Introduction to In Situ Bioremediation of Groundwater

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Module 1: Introduction

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the core metabolic pathways and microbial requirements necessary for successful in situ bioremediation (ISB) design.
- **Evaluate** the critical components of a Conceptual Site Model (CSM) to determine the feasibility of bioremediation at a specific contaminated site.
- **Select** appropriate site characterization tools, such as high-resolution site characterization (HRSC) and mass flux measurements, to optimize amendment delivery.

Executive Summary: In situ bioremediation (ISB) is a highly adaptable, cost-effective engineered technology that leverages microbial metabolism to detoxify groundwater contaminants. Success depends on a high-fidelity Conceptual Site Model (CSM) that integrates hydrogeology, biogeochemistry, and precise contaminant distribution to ensure the effective delivery and persistence of amendments.

Superfund Project Information

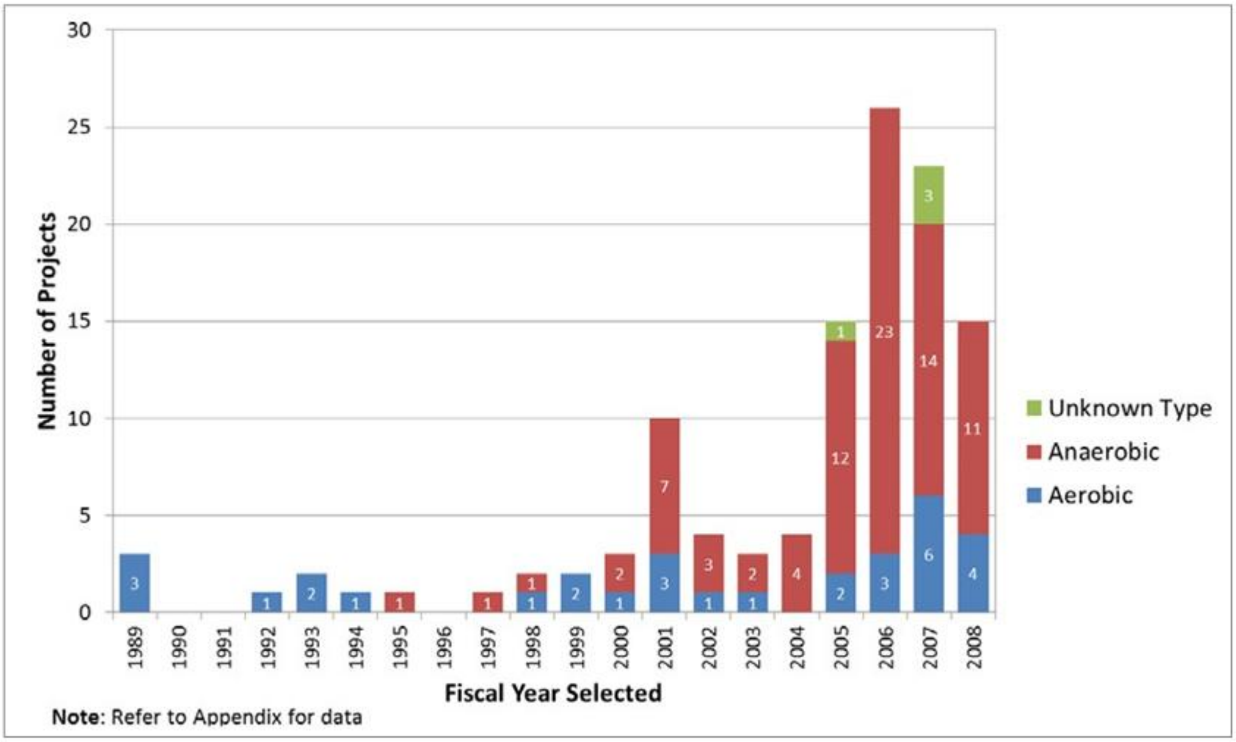
The list of ISB projects accompanying this report was derived from the Superfund Remedy Reports (Thirteenth and Twelfth Editions).

- **Data Sources:** The list includes remedial actions selected in Records of Decision (RODs), ROD amendments, and Explanations of Significant Differences (ESDs) from fiscal years 1989 through 2008.
- **Design Deferment:** While "decision documents" select the general technology (ISB), final design selection is typically deferred to the remedial design phase.
- **Project Status:** Information was last updated in November 2011, incorporating 5-year reviews and remedial action reports.

History and Background

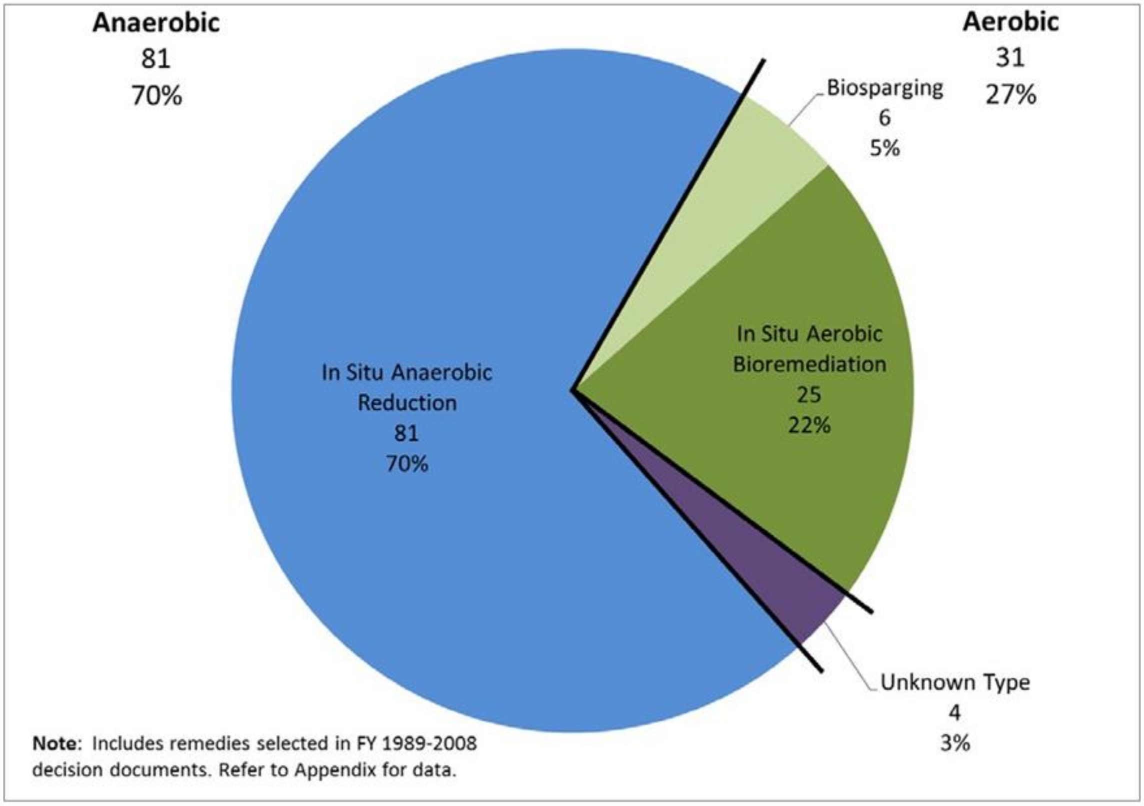
Bioremediation has been used for domestic wastewater since the mid-1800s and for petroleum waste via land treatment for several decades.

- **Aerobic Beginnings:** The first ISB application occurred in 1972 to clean up a pipeline spill in Pennsylvania using oxygen and nutrient recirculation.
- **Anaerobic Evolution:** Anaerobic methods gained popularity for treating chlorinated solvents in the 1990s.
- **Key Discovery:** In 1997, scientists isolated *Dehalococcoides ethenogenes* strain 195, the first organism known to completely dechlorinate perchloroethene (PCE) to ethene.



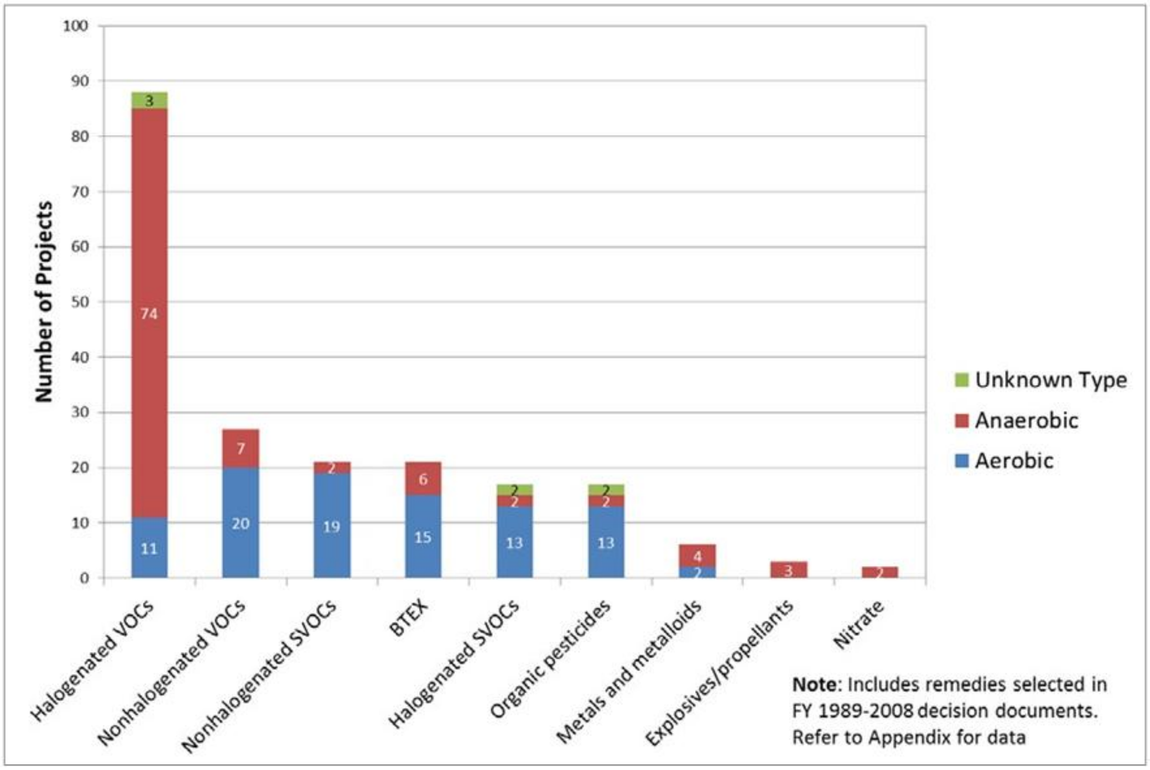
Note: Refer to Appendix for data

Figure 1. Use of In Situ Groundwater Bioremediation Technologies at Superfund Sites.



Note: Includes remedies selected in FY 1989-2008 decision documents. Refer to Appendix for data.

Figure 2. Aerobic and Anaerobic Bioremediation Projects at NPL Sites.



Note: Includes remedies selected in FY 1989-2008 decision documents. Refer to Appendix for data

Figure 3. Contaminant Groups Addressed by Bioremediation Technologies at Superfund Sites.

Microbiology

Designing an effective system requires understanding the fundamental ecology of microbes.

- **Core Requirements:** Bacteria require a carbon source for biomass, an electron donor for energy, and a terminal electron acceptor.
- **Essential Elements:** Carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur are required for life.
- **Growth Kinetics:** Microbial growth is modeled by the Monod equation; rates often slow as cleanup progresses and contaminant (substrate) concentrations decrease.

Reduction and Oxidation Chemistry and Microbial Metabolism

Bacteria generate energy by catalyzing chemical reactions that transfer electrons from an electron donor (reductant) to an electron acceptor (oxidant).

Aerobic Respiration

Aerobic bacteria use oxygen to oxidize organic molecules into carbon dioxide and water. Because of the high redox potential of oxygen, aerobic bacteria dominate wherever oxygen is present.

Anaerobic Respiration and Fermentation

In the absence of oxygen, bacteria utilize alternative electron acceptors.

- **Sequential Use:** Terminal electron acceptors are preferentially used in order: Nitrate, Manganese (IV), Iron (III), Sulfate, and then Carbonate.
- **Denitrification:** The use of nitrate as an electron acceptor produces nitrogen gas byproducts.
- **Fermentation:** When external acceptors are exhausted, bacteria use organic molecules as both donors and acceptors, generating the least amount of energy.

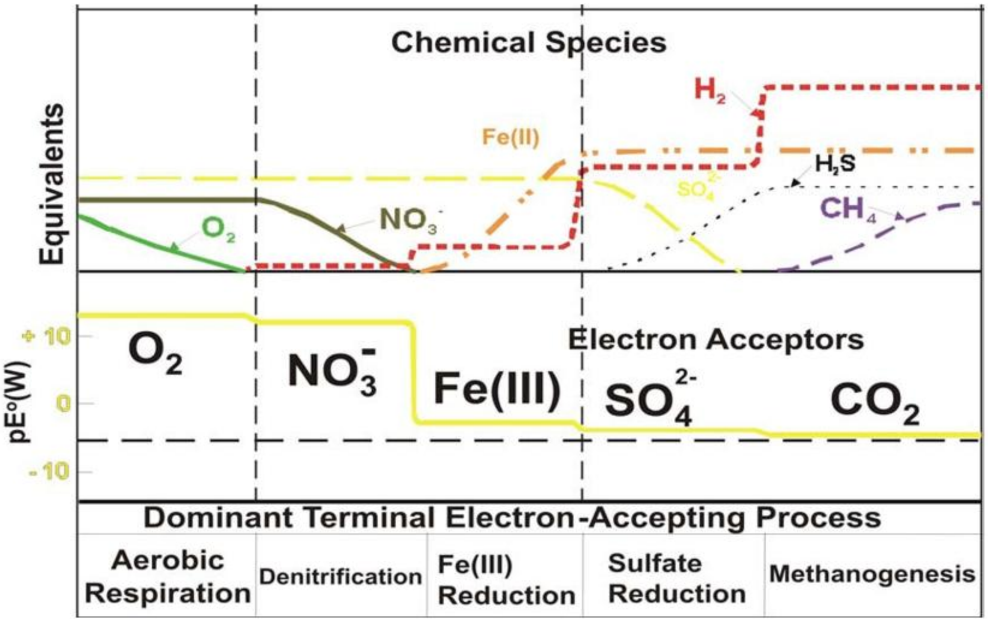


Figure 4. Dominant Terminal Electron-Accepting Process, Electron Acceptors, and Typical Chemical Species Responses (Modified from AFCEE 2004, Bouwer and McCarty 1984)

Direct Metabolism vs. 1.4.4 Cometabolism

- **Direct Metabolism:** The contaminant of concern acts directly as the electron donor or acceptor.
- **Cometabolism:** Microbes degrade a contaminant fortuitously using nonspecific enzymes (e.g., methane monooxygenase) without gaining energy from the reaction.

Abiotic Transformation

Bioremediation conditions often promote abiotic chemical transformations.

- **Chemical Reducers:** Zero-valent iron can produce hydrogen to support ISB while abiotically reducing contaminants.

- **TCA Pathways:** 1,1,1-trichloroethane (TCA) can be abiotically degraded to 1,1-DCE via dehydrochlorination, eliminating compounds that might otherwise inhibit *Dehalococcoides*.

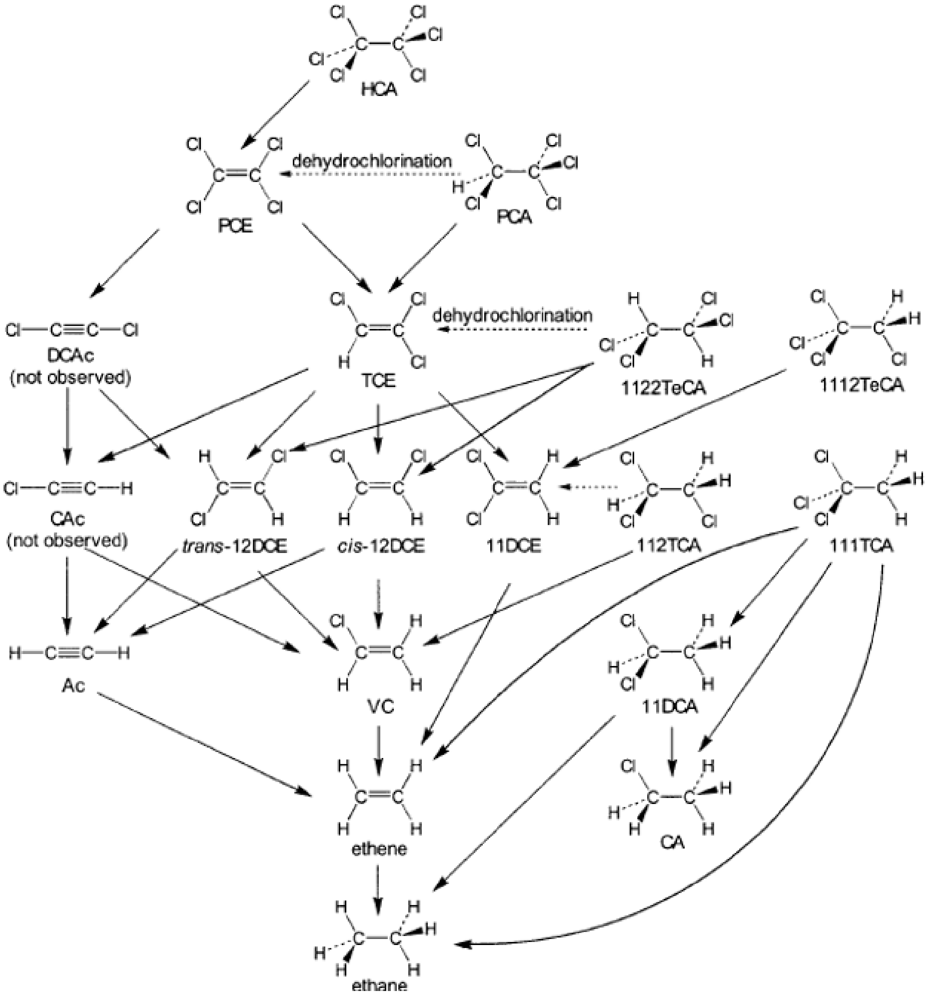


Figure 5. Example Biotic and Abiotic Degradation Pathways of Common CVOCs (EPA 2009, O'Loughlin and Burris 2004)

Conceptual Site Model (CSM)

A CSM integrates the nature and extent of impacts with media characteristics to guide remedy design.