Principles and Practices of In Situ Chemical Oxidation
A Short Course Delivered at the SERDP/ESTCP Symposium
Washington, D.C.
December 1, 2010

Supplementary Handout Materials

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Figures in handout and presentation are from:

Siegrist, R.L., M. Crimi, T.J. Simpkin (eds) (2011). In Situ Chemical Oxidation for Groundwater Remediation. Springer Science+Business Media, LLC, New York, New York. A volume in SERDP/ESTCP Remediation Technology Monograph Series, C.H. Ward (Series ed). http://www.springer.com/environment/environmental+management/book/978-1-4419-7825-7

Ia. CD Introduction

In Situ Chemical Oxidation for Groundwater Remediation

Site Specific Engineering and Technology Application

ESTCP project ER-0623

CD Purpose

This CD contains materials and tools concerning in situ chemical oxidation (ISCO) and represents the culmination of DoD's ESTCP Project ER-0623, *"In Situ Chemical Oxidation for Remediation of Groundwater – Technology Practices Manual"*. This project was completed during 2006 to 2009 as a collaborative effort between a team of academics, environmental consultants, and agency personnel associated with the Colorado School of Mines, CH2MHILL, Clarkson University, and the Navy. The enclosed CD is the first public release version of a CD (PRv1) that contains the site-specific engineering and technology application materials and tools developed through ER-0623.

PRv1 has been prepared after a series of reviews of the individual materials and tools as well as two preliminary versions of an interactive CD. PRv1 is intended for general dissemination and public distribution at this time.

In addition to, and extending the outcome of ER-0623, beyond the ISCO CD there is a new ISCO reference book.[1] This book is being edited by members of the ER-0623 project team and includes 14 chapters on the principles and practices of ISCO, which are being authored by writing teams composed of ER-0623 project team members and other experts from the U.S. and abroad. Chapters have been prepared and subjected to independent peer review.

CD Use and Navigation

The files on this CD require Adobe Acrobat v6 (or higher), and Microsoft Excel 2003 (or higher). This CD is compatible with either Microsoft Windows or Macintosh operating systems (excluding the CORT3D model program which requires a Microsoft Windows operating system). All PDF files are password protected to allow printing, but no editing. All Excel files are unprotected enabling the user to manipulate and alter the contents of the file (excluding CDISCO which is protected). These spreadsheet tools must be copied from the CD onto the user's personal computer and the macros enabled in order to function properly (note, some versions of Microsoft Office for Macintosh do not support visual basic macros). The PDF files have hyperlinks as either blue or green text that are intended to assist users as they move through the CD. The green hyperlinks allow users to open individual files with supporting information or the blue hyperlinks allow the user jump to specific discussion within the E-Protocol for Site Specific Engineering and Application. Hyperlinks to supporting tools and Excel files will open a separate window that must be closed manually by the user. At any time while viewing the contents of this CD, use the "alt" left arrow "←" key stroke to return to the previous view.

To begin using this CD, user's familiar with ISCO may simply click on any of the following hyperlinks in this file, or open individual files within the file folders. User's new to ISCO may want to walk through the individual sections as outlined below. The ISCO Master Index File within the E-Protocol file folder on this CD, contains the step by step guide for site specific engineering and application of ISCO.

[1]Siegrist, R.L., M. Crimi, T.J. Simpkin (eds). 2011. *In Situ* Chemical Oxidation for Remediation of Contaminated Groundwater. Springer Science+Business Media, LLC, New York, New York. Volume in the SERDP/ESTCP Remediation Technology Monograph Series, C.H. Ward (Series ed). In final preparation for publication and release in 2011.

CD Contents

1. **ISCO CD Introduction and User's Information (PDF file)**
2. **Frequently Asked Questions Concerning ISCO (PDF file)**
3. **E-Protocol for Site Specific Engineering and Application of ISCO (PDF file)**

ISCO Protocol
- IP.1 Introduction
- IP.2 How to Navigate This Electronic Document
- IP.3 Terminology Used in This Document
- IP.4 Figure and Table Numbering Convention

ISCO Screening
- S.1 Introduction
- S.2 Screening Process 1: ISCO Site Characterization Data Needs
  - Attachment 1: ISCO Site Characterization Needs (PDF)
- S.3 Screening Decision A: Is ISCO Relevant to Site COCs, Geology and Goals?
  - Attachment 2: ISCO Relevance to COCs, Geology, and Goals (PDF)
- S.4 Screening Decision B: Is the Conceptual Site Model Information Adequate?
  - Attachment 3: CSM Certainty Evaluation Tool (Excel)
- S.5 Screening Decision C: Are Pre-ISCO Processes Required, Previously Implemented, or Already Occurring?
- S.6 Screening Process 2: Consider Pre-ISCO Coupling Processes
  - Attachment 4: Pre-ISCO Coupling Processes (PDF)
- S.7 Screening Process 3: Selecting Oxidants and Injection Methods using the ISCO Screening Tool
  - Attachment 5: ISCO Screening Tool (Excel)
  - Attachment 6: ISCO Screening Tool User's Manual (PDF)
  - Attachment 7: Additional Screening Considerations (PDF)
- S.8 Screening Process 4: Determine if Value is Added by Coupling ISCO with Other Technologies
  - Attachment 8: ISCO Coupling Tables (PDF)
  - Attachment 9: ISCO Screening Tool Look-up Tables (PDF)
- S.9 Screening Decision D: Are Viable ISCO Options Available?
- S.10 Screening Decision E: Is Data Support Adequate?

ISCO Conceptual Design
- CD.1 Introduction
  - Note: Keep in mind the need to integrate regulatory requirements and information including: 1) applicable regulatory performance objectives and metrics, 2) use of existing data, and 3) building the regulatory submittal requirements using ISCO design components.
- CD.2 Conceptual Design Process 1: Select Target Treatment Zone
- CD.3 Tier 1 Conceptual Design
  - CD.3.1 Conceptual Design Process 2: Selection of Tier 1 Design Input Parameters
  - CD.3.2 Conceptual Design Process 3: Selection of Tier 1 Design Approach
    - CD.3.2.1 Conceptual Design Process 3a: Tier 1 Mass Balance Design Approach
      - Attachment 10: Oxidant Specific Design Considerations (PDF)
    - CD.3.2.2 Conceptual Design Process 3b: Tier 1 Design Tool Approach
      - Attachment 11: ISCO Spreadsheet Design Tool (CDISCO) (Excel)
      - Attachment 12: Sensitivity of CDISCO to Input Parameters (PDF)
  - CD.3.3 Conceptual Design Decision A: Is at Least One Technologically and Economically Feasible Option Available?
  - CD.3.4 Conceptual Design Process 4: Rank and Select Oxidant and Delivery Options
    - Attachment 13: Conceptual Design Ranking Tool (Excel)

CD.4 Tier 2 Conceptual Design
CD.4.1 Conceptual Design Decision B: Is Cost and Performance Confidence Acceptable?
Attachment 14: Contingency Planning Tool (Excel)
Attachment 15: Example Contingency Planning Exercise (PDF)
CD.4.2 Conceptual Design Process 5: Consider Additional Data Needs
Attachment 16: Laboratory Bench Testing for Oxidant Persistence (PDF)
Attachment 17: Laboratory Bench Testing for Contaminant Treatability and Byproducts (PDF)
Attachment 18: Field Pilot-Scale Testing Guidance (PDF)
CD.4.3 Conceptual Design Process 6: Consider Additional Modeling Needs
Attachment 19: Guidance for Additional Modeling Needs (PDF)
CD.4.4 Conceptual Design Process 7: Refine Design Considering Cost and Performance Factors
CD.4.5 Conceptual Design Process 8: Perform Feasibility Study Cost Estimate
Attachment 20: FS Cost Estimate Guidelines (PDF)
Attachment 21: FS Cost Estimate Exercise (PDF)

ISCO Detailed Design and Planning Process
DD.1 Introduction
DD.2 Preliminary Design Phase
DD.2.1 Detailed Design and Planning Process 1: Prepare Preliminary Basis of Design Report
Attachment 22: Basis of Design Report Outline Example (PDF)
DD.2.2 Detailed Design and Planning Decision A: Is the Preliminary Design Basis Adequate for Detailed Design?
DD.2.3 Detailed Design and Planning Process 2: Identify Operational Objectives and Prepare Operation and Contingency Plan
DD.2.3.1 Operational Metrics and Objectives
DD.2.3.2 ISCO Treatment Milestones
DD.2.3.3 Contingency Plan
Attachment 23: Example of Operation Decision Logic (PDF)
DD.3 Final Design Phase
DD.3.1 Detailed Design and Planning Decision B: Is a Performance-Based Implementation Contract Feasible and Cost-Effective?
DD.3.2 Detailed Design and Planning Process 3a: Prepare Performance Specifications
DD.3.3 Detailed Design and Planning Process 3b: Prepare Detailed Design Specifications and Drawings
Attachment 24: Example Design Specifications and Drawings (PDF)
DD.3.4 Detailed Design and Planning Decision C: Is the Project Constructible and Biddable?
DD.3.5 Detailed Design and Planning Process 4: Perform Value Engineering or Design Optimization Assessment to Improve Constructability / Bidability
DD.3.6 Detailed Design and Planning Process 5: Prepare Construction Cost / Engineer's Estimate
DD.3.7 Detailed Design and Planning Decision D: Is the Projected Cost within Budget?
DD.3.8 Detailed Design and Planning Process 6: Perform Value Engineering or Design Optimization Assessment to Reduce Cost
DD.3.9 Detailed Design and Planning Process 7: Refine Operation and Contingency Plan, Performance Specifications, and Detailed Design Specifications and Drawings

DD.4 Planning Phase
DD.4.1 Detailed Design and Planning Process 8: Assemble Procurement Packages, Conduct Bid Process, and Select Contractors
DD.4.2 Detailed Design and Planning Process 9: Prepare Quality Assurance, Health and Safety, and Performance Monitoring Plans
DD.4.2.1 Quality Assurance Project Plan
Attachment 25: Elements of a Quality Assurance Project Plan Contents (PDF)
DD.4.2.2 Health and Safety Plan
DD.4.2.3 Performance Monitoring Plan
Attachment 26: Elements of a Performance Monitoring Plan (PDF)

ISCO Implementation and Performance Monitoring
IM.1 Introduction
IM.2 Implementation Phase
IM.2.1 Implementation and Performance Monitoring Process 1: Complete Pre-Construction Activities
IM.2.1.1 Injection Permitting
IM.2.1.2 Utility Clearance
IM.2.1.3 Potential Receptor Survey
IM.2.1.4 Engineering Controls for ISCO Implementation
IM.2.1.5 Administrative Activities
IM.2.1.6 Health and Safety Preparations
IM.2.2 Implementation and Performance Monitoring Process 2: Install ISCO Implementation Infrastructure and Complete Baseline Monitoring
IM.2.2.1 ISCO Infrastructure
Attachment 27: Infrastructure Construction and Delivery Effectiveness QA/QC Guidelines (PDF)
IM.2.2.2 Baseline Sampling
IM.2.3 Implementation and Performance Monitoring Decision A: Do Baseline Monitoring Results Confirm the CSM and Affirm the Path Forward?
IM.2.4 Implementation and Performance Monitoring Process 3: Refine the CSM
IM.2.5 Implementation and Performance Monitoring Decision B: Are Site Conditions Significantly Different to Require Re-design?
IM.2.6 Implementation and Performance Monitoring Process 4: Review and Modify Operation and Contingency Plan to Account for Learned Site Conditions
IM.2.7 Implementation and Performance Monitoring Process 5: Initiate Operation Plan Including Delivery and Treatment Performance Monitoring
IM.3 Delivery Performance Monitoring Phase
IM.3.1 Implementation and Performance Monitoring Decision C: Are Delivery Monitoring Results Meeting Performance Criteria?
IM.3.2 Implementation and Performance Monitoring Process 6: Execute Delivery Contingency Plan
IM.3.3 Implementation and Performance Monitoring Decision D: Are Modification Achieving Delivery Performance Milestones?
IM.4 Treatment Performance Monitoring Phase
IM.4.1 Implementation and Performance Monitoring Process 7: Implement Treatment Performance Monitoring Program
IM.4.2 Implementation and Performance Monitoring Decision E: Are Treatment Monitoring Results Meeting Performance Criteria?
IM.4.3 Implementation and Performance Monitoring Process 8: Execute Treatment Contingency Plan
IM.4.4 Implementation and Performance Monitoring Decision F: Are Modifications Achieving Treatment Performance Milestones?
IM.4.5 Implementation and Performance Monitoring Decision G: Have Treatment Goals Been Achieved?

References

4. **DISCO - Database of Field Applications and Experiences with ISCO sites (PDF file)**
5. **Supplementary Information and Tools**
   a. **Annotated Review of the ISCO Literature**
      S1. Literature Review Summary (PDF file)
      S2. Annotated Literature Review Tables (Excel file)
   b. **S3. ISCO Technology Practices Workshop - Summary Proceedings (PDF file)**
   c. **CORT3D Numerical Model for Permanganate ISCO**
      S4. CORT3D User's Guide (PDF file)
      S5. CORT3D Model Program (Install) (Microsoft Windows required)

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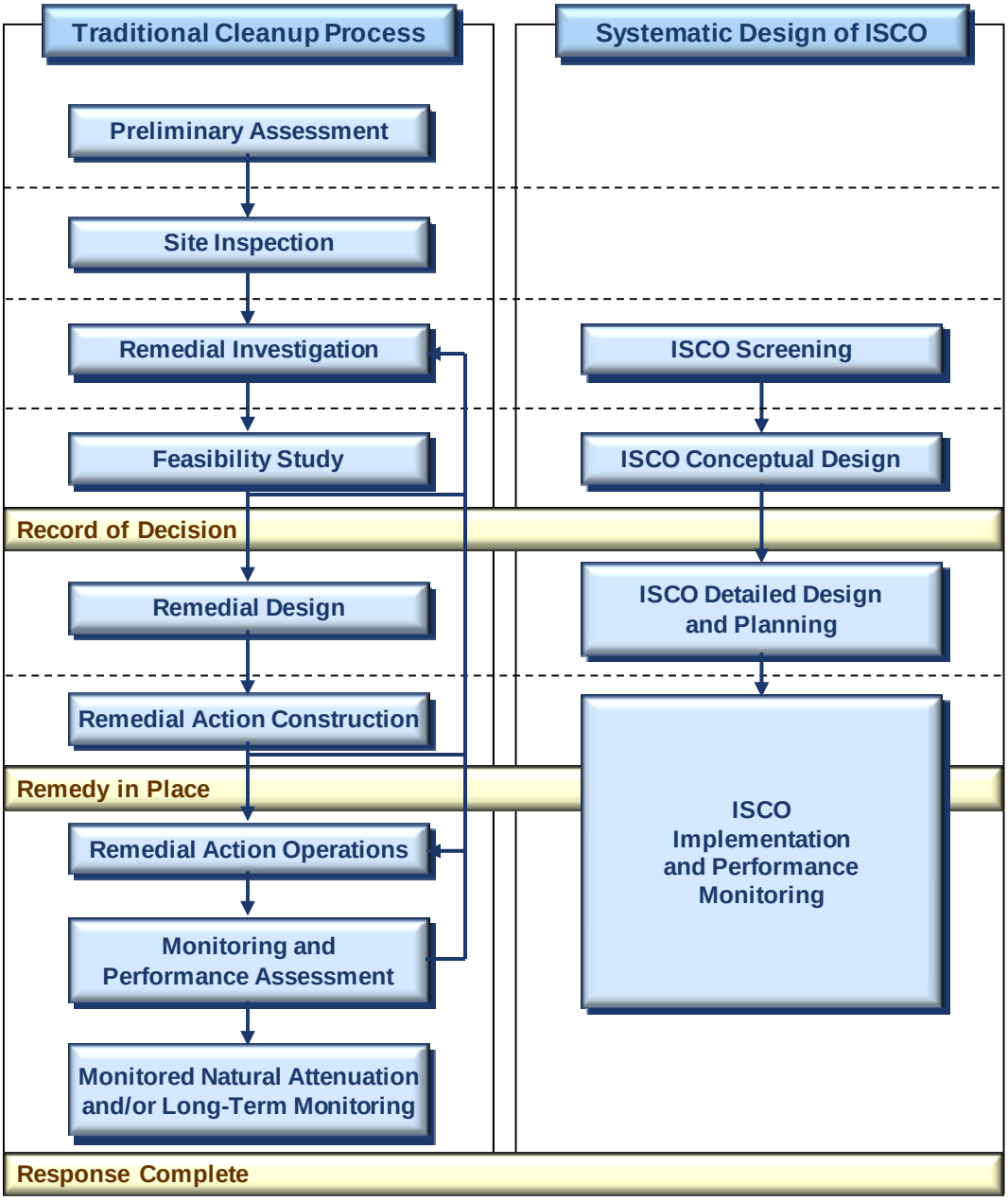
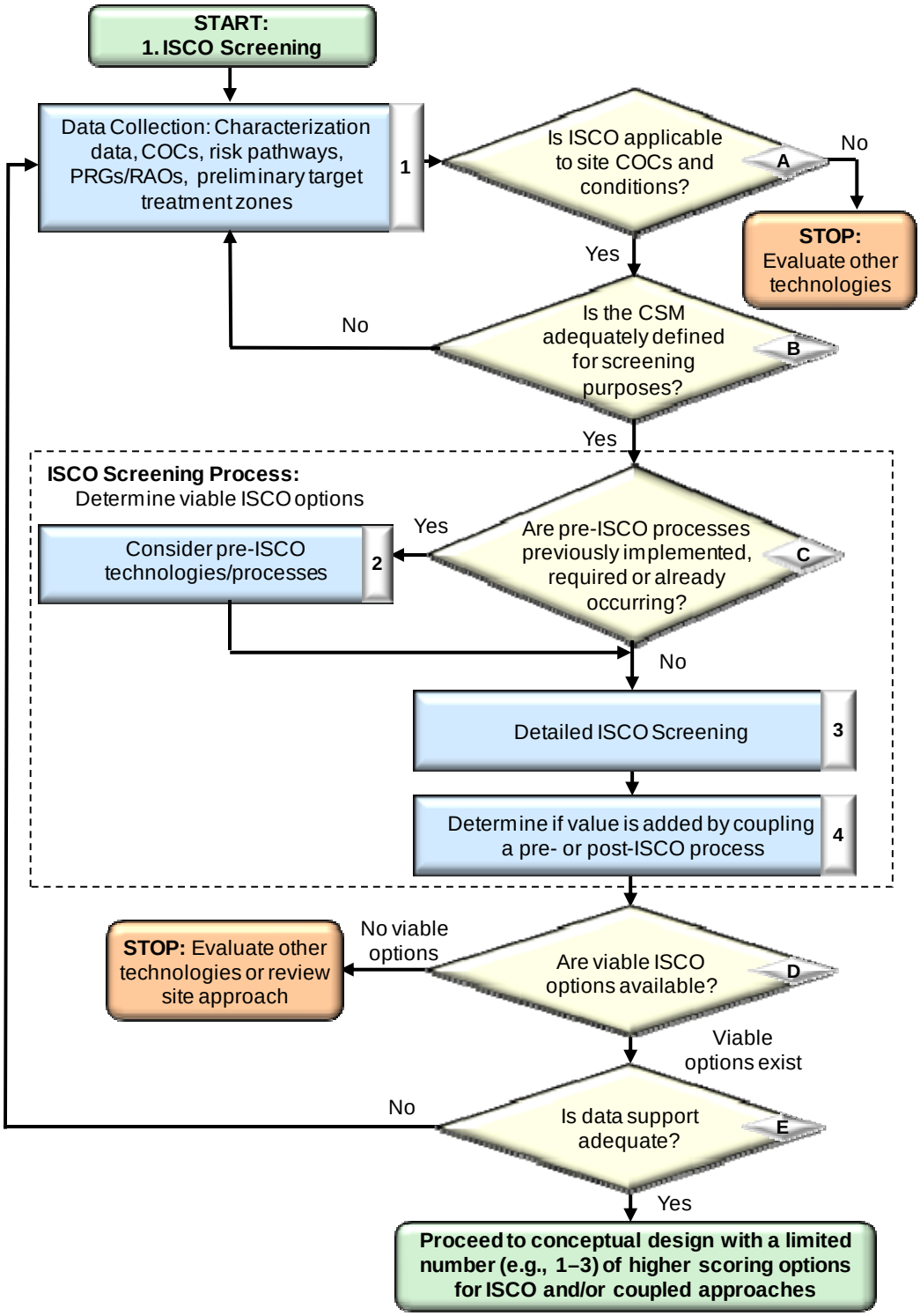
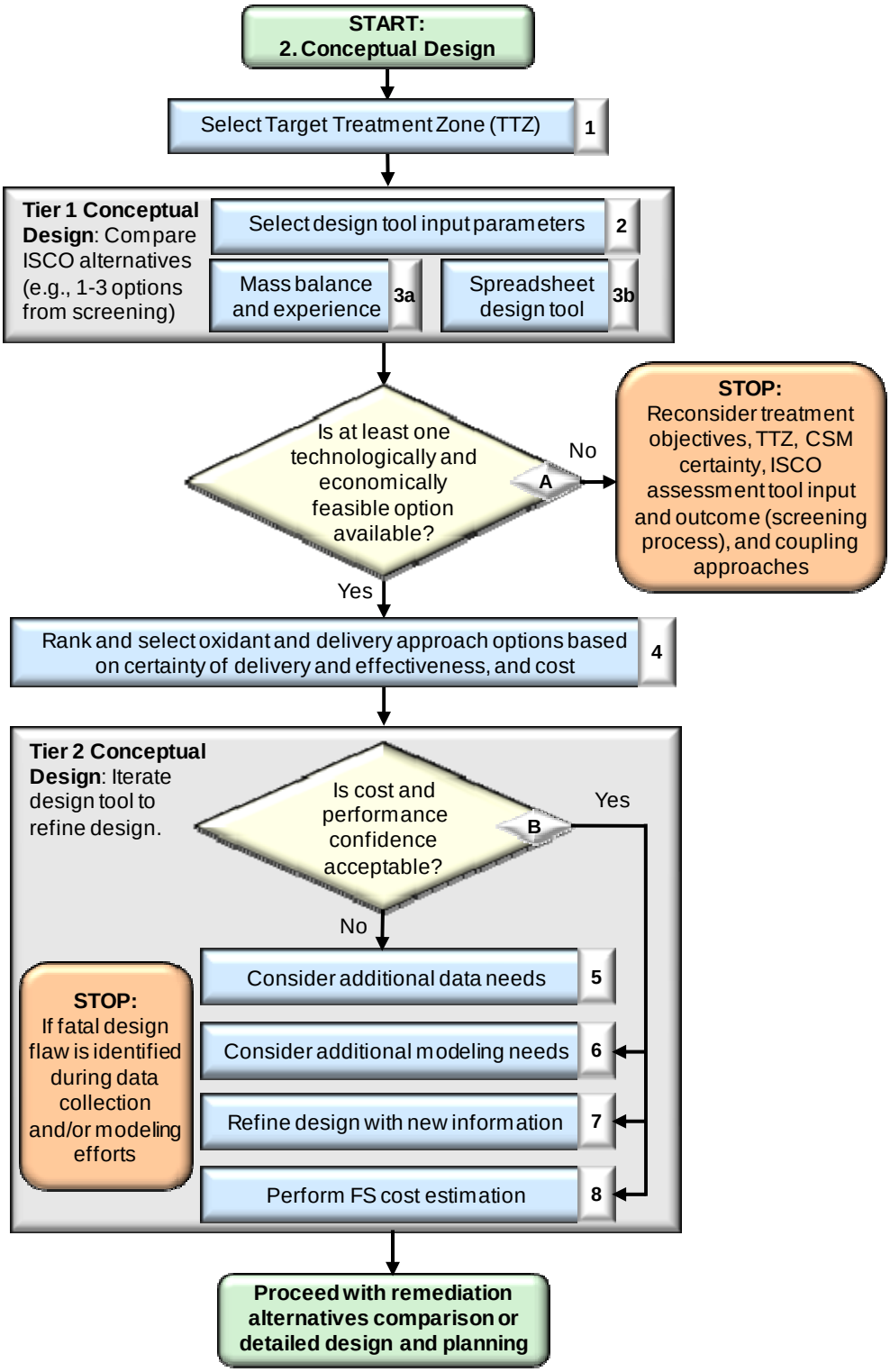
Disclaimer

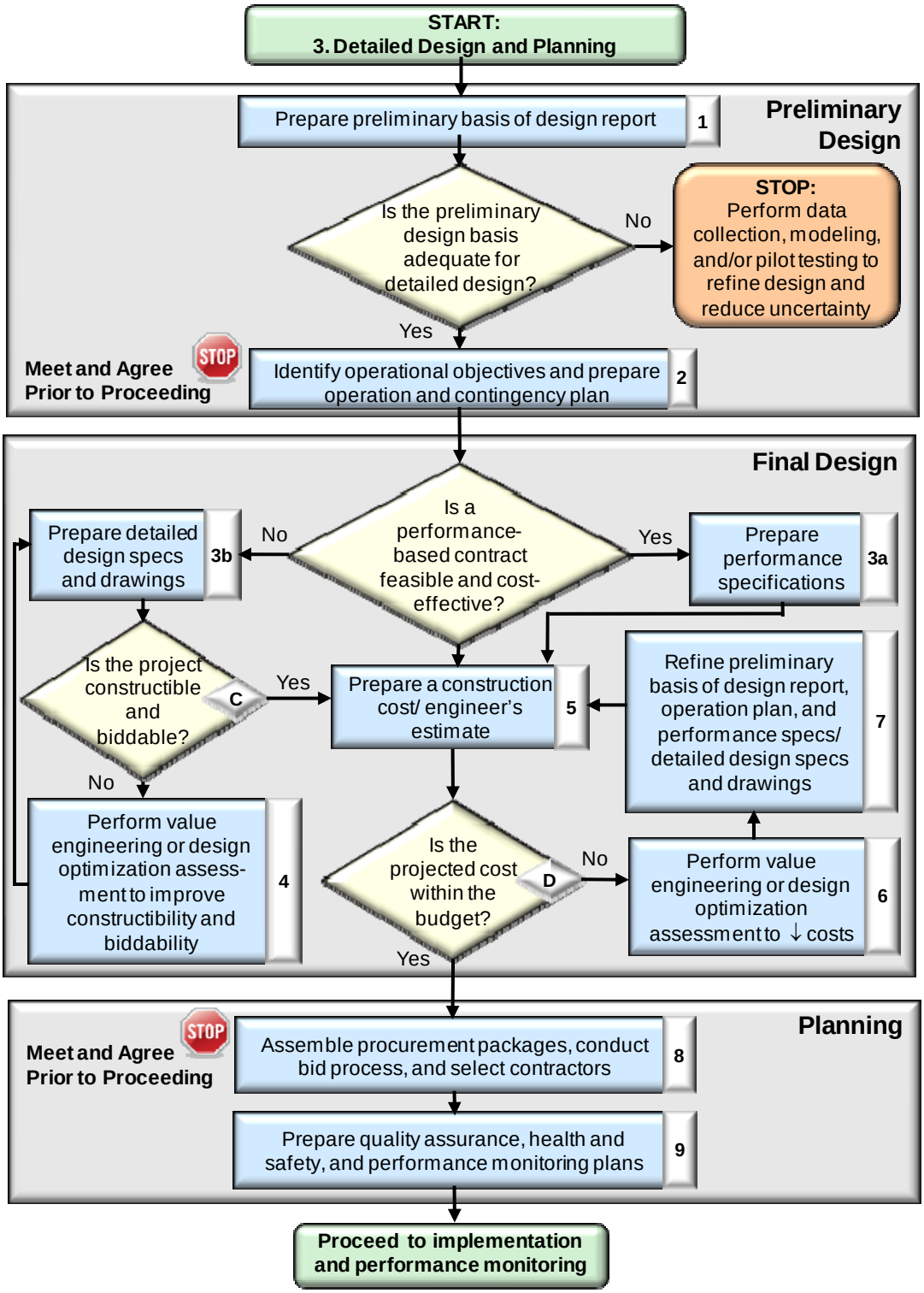
This CD was prepared by the organizations listed in this PRv1 CD and reflects the state of the practice as of 2009. Neither organization named or any person acting on their behalf makes any warranty, expressed or implied with respect to the use of any information or process disclosed in this CD, or assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information or process disclosed in this CD.

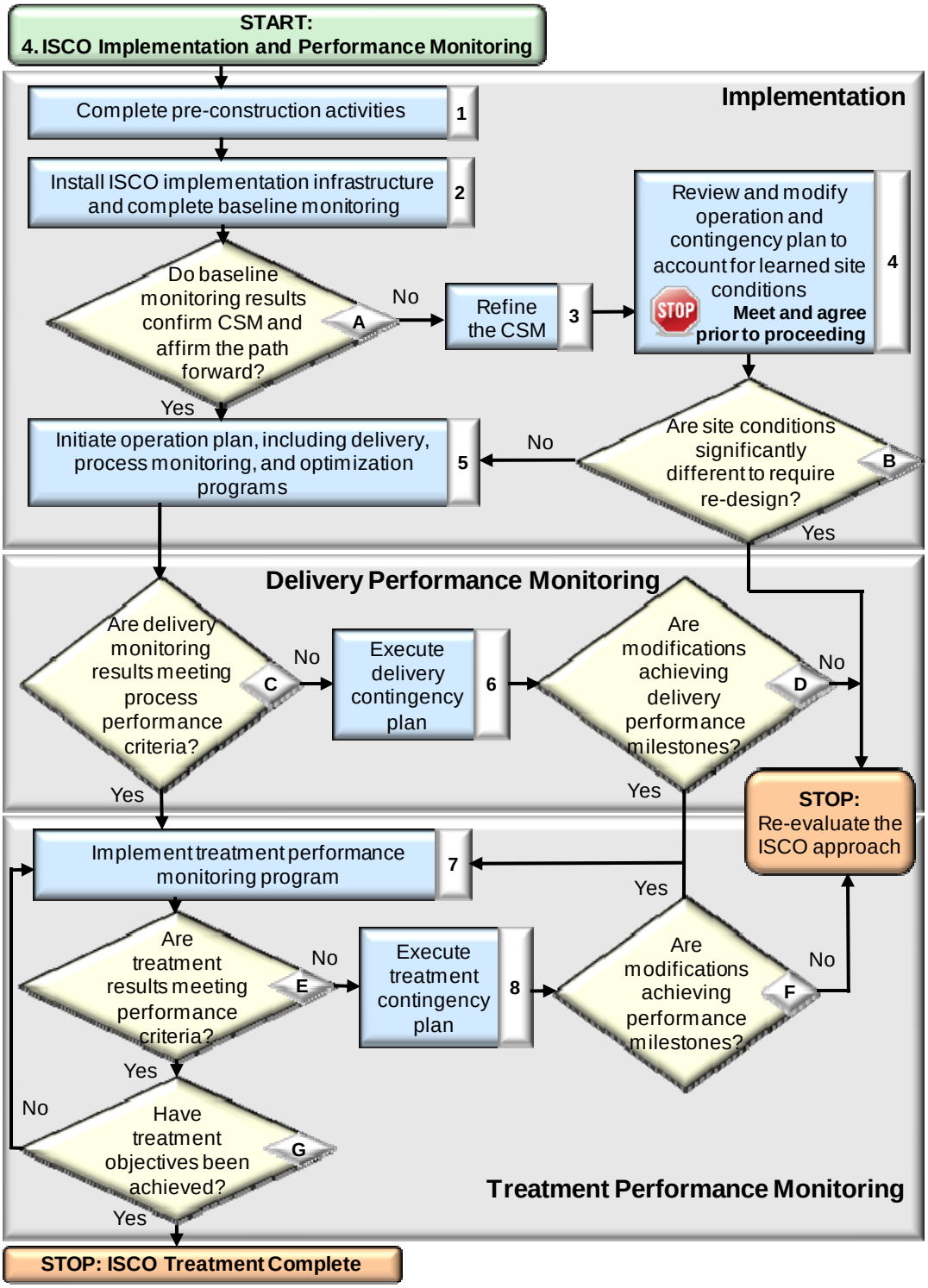
1b. Decision flow diagrams for Systematic Approach for Site-Specific ISCO Engineering and Application




START:
1. ISCO Screening
Data Collection: Characterization data, COCs, risk pathways, PRGs/RAOs, preliminary target treatment zones
1
Is ISCO applicable to site COCs and conditions?
A
No
STOP: Evaluate other technologies
Yes
Is the CSM adequately defined for screening purposes?
B
No
Yes
ISCO Screening Process:
Determine viable ISCO options
Are pre-ISCO processes previously implemented, required or already occurring?
C
Yes
Consider pre-ISCO technologies/processes
2
No
Detailed ISCO Screening
3
Determine if value is added by coupling a pre- or post-ISCO process
4
Are viable ISCO options available?
D
No viable options
STOP: Evaluate other technologies or review site approach
Viable options exist
Is data support adequate?
E
No
Yes
Proceed to conceptual design with a limited number (e.g., 1–3) of higher scoring options for ISCO and/or coupled approaches


START:
2. Conceptual Design
Select Target Treatment Zone (TTZ)
1
Tier 1 Conceptual Design: Compare ISCO alternatives (e.g., 1-3 options from screening)
Select design tool input parameters
2
Mass balance and experience
3a
Spreadsheet design tool
3b
Is at least one technologically and economically feasible option available?
A
No
STOP:
Reconsider treatment objectives, TTZ, CSM certainty, ISCO assessment tool input and outcome (screening process), and coupling approaches
Yes
Rank and select oxidant and delivery approach options based on certainty of delivery and effectiveness, and cost
4
Tier 2 Conceptual Design: Iterate design tool to refine design.
Is cost and performance confidence acceptable?
B
Yes
No
STOP:
If fatal design flaw is identified during data collection and/or modeling efforts
Consider additional data needs
5
Consider additional modeling needs
6
Refine design with new information
7
Perform FS cost estimation
8
Proceed with remediation alternatives comparison or detailed design and planning


START:
3. Detailed Design and Planning
Preliminary Design
Prepare preliminary basis of design report
1
Is the preliminary design basis adequate for detailed design?
No
STOP:
Perform data collection, modeling, and/or pilot testing to refine design and reduce uncertainty
Yes
Meet and Agree Prior to Proceeding
STOP
Identify operational objectives and prepare operation and contingency plan
2
Final Design
Is a performance-based contract feasible and cost-effective?
No
Yes
Prepare detailed design specs and drawings
3b
Prepare performance specifications
3a
Is the project constructible and biddable?
C
Yes
No
Prepare a construction cost/ engineer's estimate
5
Refine preliminary basis of design report, operation plan, and performance specs/ detailed design specs and drawings
7
Perform value engineering or design optimization assess-ment to improve constructibility and biddability
4
Is the projected cost within the budget?
D
No
Yes
Perform value engineering or design optimization assessment to ↓ costs
6
Planning
Meet and Agree Prior to Proceeding
STOP
Assemble procurement packages, conduct bid process, and select contractors
8
Prepare quality assurance, health and safety, and performance monitoring plans
9
Proceed to implementation and performance monitoring


START:
4. ISCO Implementation and Performance Monitoring
Implementation
Complete pre-construction activities
1
Install ISCO implementation infrastructure and complete baseline monitoring
2
Do baseline monitoring results confirm CSM and affirm the path forward?
A
No
Refine the CSM
3
Review and modify operation and contingency plan to account for learned site conditions
STOP
Meet and agree prior to proceeding
4
Yes
Initiate operation plan, including delivery, process monitoring, and optimization programs
5
No
Are site conditions significantly different to require re-design?
B
Yes
Delivery Performance Monitoring
Are delivery monitoring results meeting process performance criteria?
C
No
Execute delivery contingency plan
6
Are modifications achieving delivery performance milestones?
D
No
Yes
Yes
STOP:
Re-evaluate the ISCO approach
Implement treatment performance monitoring program
7
Yes
Are treatment results meeting performance criteria?
E
No
Execute treatment contingency plan
8
Are modifications achieving performance milestones?
F
No
Yes
No
Have treatment objectives been achieved?
G
Yes
Treatment Performance Monitoring
STOP: ISCO Treatment Complete

IIa. ISCO Screening tool decision charts

Table 1. Categorization of Contaminant Classes by ISCO Treatability

Category 1 Contaminant classes highly amenable to effective degradation by commonly used ISCO oxidants	Category 2 Contaminant classes degradable by common ISCO oxidants but effectiveness is less certain	Category 3 Contaminant classes not amenable to ISCO treatment
Chloroethenes BTEX TPH PAHs Chlorobenzenes Phenols (e.g., chlorophenols) Fuel oxygenates (MTBE, TAME) Alcohols 1,4-dioxane	Chloroethanes Chlorinated / brominated Explosives (RDX, TNT, etc.) Organic herbicides or NDMA Ketones PCBs Dioxins/Furans	Heavy metals Radionuclides Inorganic salts Perchlorate Nutrients (nitrate, ammonia, phosphate)

Table 2. Recommendation for Further Screening of ISCO Technologies based on COC Levels, Site Hydrogeology, and ISCO Treatment Goals

Low Contaminant Concentration/Mass									
Type of ISCO Treatment Goal	**Concentration Reduction**			**Mass Reduction**			**Mass Flux Reduction**		
Removal magnitude (%)	**50-90**	**90-99**	**99-99.9**	**50-90**	**90-99**	**99-99.9**	**50-90**	**90-99**	**99-99.9**
Unconsolidated media									
Homogeneous permeable	1	1	2	1	1	2	1	1	2
Heterogeneous permeable	1	2	2	1	1	2	1	1	2
Homogeneous low permeability	1	2	2	1	1	2	1	1	2
Heterogeneous low permeability	1	2	2	1	1	2	1	1	2
Consolidated media (fractured)									
Sedimentary	1	2	2	1	1	2	1	1	2
Igneous/metamorphic	1	2	3	1	2	3	1	1	2
Karst	1	2	3	2	2	3	1	2	3
High Contaminant Concentration/Mass									
Type of ISCO Treatment Goal	**Concentration Reduction**			**Mass Reduction**			**Mass Flux Reduction**		
Removal magnitude (%)	**50-90**	**90-99**	**99-99.9**	**50-90**	**90-99**	**99-99.9**	**50-90**	**90-99**	**99-99.9**
Unconsolidated media									
Homogeneous permeable	1	1	2	1	1	2	1	1	2
Heterogeneous permeable	1	2	3	1	1	2	1	2	3
Homogeneous low permeability	1	2	3	1	2	3	1	2	3
Heterogeneous low permeability	1	2	3	1	2	3	1	2	3
Consolidated media (fractured)									
Sedimentary	1	2	3	1	2	3	1	1	2
Igneous/metamorphic	2	2	3	2	3	3	1	2	3
Karst	2	3	3	3	3	3	2	3	3

Table 3. Amenability of Common COCs to Oxidation by Commonly Employed Oxidants

Common ISCO treated contaminants	Permanganate	Hydrogen Peroxide			Ozone	
Activation Technique		Chelated iron activation	No Activation (mineral catalysis)	Iron/acid activation	Ozone only	Ozone with peroxide
Common Contaminant Mixtures						
Light hydrocarbon fuels (gasoline, diesel, kerosene, jet fuel etc.)	*Fair*	*Good*	*Good*	*Good*	*Good*	*Good*
Heavy hydrocarbon fuels (fuel oils, bunker oil, etc.)	*Poor*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Creosote, coal tar, MGP residuals, or other PAH mixtures	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
Polychlorinated biphenyls (PCBs) or polybrominated biphenyls	*Not Recommended*	*Fair*	*Poor*	*Fair*	*Not Recommended*	*Not Recommended*
Dioxins or furans	*Not Recommended*	*Fair*	*Poor*	*Fair*	*Not Recommended*	*Not Recommended*
Common specific fuel contaminants and breakdown products						
Benzene	*Not Recommended*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Toluene	*Good*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Ethylbenzene	*Good*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Xylenes (o-, p- or m-)	*Good*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Methyl-tertbutylether (MTBE)	*Poor*	*Good*	*Good*	*Good*	*Good*	*Good*
Tert-butyl alcohol (TBA)	*Not Recommended*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Common chlorinated solvents, stabilizers, and their breakdown products						
Tetrachloroethene (PCE)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Trichloroethene (TCE)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Dichloroethenes (1,1-, cis-1,2-, and trans-1,2-)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Vinyl Chloride	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Tetrachloroethanes (1,1,1,2- and 1,1,2,2-)	*Not Recommended*	*Fair*	*Fair*	*Poor*	*Fair*	*Fair*
Trichloroethanes (1,1,1- and 1,1,2-)	*Not Recommended*	*Good*	*Good*	*Poor*	*Good*	*Good*
Dichloroethanes (1,1- and 1,2-)	*Not Recommended*	*Good*	*Good*	*Fair*	*Good*	*Good*
Chloroethane	*Not Recommended*	*Good*	*Good*	*Fair*	*Good*	*Good*
Carbon tetrachloride	*Not Recommended*	*Excellent*	*Good*	*Poor*	*Not Recommended*	*Not Recommended*
Chloroform	*Not Recommended*	*Good*	*Good*	*Poor*	*Poor*	*Poor*
Dichloromethane	*Not Recommended*	*Good*	*Fair*	*Poor*	*Poor*	*Poor*
Methylene Chloride	*Not Recommended*	*Good*	*Fair*	*Poor*	*Poor*	*Poor*
1-4-Dioxane	*Good*	*Excellent*	*Excellent*	*Excellent*	*Good*	*Good*
Chlorinated aromatic contaminants						
Pentachlorophenol (PCP)	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
Tri and tetrachlorophenols	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
Dichlorophenols and chlorophenols	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
chlorobenzene	*Poor*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Di and trichlorobenzenes	*Poor*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Hexachlorobenzene	*Not Recommended*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Explosives, energetics, and breakdown products						
RDX and HMX	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
TNT and DNT	*Good*	*Good*	*Fair*	*Fair*	*Good*	*Good*
Di and Trinitrobenzenes	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Mono and dinitrophenols	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*

Table 3. Amenability of Common COCs to Oxidation by Commonly Employed Oxidants (cont'd)

Common ISCO treated contaminants	Percarbonate	Persulfate					
Activation Technique		Alkaline activation	Thermal activation	Iron / acid activation	Chelated activation	No activation (mineral catalysis)	Peroxide activation
Common Contaminant Mixtures							
Light hydrocarbon fuels (gasoline, diesel, kerosene, jet fuel etc.)	*Good*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Good*	*Excellent*
Heavy hydrocarbon fuels (fuel oils, bunker oil, etc.)	*Fair*	*Good*	*Good*	*Poor*	*Fair*	*Poor*	*Good*
Creosote, coal tar, MGP residuals, or other PAH mixtures	*Good*	*Good*	*Good*	*Fair*	*Fair*	*Poor*	*Good*
Polychlorinated biphenyls (PCBs) or polybrominated biphenyls	*Fair*	*Fair*	*Good*	*Poor*	*Poor*	*Not Recommended*	*Fair*
Dioxins or furans	*Fair*	*Fair*	*Good*	*Poor*	*Poor*	*Not Recommended*	*Fair*
Common specific fuel contaminants and breakdown products							
Benzene	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Toluene	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Ethylbenzene	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Xylenes (o-, p- or m-)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Methyl-tertbutylether (MTBE)	*Good*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Tert-butyl alcohol (TBA)	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Poor*	*Good*
Common chlorinated solvents, stabilizers, and their breakdown products							
Tetrachloroethene (PCE)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Trichloroethene (TCE)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Dichloroethenes (1,1-, cis-1,2-, and trans-1,2-)	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Vinyl Chloride	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Tetrachloroethanes (1,1,1,2- and 1,1,2,2-)	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Trichloroethanes (1,1,1- and 1,1,2-)	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Poor*	*Good*
Dichloroethanes (1,1- and 1,2-)	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Poor*	*Good*
Chloroethane	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Poor*	*Good*
Carbon tetrachloride	*Fair*	*Excellent*	*Fair*	*Not Recommended*	*Not Recommended*	*Not Recommended*	*Excellent*
Chloroform	*Fair*	*Good*	*Not Recommended*	*Not Recommended*	*Not Recommended*	*Not Recommended*	*Good*
Dichloromethane	*Fair*	*Fair*	*Not Recommended*	*Not Recommended*	*Not Recommended*	*Not Recommended*	*Fair*
Methylene Chloride	*Fair*	*Good*	*Fair*	*Poor*	*Poor*	*Poor*	*Good*
1-4-Dioxane	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Chlorinated aromatic contaminants							
Pentachlorophenol (PCP)	*Good*	*Good*	*Good*	*Fair*	*Fair*	*Fair*	*Good*
Tri and tetrachlorophenols	*Good*	*Excellent*	*Excellent*	*Good*	*Good*	*Good*	*Excellent*
Dichlorophenols and chlorophenols	*Good*	*Excellent*	*Excellent*	*Good*	*Good*	*Good*	*Excellent*
chlorobenzene	*Fair*	*Excellent*	*Excellent*	*Good*	*Good*	*Good*	*Excellent*
Di and trichlorobenzenes	*Fair*	*Excellent*	*Excellent*	*Good*	*Good*	*Good*	*Excellent*
Hexachlorobenzene	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Fair*	*Good*
Explosives, energetics, and breakdown products							
RDX and HMX	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*
TNT and DNT	*Fair*	*Good*	*Good*	*Fair*	*Fair*	*Fair*	*Good*
Di and Trinitrobenzenes	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*	*Good*
Mono and dinitrophenols	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*	*Good*

Table 4. Applicability of Oxidants to Common Geochemical Conditions

Parameter	Permanganate	Ozone		Hydrogen peroxide		
		Ozone only	Ozone with peroxide	Chelated activation	Hydrogen peroxide only	Iron / acid amended activation
Amenability of COCs to oxidative degradation						
pH range						
<5	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
5-6	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
6-7	Excellent	Excellent	Excellent	Excellent	Good	Good
7-8	Excellent	Good	Good	Good	Fair	Fair
8-9	Excellent	Good	Fair	Good	Poor	Poor
>9	Good	Fair	Poor	Poor	Not Recommended	Not Recommended
Alkalinity mg/L as $CaCO_3$						
0-300	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
300-1000	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
1000-3000	Excellent	Good	Good	Good	Good	Good
>3000	Excellent	Good	Fair	Fair	Fair	Fair
Chloride Concentration (mg/L) (should include chloride equivalent based on contaminant concentrations)						
0-300	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
300-1000	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
1000-3000	Excellent	Good	Good	Good	Good	Good
3000-10000	Excellent	Fair	Fair	Fair	Fair	Fair
>10000	Good	Poor	Poor	Poor	Poor	Poor
Amenability of oxidant approach to saturated zone foc						
foc>3.0%	Not Recommended	Not Recommended	Not Recommended	Not Recommended	Not Recommended	Not Recommended
foc<3.0% but foc>1.0%	Poor	Poor	Poor	Poor	Poor	Poor
foc<1.0% but foc>0.3%	Good	Good	Good	Good	Good	Good
foc<0.3% but foc>0.1%	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
foc<0.1%	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Contaminant mass distribution						
Very Low (<10 mg/kg or <100 mg/L)	Good	Excellent	Excellent	Excellent	Excellent	Excellent
Low (10-100 mg/kg or 0.1-1 mg/L)	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Moderate (100-1,000 mg/kg or 1-10 mg/L)	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
High (1,000-10,000 mg/kg or 10-100 mg/L)	Good	Fair	Fair	Good	Good	Good
Very high (>10,000 mg/kg or >100 mg/L)	Good	Poor	Poor	Fair	Fair	Fair

Table 4. Applicability of Oxidants to Common Geochemical Conditions (cont'd)

Parameter	Percarbonate	Persulfate					
		Alkaline activation	Thermal activation	Iron / acid activation	Chelated activation	No activation (mineral activation)	Peroxide activation
Amenability of COCs to oxidative degradation							
pH range							
<5	Not Recommended	Not Recommended	Excellent	Excellent	Excellent	Excellent	Excellent
5-6	Fair	Poor	Excellent	Excellent	Excellent	Excellent	Excellent
6-7	Good	Fair	Excellent	Good	Excellent	Excellent	Excellent
7-8	Excellent	Good	Excellent	Fair	Good	Good	Good
8-9	Excellent	Excellent	Good	Poor	Good	Fair	Fair
>9	Excellent	Excellent	Fair	Not Recommended	Poor	Poor	Poor
Alkalinity mg/L as $CaCO_3$							
0-300	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
300-1000	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
1000-3000	Excellent	Excellent	Good	Good	Good	Good	Good
>3000	Excellent	Excellent	Fair	Fair	Fair	Fair	Fair
Chloride Concentration (mg/L) (should include chloride equivalent based on contaminant concentrations)							
0-300	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
300-1000	Excellent	Excellent	Good	Excellent	Excellent	Excellent	Excellent
1000-3000	Good	Good	Fair	Good	Good	Good	Good
3000-10000	Fair	Fair	Poor	Fair	Fair	Fair	Fair
>10000	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Amenability of oxidant approach to saturated zone foc							
foc>3.0%	Not Recommended	Poor	Poor	Poor	Poor	Poor	Poor
foc<3.0% but foc>1.0%	Poor	Fair	Fair	Fair	Fair	Fair	Fair
foc<1.0% but foc>0.3%	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
foc<0.3% but foc>0.1%	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
foc<0.1%	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Contaminant mass distribution							
Very Low (<10 mg/kg or <100 mg/L)	Excellent	Good	Good	Good	Good	Good	Good
Low (10-100 mg/kg or 0.1-1 mg/L)	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Moderate (100-1,000 mg/kg or 1-10 mg/L)	Excellent	Excellent	Excellent	Excellent	Excellent	Good	Excellent
High (1,000-10,000 mg/kg or 10-100 mg/L)	Good	Good	Good	Good	Good	Fair	Good
Very high (>10,000 mg/kg or >100 mg/L)	Fair	Good	Good	Fair	Fair	Fair	Good

Table 5. Appropriateness of Delivery Methods for Different Oxidants

Distribution Technique	Permanganate	Hydrogen Peroxide	Percarbonate	Ozone	Persulfate
Direct-push Probe Injection					
	Frequently Implemented	Frequently Implemented	Technically Possible	Technically Impractical	Frequently Implemented
Well injection					
Vertical Wells	Frequently Implemented	Frequently Implemented	Technically Possible	Frequently Implemented	Frequently Implemented
Horizontal Wells	Implemented, but rarely	Technically Possible	Technically Possible	Implemented, but rarely	Implemented, but rarely
Recirculation					
Vertical Wells	Less Frequently Implemented	Technically Impractical	Technically Possible	Technically Impractical	Technically Possible
Horizontal Wells	Technically Possible	Technically Impractical	Technically Possible	Technically Impractical	Technically Possible
Trench or curtain Injection (i.e., intercept a plume)					
	Technically Possible	Technically Possible	Technically Possible	Less Frequently Implemented	Technically Possible
Soil Mixing					
	Implemented, but rarely	Implemented, but rarely	Technically Possible	Technically Impractical	Implemented, but rarely
Fracture emplaced ISCO amendment*					
Pneumatic	Implemented, but rarely	Technically Impractical	Technically Possible	Technically Impractical	Technically Possible
Hydraulic	Implemented, but rarely	Technically Impractical	Technically Possible	Technically Impractical	Technically Possible
Surface application or infiltration gallery					
	Frequently Implemented	Technically Impractical	Technically Possible	Technically Impractical	Frequently Implemented

Table 6. Applicability of Delivery Methods to Common Hydrogeological Conditions

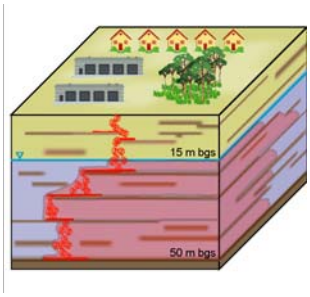
Parameter	Vertical Injection Wells	Vertical Wells - Recirculation	Horizontal Wells	Direct-push Probe Injection	Soil mixing
Amenability to media type					
Unconsolidated media	Excellent	Excellent	Excellent	Excellent*	Excellent*
Consolidated media	Excellent	Good	Excellent	Not recommended	Not recommended
Consolidated media properties					
Fracture continuity					
Good fracture continuity	Good	Good	Fair	Not recommended	Not recommended
Poor fracture continuity	Fair	Poor	Poor	Not recommended	Not recommended
Permeability (both primary and secondary)					
Low	Good	Good	Fair	Not recommended	Not recommended
High	Fair	Poor	Poor	Not recommended	Not recommended
Transmissivity					
Low	Good	Good	Fair	Not recommended	Not recommended
High	Fair	Poor	Poor	Not recommended	Not recommended
Unconsolidated media properties					
Hydraulic conductivity					
$>10^{-3}$ cm/sec (>3 ft/day)	Excellent	Excellent	Excellent	Excellent	Excellent
$<10^{-3}$ but $>10^{-4}$ cm/sec (0.3 – 3 ft/day)	Good	Fair	Fair	Excellent	Excellent
$<10^{-4}$ but $>10^{-5}$ cm/sec (0.03 – 0.3 ft/day)	Fair	Poor	Poor	Good	Excellent
$<10^{-5}$ but $>10^{-6}$ cm/sec (0.003 – 0.03 ft/day)	Poor	Not recommended	Not recommended	Fair	Excellent
$<10^{-6}$ cm/sec (<0.003 ft/day)	Not recommended	Not recommended	Not recommended	Not recommended	Excellent
Magnitude of Heterogeneity					
Kmax/Kmin <1,000	Excellent	Excellent	Excellent	Excellent	Excellent*
Kmax/Kmin >1,000	Fair	Fair	poor	Good	Excellent
Type of heterogeneity if Kmax/Kmin >1,000					
Layered heterogeneous	Fair	Fair	Poor	Good	Excellent
Randomly heterogeneous	Fair	Fair	Fair	Good	Excellent
Scale of heterogeneities (i.e. distance between lenses of alternating materials)					
Small (<0.3 m)	Good	Good	Poor	Good	Excellent
Medium (0.3-1 m)	Fair	Fair	Poor	Fair	Excellent
Large (>1 m)	Fair	Fair	Fair	Good	Excellent
Other important delivery parameters					
Depth of delivery					
<5 m bgs (< 15 ft)	Excellent	Excellent	Excellent	Excellent	Excellent
<10 m bgs but >5 m bgs (15 – 35 ft)	Excellent	Excellent	Excellent	Excellent	Excellent
<25 m bgs but >10 m bgs (35 – 80 ft)	Excellent	Excellent	Good	Fair	Poor
<50 m bgs but >25 m bgs (80 – 165 ft)	Good	Good	Poor	Poor	Not recommended
>50 m bgs (>165 ft)	Good	Good	Not recommended	Not recommended	Not recommended
Site activity disruption intensity					
Disruption of surface activities overlying TTZ	Light	Moderate	Very Light	Moderate	Intense
Disruption of subsurface activities within TTZ	Light	Light	Light	Moderate	Intense
Ability to treat contaminant density					
Very Low (<10 mg/kg or <100 mg/L)	Excellent	Excellent**	Excellent**	Excellent	Excellent
Low (10-100 mg/kg or 0.1-1 mg/L)	Excellent	Excellent	Excellent	Excellent	Excellent
Moderate (100-1,000 mg/kg or 1-10 mg/L)	Good	Excellent	Excellent	Excellent	Excellent
High (1,000-10,000 mg/kg or 10-100 mg/L)	Good	Excellent	Excellent	Excellent	Excellent
Very high (>10,000 mg/kg or >100 mg/L)	Fair	Good	Good	Good	Excellent

IIb. Example problems for ISCO Screening and ISCO Conceptual Design

Example #1 ISCO Screening

Key Features of the Site

- Active military facility
- Large volume of TCE was released to subsurface until ~20 yrs ago
- DNAPL confirmed – residual and pools
- Chlorobenzene co-contamination at low concentrations
- Contamination to about 50 m below ground surface (bgs)
- Fine sandy soil with thin clay-silt lenses interbedded
- Plume approximately ½ km long downgradient
- Treatment goal = **MASS REDUCTION**



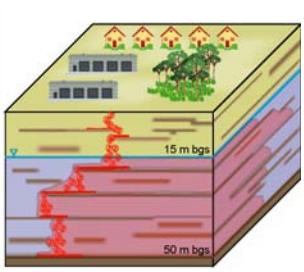
Hydrogeology	
Geologic setting	Unconsolidated porous media
Media type	Silt with sand stringers
Morphology	Layered heterogeneous
Hydraulic conductivity (cm/s)	10^{-4} in fine sand; 10^{-6} in clay-silt stringers
Hydrology	Saturated unconfined aquifer
Depth to groundwater surface	15 m bgs
Depth to aquitard	50 m bgs
Average pore velocity	0.1 m/d
Geochemistry	
Organic carbon content (f_{oc})	0.015 in silt; 0.003 in uncontaminated sand
Alkalinity	80 mg/L as $CaCO_3$
pH	7.0
Eh	0.10 V
Temperature	15 C
Dissolved iron	0.2 μg/L
Dominant iron mineralogy	Geothite
Contaminant hydrology	
Contaminant	TCE DNAPL with low levels of chlorobenzene
Source zone size	8,000 m2
Plume size	80,000 m2
Maximum depth of contamination	50 mg bgs

Is ISCO Viable?
What if the goal is 99.9% concentration reduction?

Example #2 ISCO Screening

<u>Key Features of the Site</u>

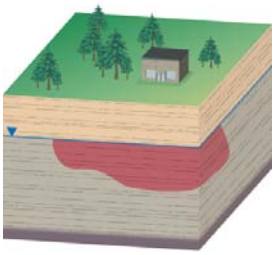
- Industrial facility, inactive
- Chlorobenzene, NAPL suspected
- Contamination to about 50 m below ground surface (bgs); Majority between 15 – 25 feet
- Glacial till; permeable and heterogeneous
- Treatment goal = **MASS REDUCTION**



Hydrogeology	
Geologic setting	Unconsolidated porous media
Media type	Glacial till
Morphology	Permeable, heterogeneous
Hydraulic conductivity (cm/s)	0.02
Hydrology	Saturated unconfined aquifer
Depth to groundwater surface	15 m bgs
Depth to aquitard	50 m bgs
Average pore velocity	0.5 m/d
Geochemistry	
Organic carbon content (f_{oc})	0.1%
Alkalinity	80 mg/L as $CaCO_3$
pH	6.0
Eh	0.10 V
Temperature	15 C
Dissolved iron	0.2 μg/L
Dominant iron mineralogy	Geothite
Contaminant hydrology	
Contaminant	Chlorobenzene DNAPL
Source zone size	5000 m^2
Plume size	500 m^2
Maximum depth of contamination	50 m bgs

What oxidants are feasible? What delivery approaches are feasible?

Example #3 ISCO Screening



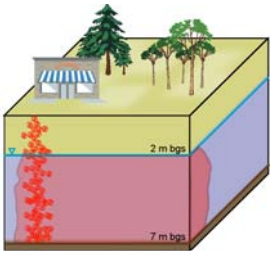
Key Features of the Site

- Dry cleaner in New York State
- Tetrachloroethylene (PCE) DNAPL
- PCE has penetrated homogeneous, low permeability clay
- Groundwater at 2 m bgs and bedrock at 10 m bgs; plume extends to 6 m bgs
- Groundwater pore velocity is 0.5 cm/day
- Treatment goal = **MASS REDUCTION**

Hydrogeology	
Geologic setting	Unconsolidated porous media
Media type	Clay
Morphology	Homogeneous
Hydraulic conductivity (cm/s)	10^{-7}
Hydrology	Saturated unconfined aquifer
Depth to groundwater surface	2 m bgs
Depth to aquitard	10 m bgs
Average pore velocity	0.01 m/d
Geochemistry	
Organic carbon content (f_{oc})	0.03%
Alkalinity	80 mg/L as $CaCO_3$
pH	6.5
Eh	-0.10 V
Temperature	15 C
Dissolved iron	35 mg/L
Dominant iron mineralogy	Siderite / Geothite
Contaminant hydrology	
Contaminant	PCE sorbed and DNAPL
Source zone size	None
Plume size	500 m^2
Maximum depth of contamination	6 m bgs

What oxidants are feasible? What delivery approaches are feasible?

Example #4 ISCO Screening & Conceptual Design



Key Features of the Site

- Dry cleaner in Florida
- Tetrachloroethylene (PCE) DNAPL not suspected
    - Maximum concentration of 1 mg/L in groundwater
    - Maximum concentration of 49 mg/kg in porous media
- PCE has leaked into homogeneous, permeable sand
- Contamination to confining layer at 20 ft bgs
- Homogeneous, permeable sand
- Treatment goal = **MASS REDUCTION**

Hydrogeology	
Geologic setting	Unconsolidated porous media
Media type	Silica sand
Morphology	Homogeneous
Hydraulic conductivity (cm/s)	10^{-3}
Hydrology	Saturated unconfined aquifer
Depth to groundwater surface	10 ft bgs
Depth to aquitard	20 ft bgs
Average pore velocity	1.5 m/day
Bulk density of media	1.6 kg/L
Porosity	0.3
Geochemistry	
Organic carbon content (f_{oc})	0.01
Alkalinity	>3,000 mg/L as $CaCO_3$ (brackish… chloride = 3,000 mg/L)
pH	6.0
Eh	0.15 V
Temperature	25 C
Dissolved iron	0.2 μg/L
Dominant iron mineralogy	Geothite
Contaminant hydrology	
Contaminant	PCE (DNAPL not suspected), dissolved TCE and 1,2-cis DCE detected
Source zone size	None
Plume size	10,000 ft^2
Maximum depth of contamination	20 ft bgs
Natural oxidant demand (permanganate)	
NOD	Expected between 0.2 – 1.0 g/kg; 50% fast,; slower rate = 0.01 L/mmol-d

Determine an appropriate design for permanganate application using direct push or injection wells. Determine the "best" oxidant concentration (between 1,000 and 10,000 mg/L) to achieve 100 mg/L at the delivery radius of influence for 10 days (to allow for some desorption / dissolution). How many injection wells or points are needed? What is the associated cost (roughly)? What is the added cost for a 2nd injection? A third?

IIc. Table of conversion factors

Length	
1 inch	2.54 cm
1 ft	0.305 m
1 mi	5,280 feet
	1,609 m
	1.6 km
Volume	
1 U.S. gallon	231 cubic inches
	0.1337 ft^3
	3.785 L
	0.0038 m^3
1 ft^3	7.48 U.S. gallons
	0.0283 m^3
Flow Rate	
1 ft^3/s	448.8 gal/min
	0.0283 m^3/s
Velocity	
1 ft/d	0.305 m/d
	0.000353 cm/s
Concentration	
1 mg/L	1,000 μg/L
1 ppm	1,000 ppb
1 ppm concentration in water	1 mg/L
1 ppm concentration in soil	1 mg/kg