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Bench-Scale/Field-Scale Interpretations: An Overview

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ABSTRACT

In situ bioremediation involves complex interactions between biological, chemical, and physical processes and requires integration of phenomena operating at scales ranging from that of a microbial cell (10^{-6} m) to that of a remediation site (10 to 1,000 m). Laboratory investigations of biodegradation are usually performed at a relatively small scale, which is governed by convenience, cost, and expedience. However, extending the results from a laboratory-scale experimental system to the design and operation of a field-scale system introduces (1) additional mass transport mechanisms and limitations; (2) the presence of multiple phases, contaminants, and competing microorganisms; (3) spatial geologic heterogeneities; and (4) subsurface environmental factors that may inhibit bacterial growth, such as temperature, pH, nutrient, or redox conditions. Field bioremediation rates may be limited by the availability of one of the necessary constituents for biotransformation: substrate, contaminant, electron acceptor, nutrients, or microorganisms capable of degrading the target compound. The factor that limits the rate of bioremediation may not be the same in the laboratory as it is in the field, thereby leading to development of unsuccessful remediation strategies (Goldstein et al. 1985; Lee et al. 1988).

INTRODUCTION

Current bioremediation literature is dominated by the investigation of individual phenomena, usually at the bench scale. Relatively few studies address interactions among bioremediation phenomena or consider how phenomenological effects can be integrated to make predictions of field-scale process behavior. The relative absence of practitioner-oriented tools for decision making suggests that a "process engineering" approach is needed to improve the state-of-the-art of bioremediation practice. Process engineering, in the context of bioremediation, involves the integration of site historical information; site geologic, hydrologic, chemical, and microbiological characteristics; lab and field data; and possible remedial actions to make predictions and design decisions. This integration

may be in the form of computational tools, such as flow and transport models, that can aid in site-specific system design, operation strategy, and data analysis. Ultimately, a priori predictions need to be compared with field observations of remediation system performance. Publication of evaluation studies will better define the overall uncertainty that surrounds decision-making in bioremediation.

PROCESS SCALEUP

The papers presented in this book are based on a scales-of-observation approach, along with other process engineering concepts, to provide a framework for understanding factors affecting the rate and extent of biotransformation; the intent is to improve the design of subsurface bioremediation systems. Use of three scales of observation (micro-, meso-, and macroscale) facilitates the engineering of bioremediation systems. The scale definitions are arbitrary, but provide a useful conceptual structure for approaching the scaleup problem.

At the microscale, chemical and microbiological species and reactions can be characterized independently of any transport phenomena. Examples of microscale features are the composition of the microbial population and kinetics and stoichiometry of biotransformation reactions. The physical scale of these phenomena is at, or less than, the dimension of the microbial cell (10^{-6} to 10^{-5} m). At the mesoscale, transport phenomena and system geometry are first apparent, with the exclusion of advective or mixing processes. Mesoscale phenomena include diffusion, nonequilibrium sorption, and interphase mass transfer. Mesoscale phenomena reflect, for example, the size of pore channels or soil particles, the characteristic diffusion length, or the dimension of microbial aggregates. The length scale for such features ranges from approximately 10^{-5} to 10^{-2} m. The ability to discern advective or mixing phenomena defines the macroscale. Advection, dispersion, and geologic spatial heterogeneity are examples of macroscale phenomena; the corresponding physical scale is approximately 10^{-2} to 10^2 m or even larger. Table 1 summarizes the scale for many of the phenomena that influence bioremediation. Phenomena are classified according to the smallest scale at which they can be observed. Many of the potentially rate-controlling variables in Table 1 are important at the microscale, but are controlled by transport processes at the macroscale. It is this breadth of scales that must be accounted for during the design of in situ biotransformations.

The phenomena in Table 1 must be considered to determine if bioremediation is applicable to a specific site. The phenomena that limit the actual rate of biotransformation must be determined on a case-by-case basis. For example, if the concentration of active biomass is too low, the (microscale) kinetic reaction rate may limit the overall rate of contaminant bioremediation. If the soil organic carbon content is high, the rate of (mesoscale) desorption of contaminant from within the soil matrix may limit bioremediation. Alternatively, if low pore velocities prevail, (macroscale) advection and dispersion may be the rate-limiting processes. The need to identify and estimate the appropriate rate-controlling

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TABLE 1. Phenomena influencing bioremediation.

Scale	Representative Characterization Methods
Microscale	
Microorganisms	Plate counts, gene probe
Degradation pathways	Batch reaction studies
Reaction stoichiometry	Batch reaction studies
Reaction kinetics	Batch reaction studies
Electron acceptors	Chemical analysis for N, P
Nutrients	Chemical analysis
Inhibitors, toxicity	Batch reaction studies
Water activity, pH	Electrochemical probes
Reactions with soil or aquifer matrix	
chemical equilibria	Abiotic reaction studies
Sorption (equilibrium)	Abiotic batch sorption studies
Mesoscale	
Sorption (nonequilibrium)	Abiotic sorption studies
Attachment/detachment (microorganisms)	Biofilm studies
Diffusion	Diffusion chamber tests
Plugging/filtration	Column studies, pressure drop
Interphase transport	Multiphase column studies
Macroscale	
Advection	Well elevations, pump, and tracer tests
Dispersion	Conservative tracer studies
Spatial heterogeneity	Well logs, core permeabilities
Hydrologic properties	Core permeabilities

phenomena dominates the feasibility of an in situ bioremediation project. It is also clear that heterogeneities in the field can substantially complicate the issue in that different phenomena may limit the biotransformation at different locations at a given site.

The approach to scaleup should therefore include the following steps: (1) relevant phenomena must be analyzed to determine which will limit the contaminant biotransformation rate at prevailing subsurface environmental conditions (because the subsurface environment may vary considerably across the site, analysis may conclude that several different phenomena are limiting, depending on the exact location); (2) once a particular remediation strategy is proposed (e.g., pump and treat or nutrient injection/recovery), the situation must be reassessed to determine a new set of probable biotransformation rates and their limiting phenomena; and (3) the outcome of steps 1 and 2 can be used to assess the feasibility of a system design.

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Bioremediation of Spills in Terrestrial

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