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DESIGN AND QUALITY ASSURANCE/ QUALITY CONTROL CONSIDERATIONS FOR IN SITU CHEMICAL OXIDATION

By
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Battelle

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The purpose of this document is to provide a framework for design submittals of in situ remedial systems using the in situ chemical oxidation (ISCO) technology. The document provides a summary of best practices for ISCO design, tips for appropriate quality assurance and quality control (QA/QC) measures, and links to available standards and references.

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ACRONYMS AND ABBREVIATIONS

ARTT	Alternative Restoration Technology Team
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing Materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CLEAN	Comprehensive Long-Term Environmental Action Navy
COC	contaminant of concern
CORT3D	Chemical Oxidation Reactive Transport in 3-D
CQC	construction quality control
CSC	Construction Specifications Canada
CSI	Construction Specifications Institute
CSM	conceptual site model
DB	Design-Build
DBB	Design-Bid-Build
DO	dissolved oxygen
DON	Department of Navy
DPT	direct push technology
FEAD	Facilities Engineering and Acquisition Division
ISCO	in situ chemical oxidation
ITRC	Interstate Technology and Regulatory Council
NAPL	non-aqueous phase liquid
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
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

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 and other conventional environmental or non-environmental systems (e.g., pump and treat systems, water and wastewater treatment systems, and landfill covers); therefore, design information, formats, and standards are generally not as readily available and consistent as those of conventional systems. 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 in situ remedial systems using ISCO technology. The document provides a summary of best practices for ISCO design, tips for appropriate quality assurance and quality control (QA/QC) measures, and links to available standards and references. The ultimate goal is to assist in the development of improved and consistent design submittals within the Department of Navy (DON) Environmental Restoration Program.

This document was developed by the Alternative Restoration Technology Team (ARTT). It incorporates lessons learned on the design and implementation of ISCO at Navy sites. The information described here can be used in several design formats including draft, draft final, and final designs as defined in project deliverables or in formal design packages following a Naval Facilities Engineering Command (NAVFAC) Master Format.

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 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 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.

Because of the simpler 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 the 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 Navy 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. 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 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.

Table 1. Key CSM Elements for ISCO Applications

CSM Element	Description
Nature and extent of contamination	Determine horizontal and vertical distribution of COCs including presence of non-aqueous phase liquids (NAPLs). Dictates the horizontal and vertical locations to introduce oxidants.
Human and ecological health risks	Consider risks presented by COCs, as well as risks associated with the introduction and persistence of the oxidants (which can influence treatment goals, number of applications required, etc.)
Fate and transport of the COCs	Determine how it impacts the location of injections, concentrations of oxidants, flow rates, and 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 influence injection locations and overall strategy.
Hydrogeology	Understand lithology (lithologic units, heterogeneities, grain size, permeability, presence of bedrock, etc.), hydrogeology (gradients, confined or unconfined conditions, saturated thickness, conductivities, flux, Darcy velocity, anisotropy, etc.), and mineralogy (e.g. could contribute to metal mobilization), which are key factors to determine the approach that will be used to introduce the oxidants into the aquifer.
Hydrogeochemistry	Document distribution coefficients (K_d), pH, and buffering capacity

Several of these elements can have a significant impact on ISCO design and introduction and distribution of ISCO reagents into the subsurface. Some of the more common impacts are listed in Table 2.

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 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 or sorbed contaminants	• Impacts oxidant demand • Contributes to substantial rebound if only dissolve phase is treated • Contributes to matrix 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 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 • 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 potentially causing reagents to flow into undesirable locations (e.g., streams, sewers) rather than contacting the CoCs • 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

3.2 Remedial Action Objectives and Remedial Performance Goals

Remedial action objectives (RAOs) are site-specific goals that are formed based on the nature, extent, and fate and transport of COCs, the impacted media, and those 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 requiring a particular remedial technology to be operated until final remediation goals are achieved.

Treatment goals are endpoints that must be achieved to ultimately achieve the remediation goals for the site. These endpoints are interim goals and typically apply to one particular part of the treatment train. These endpoints should be realistic, achievable, and flexible enough to respond to situations where it becomes impracticable to achieve a particular remedial goal due to site-specific constraints. One of the most important treatment goals for ISCO applications is to demonstrate that a sufficient quantity of oxidant (and any activator) has been delivered at sufficient concentrations and distributed successfully into the target treatment zone.

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 ARTT 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 that 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).

4.0 KEY DESIGN ELEMENTS

This section discusses key design elements related to oxidant selection, the development of an injection plan, and planning for QA/QC measures. This summary of 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 evaluating reaction chemistry 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 are not easily scalable 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, and potential incompatibilities with site activities or infrastructure (e.g., heat and gas generation, pH changes, etc.). 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. However, they are more costly and time consuming to implement. The information gathered during the pilot test includes determination of optimum injection flow rates and pressure, radius of influence (ROI), geochemical impacts to aquifer, and the potential for rebound.

4.2 Oxidant Selection

Common ISCO reagents include hydrogen peroxide, sodium persulfate, potassium permanganate, sodium permanganate, and sodium percarbonate. There are a number of guidance documents available to aid the practitioner to select 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 (Interstate Technology and Regulatory Council [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. 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 • Natural organic matter (NOM) has a large natural oxidant demand, which can limit distribution of peroxide due to reactions in the immediate vicinity of the injection • May require injection and distribution of additional reagents to activate (iron and acid or chelating agent[1]) which must also be distributed into the aquifer • If significant heat is generated in the subsurface, it may be necessary to use materials other than polyvinyl chloride to construct injection and monitoring wells
Persulfate	• Highly corrosive. 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) • The presence of naturally-occurring carbonate or bicarbonate has been noted to reduce

[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 EDTA are used to bind ferrous iron to maintain its solubility.

Table 3. Design Considerations for the Application of ISCO Reagents (Continued)

ISCO Reagent	Injection/Distribution Design Considerations and Challenges
	oxidation rates, which could impact distribution • Being the most recent of the oxidants to be applied, there is less of a knowledge-base of specific factors that may impact transport and distribution
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 so not applicable to some COCs.

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 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. Since the ability of distributing the treatment reagents is site-specific, it is preferred that the injection 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:

- 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;
- Treatment well/point spacing and layout, ensuring that the wells 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). Drawings also must be included that depict the extent of the plume, the extent of the TTZ, and the locations of injection and extraction wells/points that may be used;
- Specifications for pumps, tanks, and ancillary equipment that will be used during the injection process;
- A description and operational procedures for the method that will be used to introduce the oxidants into the aquifer;
- A description of the monitoring program to evaluate the effectiveness of the injection strategy; and
- Appropriate endpoints and milestones for effective oxidant delivery and distribution.

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 volume, concentration, and frequency of introductions into the aquifer. Insufficient loading rates increase the probability that the oxidant will not be adequately distributed and reduce the likelihood of achieving RAOs. Conversely, excess oxidants and activating agents can create undesirable changes in the aquifer such as plugging the formation with insoluble reaction products, changing aquifer pH, 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 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 aquifer properties including total organic carbon, hydraulic conductivity, anisotropy; chemical and physical properties of the reagents and aquifer material including viscosity, density, solubility, sorption coefficients, natural oxidant demand, etc.; reaction kinetics and thermodynamics of the system; 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., concentrations of activating agents). Results of these tests are used to determine the optimal oxidant concentration 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 oxidant type and the injection design. A checklist for determining oxidant dosing is provided in Table 4.

Table 4. General Guidance for Determining Reagent Dosing

Guidance and Considerations for Reagent Dosing and Longevity
• Perform bench- and pilot-scale tests using site groundwater and aquifer material • Determine the number of PV that will be injected or recirculated for ISCO reagents. A pilot-test can be performed to determine optimum number of PVs, as well as reagent concentrations and flow rates. • Evaluate tradeoffs between concentration of reagents, injection flow rate, and number and frequency of injections. For instance: o Highly reactive oxidants may need to be introduced at a greater flow rate (or concentration) to minimize the likelihood of consumption to an unacceptable level at the design ROI due to non-target reactions o A low concentration and possibly continuous flow rate may be appropriate for soluble compounds, especially if the groundwater velocity is high 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 injection events may allow time between events for oxidants to passively diffuse into the aquifer matrix and also allow a significant back diffusion from the aquifer matrix to occur • 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 NOM; o It is not desirable to mix peroxide with an activator aboveground prior to injection due to the fast kinetics and exothermic nature of the reaction 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. • Consider potential impacts of overdosing (health and safety concerns, fouling, groundwater chemistry changes, formation of adverse byproducts, impacts to distribution, proximity to water supplies and other sensitive eco systems, etc.)

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 three 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.

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 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. Table 5 lists some considerations associated with each type of injection strategy.

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. Site-specific considerations that impact the ROI and should be considered during the design include:

- Oxidant reaction kinetics
- Oxidant concentration
- Soil retardation factors
- Injection flow rate
- PV of 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)

Table 5. Injection Strategy Considerations

Consideration	Direct Injection	Recirculation	Pull Push[(a)]
Ability to hydraulically control fluids	Has greater potential for "pushing" 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
Need for source of water	Requires a source of water is available for mixing reagents	Extracted water can be amended with oxidant and reinjected	Extracted water can be amended with oxidant and reinjected
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 mob/demob to multiple locations
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
Need for above ground treatment	Relatively little aboveground equipment required	Aboveground tanks and mixing equipment required	Aboveground tanks and mixing equipment required
Ability to achieve mixing of reagents and contact with COCs	Difficult to ensure adequate contact and mixing of reagents with contaminated groundwater	Aboveground mixing and treatment of COCs easily achieved	Aboveground mixing and treatment of COCs easily achieved

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

There are a number of available design tools and models that the practitioner may 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 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; 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. 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 typically is 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	• Low cost • We well-suited for consolidated materials • Injection locations can be easily changed or added during application based on real time observations	• 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
Permanent 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 flow rates due to formation material	• High cost • Additional wells may be required if real time observations dictate contamination in other areas or radius of influence is limited, etc. • Fouling 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 them
- Locations of all of the injection wells and points and the design basis for selecting them
- 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 flow rate, 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, and in-line mixers. A variety of flow and pressure measuring devices also are used to monitor 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:

- Equipment is chemically compatible with the oxidants and any activating agents 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 shower, fire extinguisher, etc. is specified appropriately based on the oxidants and activators that will be present on site.
- Green and sustainable remediation practices are incorporated into the design as applicable

Useful design information may be found in a number of locations. Several sources include:

- 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.

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[2]ASTM provides a wide-range of specifications for pumps and other types of equipment.

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 introducing the reagents. Parameters such as design pressures, flow rates, and other key operational parameters should be included
- Procedures to ascertain and mitigate potential surfacing of reagents
- If multiple injection events are required, procedures for addressing fouling of well screen should be included
- Procedures to ensure the health and safety of workers and the surrounding community
- Monitoring requirements, procedures, and required equipment (see Section 4.4)
- 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) determine when it is appropriate to discontinue all applications and transition to a less aggressive technology or site closure. Endpoints may be based on completing a specific portion of the process or plan or may be based on achieving a specific response in the aquifer that results from applying the oxidants. An endpoint may be defined as achieving a specific concentration of contaminant of concern 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.

4.4 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, it provides metrics to evaluate the efficacy of the injections, and it provides 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
- Applicable milestones
- Contingency triggers (i.e., additional injections, alternate technology) in the event that milestones are not being achieved
- Specific criteria that define the endpoint of the technology that is being applied.

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 lb of persulfate into each of 20 points	Complete injection of 1,000 lb of persulfate into 5, 10, 15, and 20 points	Mass of persulfate injected into each point
	Perform recirculation of groundwater until three PV (100,000 gal) have been exchanged	Exchange 25, 50, 75, and 100% of total	Volumetric flow rate
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 to a defined (reasonable) value	Achieve a specified reduction(2)	Changes in concentrations in monitoring wells

(1) Additional milestones, such as those listed above (i.e., achieve a specified pore volume 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.

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 ISCO. Design guidance for both types of monitoring is provided in the remainder of this section.

4.4.1 Tips for Inspection and Process Monitoring

Process monitoring involves observing and measuring parameters that provide information on the state of the remedial action during implementation. For application of ISCO, this consists of confirming that the oxidant is introduced and distributed into the aquifer according to the design. Changes in physical parameters such as pressures, temperatures, flow rates, 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 dissolved oxygen (DO), oxidation-reduction potential (ORP), pH, and conductivity are measured to evaluate the distribution of oxidants and the need to perform additional injections.

Typical process monitoring techniques and their intended purpose are presented in Table 8. 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.

4.4.2 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 that will perform 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) also are developed. The QAPP should comply with the *Uniform Federal Policy for Quality Assurance Project Plans Manual* (U.S. EPA, 2005). 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 will depend on the complexity of the project.

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 • 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 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 flow rate 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 • Concentrations in monitoring wells to evaluate distribution 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 exothermic (e.g., hydrogen peroxide). Application should be discontinued if groundwater temperature cannot be controlled
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 spectrophotometer	• Provides a line of evidence to assess distribution of oxidant and changes due to oxidation of organic matter
Metal concentration	Colorimetric kits 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 generates a substantial volume of gas, which can volatilize COCs and transport them to ground surface. • Monitor for potential vapor intrusion

Table 9. Performance Monitoring Checklist

Considerations	Monitoring Recommendations
Are there any nearby receptors?	Installation and monitoring of sentinel wells 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, 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-ISCO events will be required to establish a trend in concentrations of COCs
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?	Monitoring parameters that impact alternate technology and are affected by ISCO. Application of ISCO can substantially change groundwater water chemistry, impact the microbial community, and create byproducts that could impact other remedial technologies

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
- **Target treatment area schematic**: Depicting the horizontal (and vertical) extent of the plume and portions that will be impacted by the remedy.
- **Injection 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 also may be included.
- **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 (DOD, 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.

6.0 SPECIFICATIONS AND STANDARDS

This section provides an overview of key design requirements for projects involving review by the Facilities Engineering and Acquisition Division (FEAD) and RPMs. FEAD requires adherence to the UFC system. The UFC system is prescribed by MIL-STD-3007 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.

An archive of NAVFAC UFC documents is maintained at the Whole Building Design Guide (WBDG) Web site at http://www.wbdg.org/ndbm/design_guidance.php. Of the numerous UFCs available, there are two in particular that are directly applicable to ISCO projects that will be reviewed by FEAD. The first is UFC 1-300-09n (revised February 9, 2011), 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 Request for Proposals for shore facilities, and is applicable to both DBB and DB projects. Specifically, UFC 1-300-09n provides standardized design guidance pertaining to:

- Requirements for requests for proposal for design-build projects,
- Specifications for construction drawings,
- UFG Specifications,
- Contract Line Item requirements,
- Electronic design deliverable requirements, which also includes drawing requirements and specifications,
- Design review and submittal requirements.

The second UFC document that applies to environmental restoration projects is UFC 3-800-10n, Environmental Engineering for Facility Construction (Final Draft July 2006). This document provides environmental engineering design and analysis criteria for design-build projects. Requirements and specifications pertaining to environmental issues such as lead, asbestos, tank removal, contaminated soil and groundwater assessments are provided.

The UFC system incorporates MasterFormat™ specification templates, which are publications of the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC). MasterFormat™ is a standardized list of titles and numbers used to organize specifications and other project information for most commercial building design and construction projects. MasterFormat™ consists of 50 Specification Groups (referred to as Divisions), 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.

The MasterFormat™ prescribes that each specification is divided into three principal sections including:

- **Part 1. General –** Provides background information for the specification such as administrative, procedural, and quality assurance requirements
- **Part II. Products –** Describes equipment, materials, and products that are to be used in the project
- **Part III. Execution –** Describes how the products will be incorporated into the project

NAVFAC, Army Corps of Engineers, and National Aeronautics and Space Administration use a software package, SpecsIntact, to facilitate preparation of government facility construction projects using MasterFormat™ specifications. SpecsIntact is available for download at http://www.wbdg.org/tools/specsintact.php. As mentioned above, contractors may be required to use this system to develop specifications for DBB and DB projects and could be requested to do so for other types of contracts at the discretion of the Navy RPM and/or FEAD. Examples of MasterFormat™ specifications that are common to ISCO projects and available through SpecsIntact are provided in Table 10. Table 10 is not a comprehensive list; other specifications may apply to various aspects of the ISCO design.

Some activities have modified UFG specifications for their region. These specifications are available on the WBDG Web site at http://www.wbdg.org/ccb/browse_cat.php?o=3&c=43. These specifications contain local requirements, which are not necessarily imposed across all NAVFAC installations.

In some instances, it may not be necessary to adhere to the UFC system for design and construction of ISCO remediation projects. However, 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, airplane, 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.

Table 10. UFG Specifications Relevant to ISCO Design

Division	Name	Title	Revision Date
General	01 35 45.00 20	Chemical Data Quality Control	04/06
	01 50 00	Temporary Construction Facilities	08/09
	01 78 23	Operation and Maintenance Data	07/06
Existing Conditions	02 32 00	Subsurface Drilling, Sampling, and Testing	05/10
	02 61 13	Excavation and Handling of Contaminated Material	02/10
	02 62 16	Commissioning and Demonstration for Soil Vapor Extraction Systems	02/10
Plumbing	22 10 00.00 10	Vertical, Axial-Flow and Mixed-Flow Impeller Pumps	07/07
	22 11 23.00 10	Submersible, Axial-Flow and Mixed-Flow Pumps	07/07
Utilities	33 24 13	Groundwater Monitoring Wells	08/08
	33 24 00.00 20	Extraction Wells	04/06
Process Gas and Liquid Handling, Purification and Storage Equipment	43 11 00	Fans/Blowers/Pumps; Off-Gas	04/08
	43 21 13	Pumps: Water, Centrifugal	01/08
	43 32 69	Chemical Feed Systems	04/06
	43 41 16 16 40	Vertical Atmospheric Tanks and Vessels	02/11

In addition to the MasterFormat™ specification templates and the UFC system described above, there are a number of standards available from various organizations that relate to the design, application, and monitoring of ISCO remedies. For instance, the American Society of Testing Materials (ASTM) has developed many standards pertaining to drilling, sampling various media, and for performing a wide-variety of analyses. For instance ASTM D 7262 is a standard test method for estimating the natural oxidant demand of soil exposed to permanganate.

DoD-specific design criteria are available on the WBDG Web site (http://www.wbdg.org/ccb/browse_cat.php?o=29&c=4) and from the Construction Criteria Base Web site (http://www.wbdg.org/ccb.). In addition, other standards may apply such as those by the American Society of Mechanical Engineers (ASME).

7.0 SCHEDULE

A schedule for implementing the remedy must be included as part of the design. Table 11 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 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 injections and after the final injection to monitor changes in groundwater chemistry and rebound of COCs.

Table 11. 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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