed for adequate treatment; this will reduce significantly the amount of greenhouse gas emissions, as well as the amount of energy utilized as the environmental footprint is primarily driven by the manufacturing of the oxidant • Consider the carbon footprint of oxidants during the selection process. Footprints of the most commonly used oxidants include: hydrogen peroxide, 1.2 tons carbon dioxide (CO_2) per ton; sodium persulfate, 1.25 tons CO_2 per ton; potassium permanganate, 4 tons CO_2 per ton (Siegrest et al., 2011) • Consider reusing existing wells for injections and monitoring to the extent practical • Consider the use of existing buildings instead of new construction, where feasible, for housing ISCO equipment • Recycle routine waste and recycle or salvage scrap material during construction and demolition. • Consider using "green" concrete, which contains a percentage of re-purposed fly ash, where needed on site • Request electronic submittals of project documents rather than hard copies as much as possible to minimize use of materials as well as fuel for shipping
Optimize Equipment Use • Consider optimizing the use of equipment, particularly the use of the DPT drill rig, and even the type of equipment used during injection operations • Consider sizing and maintaining equipment properly for the intended use so that it will perform efficiently. • Consider the use of 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, and 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)
Energy Use • Consider optimization of electricity usage by generators. This optimization can be achieved by either changing generators (model, size) or considering another type of fuel. The use of renewable sources of energy (if possible) could be an option • Consider the use of high-efficiency or premium-efficiency motors for systems that operate continuously. • Consider the use of variable frequency drives instead of fixed-speed drives for pumps, compressors, etc. to improve energy efficiency • If high-pressure injection is not necessary for proper distribution of amendments in certain geologic

Table 11. BMPs for Improving the Sustainability of ISCO (Continued)

Green and Sustainable Remediation BMPs for ISCO
units, consider using gravity feed • Use energy efficient lighting for site trailers and buildings
Transportation • Consider ways to reduce vehicle mileage to reduce worker risk as well as energy use and emissions • Encourage site workers to carpool daily to the site to reduce total vehicle mileage. The impacts from transportation of personnel could be lowered if the use of alternative fuels or fleet of vehicles is possible • Consider reduction in transportation use; number of trips for mobilization, operation and monitoring and scheduling simultaneous tasks • Employ qualified local contractors, material suppliers and subcontractors for drilling, injections, etc. to minimize travel requirements • Use remote sensing or telemetry to monitor groundwater to the extent practical to reduce transportation to the site • Hold virtual meetings to avoid unnecessary travel • Use rail transportation, if available, rather than trucks for shipping equipment and/or supplies that are needed in large amounts to reduce carbon dioxide emissions
Alternative Fuel • Consider the use of green fuel (e.g., biodiesel or ultra-low sulfur diesel) for DPT drill rigs, trucks other electric or hybrid transportation for smaller vehicles • Consider alternative sources of energy (such as solar, photovoltaics, wind power, micro turbines if possible) to reduce the load of generating electricity through the grid for ISCO 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
Emission Control Measures • Consider implementing emission control methods such as after treatment technologies on DPT drill rigs, trucks. Examples of after-treatment technologies include: diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reduction (SCR), and/or diesel multistage filter (DMF) • Implement idle control on chemical delivery trucks, field trucks and other operating strategies to improve efficiency of site activities • Consider minimizing the use of heavy equipment that requires large amounts of fuel • Reduce the atmospheric release of toxic or priority pollutants during recirculation of contaminated groundwater
Monitoring Program • Design an optimized sampling schedule that minimizes the number of samples, trips and analysis, given that the laboratory analytical services are one of the major drivers in some of the impact categories • Consider periodically re-evaluating and optimizing the monitoring program as treatment progresses and the plume size and concentration decreases; optimizing could include reducing sample analyses, sample frequency, and/or the number of sample locations • Consider the use of passive sampling devices for groundwater monitoring to use less energy and generate less waste
Optimize Water Consumption • Consider the optimal use of injection water during the implementation • Consider the beneficial re-use of extracted groundwater as makeup water for additional injections to minimize fresh water consumption • Protect any nearby and downstream surface water to avoid impacts from accidental spills

Table 11. BMPs for Improving the Sustainability of ISCO (Continued)

Green and Sustainable Remediation BMPs for ISCO
Ecosystem Protection • Use minimally invasive ISCO designs, where feasible • Minimize 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
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 ISCO system construction, chemical delivery and implementation

5.0 DRAWINGS

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

- **Site layout drawing**: Depicting existing infrastructure, nearby receptors, and the proposed treatment area
- **TTZ schematic**: Depicting the horizontal (and vertical) extent of the plume and portions that will be impacted by the remedy. COC architecture
- **Injection location drawings**: This can be a combination of two-dimensional and three-dimensional drawings depicting the locations of the injection extraction, and monitoring wells and screened intervals in relationship to the lithology and COCs present in the TTZ should be provided
- **Well and/or injection point design**: Includes all pertinent construction and design details
- **Process and instrumentation diagram for aboveground portion of injection and treatment equipment**: This drawing is of particular importance when recirculation systems are applied 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, ISCO projects require conceptual level drawings, which can be prepared using a variety of graphic design software. However, design-build contracts, for which Uniform Federal Criteria (UFC) specifications may be required, must follow the requirements documented in the Uniform Federal Criteria Design Procedures (Department of Defense, 2011), which is explained in further detail in Section 6. Drawings should be provided in both the native format in addition to 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 (PE) or a Professional Geologist (PG), registered in the state where the ISCO project will be conducted, may be required to sign and seal the drawings.

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6.0 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 ISCO 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 ISCO design.

Table 12. UFGS Relevant to ISCO Design

Division	Name	Title	Revision Date
General	UFGS 01 35 45.00 20	Chemical Data Quality Control	04/06
	UFGS 01 50 00	Temporary Construction Facilities	08/09
	UFGS 01 78 23	Operation and Maintenance Data	07/06
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 62 16	Commissioning and Demonstration for Soil Vapor Extraction Systems	02/10
Plumbing	UFGS 22 10 00.00 10	Vertical Pumps, Axial-Flow and Mixed-Flow Impeller-Type	07/07
	UFGS 22 11 23.00 10	Submersible Pump, Axial-Flow and Mixed-Flow Type	07/07
Utilities	UFGS 33 24 13	Groundwater Monitoring Wells	08/08
	UFGS 33 24 00.00 20	Extraction Wells	04/06
Process Gas and Liquid Handling, Purification and Storage Equipment	UFGS 43 11 00	Fans/Blowers/Pumps; Off-Gas	04/08
	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

Some activities have modified UFGS for their region. These specifications are available on the WBDG Web site. These specifications contain local requirements, which are not necessarily imposed across all NAVFAC installations. In addition, a number of standards are available from various organizations that relate to the design, application, and monitoring of ISCO remedies. For instance, ASTM has developed many standards pertaining to drilling, sampling various media, and performing a wide-variety of analyses. ASTM D 7262 is a standard test method for estimating the NOD of soil exposed to permanganate.

In some instances, it may not be necessary to adhere to the UFC system for design and construction of ISCO remediation projects. At many sites, the design of ISCO 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 2.0, a 35 to 50% design may be satisfactory for ISCO 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.

7.0 SCHEDULE

A schedule for implementing the remedy must be included as part of the design. Table 13 lists milestones for a hypothetical ISCO project for which three injection events are required. 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 anticipated. Both can vary from project to project and from state to state. In addition, time must be allotted between injections and after the final injection to monitor changes in groundwater chemistry and rebound of COCs.

Table 13. Typical Schedule Milestones for ISCO Design and Implementation

Example Milestones
Submittal and Acceptance of 30%, 60%, 90%, and 100% Designs
Completion of Site Preparatory Activities
Completion of First (Second and Third) Injection Event
Completion of First (Second and Third) Groundwater Monitoring Event
Completion of First, Second, Third, and Fourth Quarterly Post-ISCO Monitoring Events
Submittal and Acceptance of Remedial Action Completion Report

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