Evaluating *In Situ* Bioremediation for Groundwater Cleanup

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This systematic approach can be used to assess the suitability of *in situ* bioremediation for a particular contaminated site.

Documents submitted to regulatory authorities for *in situ* bioremediation (ISB) of groundwater are not typically prepared or evaluated consistently, based on standardized, accepted criteria. This results in inefficient and conflicting decision-making processes.

This article, based on guidance documents *(1–4)* published by the Interstate Technology Regulatory Council (ITRC), provides information to help the engineer or site evaluator make a preliminary determination as to whether ISB has potential for cleaning up a particular site.

In situ bioremediation

Bioremediation is the process by which living organisms act to transform or degrade contaminants. It involves control and manipulation of microbial processes, either in above-ground (*ex situ*) reactors, or in place, for *in situ* ISB.

Various carbon amendments can be used to stimulate bioremediation. Energy from organic nutrients is used for contaminant biotransformation/degradation and synthesis of new microbes and cellular materials. Nutrient amendments need to provide a balanced ratio of carbon:nitrogen:phosphate:sulfur (C:N:P:S) and include specific micronutrients and vitamins for optimal biotransformation/degradation. Often, adequate biotransformation/degradation rates can be achieved simply by providing a carbon source and/or additional nitrogen or phosphate. This is possible because micronutrient sources are often available in the contaminant matrix, the contaminated materials, or within microbes already populating the site.

For ISB to be effective, various microbiological, chemical, hydrogeological, geological and engineering elements must be coordinated to create and optimize subsurface conditions that will induce specific microbial growth and the degradation of contaminants at accelerated rates *(5).* Although contaminants and their biodegradation pathways vary widely, many of the site characteristics that impact the feasibility of any ISB are similar. Once site characterization and biotreatability studies have identified and evaluated site contaminants, degradation products, and relevant site-specific parameters, and confirmed the feasibility of ISB, engineered approaches can be designed, pilot-tested and deployed.

Generally, only a few situations absolutely preclude ISB either as a complete treatment or as part of a staged remediation approach. These include:

- high contaminant or co-contaminant (analyte) concentrations that are toxic to the microbes
- high or low environmental variables, such as temperature or pH

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* ITRC is a state-led, national coalition of regulatory and technology program personnel from 40 states and the District of Columbia; three federal agencies; and tribal, public and industry stakeholders. ITRC is devoted to lowering regulatory barriers to acceptance and deployment of innovative, improved and cost-effective environmental technologies.

- the physical inability to get the ISB treatment into the contaminated area or in front of a moving contaminant zone.

The greatest limiting factors for ISB application can be treatment time and the ability to reach the desired endpoints in all areas of the contaminated *in situ* environment.

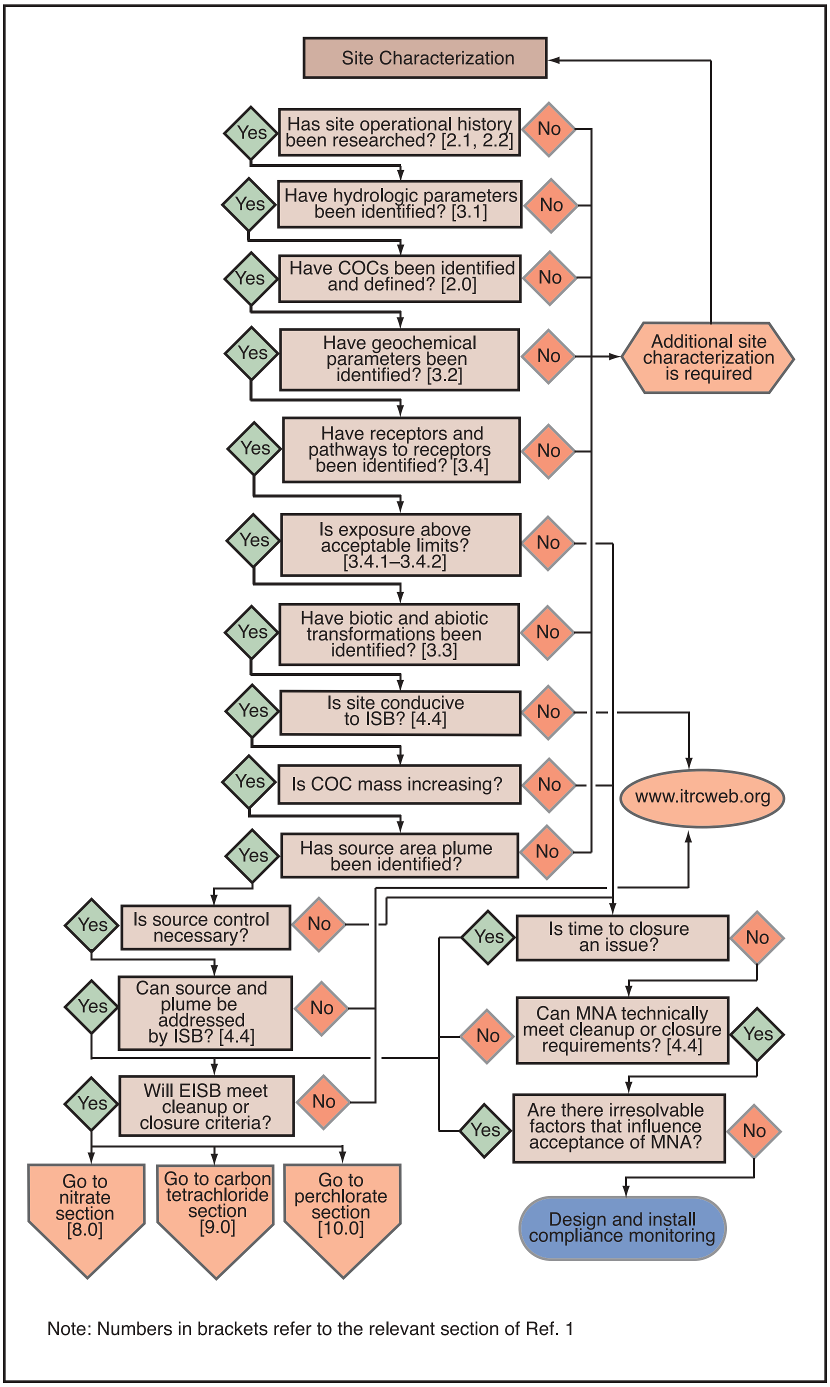
The most significant benefits of ISB are low treatment costs combined with high treatment effectiveness, and the ability to treat a broad range of contaminant concentrations, removing the contaminants to extremely low endpoints in the environments where ISB can be optimized.

The systematic approach to ISB outlined here involves first developing a site conceptual model, which creates a picture of the physical, chemical, biochemical, microbiological, geological and hydrological characteristics of the subsurface needed to develop a plan for ISB. Information is collected about site background and contamination history, geochemistry, hydrogeology, contaminant fate and transport, contaminant transformation (abiotic and biotic) and receptors. Then the potential of natural attenuation and/or ISB technologies is evaluated using the step-wise decision tree of relevant site-specific parameters and criteria in Figure 1.

Site background information

The first step in developing the site conceptual model is to review existing data to identify data collection needs and prepare further data-collection plans. Site-specific contaminant information can identify the biogeochemical reactions already occurring, as well as any other anionic, cationic, nonionic and amphoteric substances or co-contaminants present.

All this information is used to evaluate the applicability of ISB at a particular site. Even when the biodegradable contaminants are known with certainty, site conditions and co-contaminants can govern the overall effectiveness of ISB at meeting remediation goals. For example, seasonal precipitation fluctuations can greatly influence contaminant and co-contaminant concentrations, dissolved oxygen levels and pH.

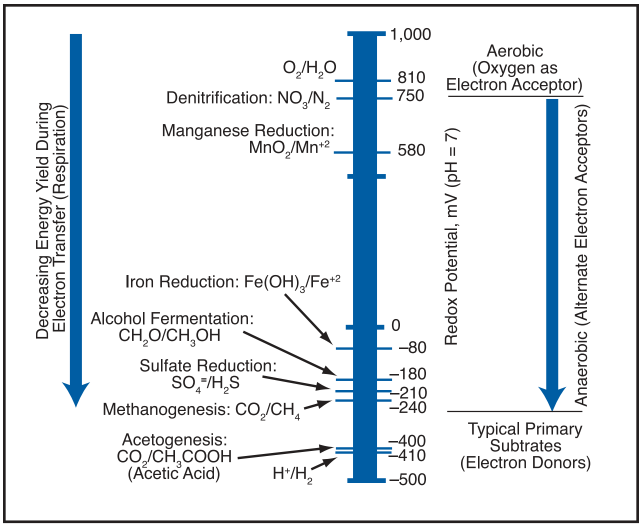


Note: Numbers in brackets refer to the relevant section of Ref. 1

Figure 1. Decision tree for site characterization. Source: *(1).*

Geochemistry

The geochemical environment largely controls the distribution of subsurface contaminants and bioremediation treatment. The most important geochemical factors influencing subsurface transport, contaminant fate and the ability to treat the contaminants *in situ* are oxidation-reduction



■ Figure 2. Equilibrium potential of redox couples of commonly monitored chemical species.

potential (ORP) and the analytes present. These two factors are, in turn, influenced by subsurface material composition, moisture level, and other parameters, such as pH and dissolved oxygen concentration.

Oxidation-reduction potential (ORP). From a geochemical and an ISB perspective, ORP is defined by dissolved oxygen concentration, pH, temperature, and contaminant distribution and concentration in the source area(s). ORP is denoted E_h, which is the reduction-oxidation (redox) potential referenced to a hydrogen scale in mV.

ORP can be used as an indirect indicator of *in situ* redox conditions, *i.e.*, which electron-donating and electron-accepting processes are active, and to infer if conditions are suitable for a particular contaminant transformation or degradation reaction.

Figure 2 shows the equilibrium potentials of some relevant redox reactions. At E_h values greater than the equilibrium potential of a given redox couple, the reduced species is thermodynamically less stable than the oxidized species and its oxidation is favored. Conversely, at E_h levels below the equilibrium potential, reduction of the oxidized species is favored. Because many redox equilibria are pH-dependent, they should be evaluated with regard to site-specific pH conditions, since in some cases the relative positions of specific redox equilibrium potentials may be reversed.

Analytes. Chemicals and/or elements other than target contaminants are always present at the site. These are known as analytes, and include anions, cations, nonionic materials, amphoteric substances and metabolites. These materials can increase or decrease biotransformation rates, thus affecting ISB effectiveness. Trace elements (*e.g.*, manganese, magnesium and iron) present in appropriate amounts may increase microbial enzyme production and function. Conversely, analytes such as arsenic, copper, mercury and many others, can inhibit microbial growth or considerably slow contaminant metabolism. The table lists several analytes and breakdown products that can be useful in characterizing and evaluating ISB systems.

Hydrogeology

Hydrogeologic site characterization provides a basis for predicting how fluids, solutes and ISB treatments move through the subsurface. It includes site- and contaminant-specific parameters.

Site-specific parameters. These describe the subsurface system in terms that favor or detract from ISB application. The more important terms include:

- hydrostratigraphic units, *i.e.*, geologic units and their associated hydraulic properties, determine whether the ISB approach should be used to treat the contaminant in a relatively fixed location or treat it in a permeable barrier as it travels down-gradient
- hydrologic boundaries, *i.e.*, geologic areas that have different hydraulic properties, define whether or not the contaminant and ISB treatment will be somewhat stationary, travel down-gradient, or spread to other areas
- matrix type or geological compositions determine the availability of the contaminant and ISB treatment materials and how an ISB treatment will move or diffuse in the treatment area
- groundwater flow through various geological matrices at the site determines the contaminant mobility potential, and thus, which ISB approaches might be practical
- contaminant and analyte concentration and distribution affect the fate and transport of contaminants and determine where in the contaminated site ISB might be most effective (for example, if contaminant concentrations are too high, they can be toxic to microbes used for contaminant transformation or degradation).

Contaminant-specific parameters. These control transport and distribution of contaminants and amendments in the subsurface. They are almost always not ideal for any one particular type of treatment, but are used collectively to determine the best ISB approach(es). They include:

- lithology, *i.e.*, the nature of the rock, sand and clay materials present and their composition; contaminated sandy materials within a geological or physically contained area represent a best-case ISB treatment situation
- hydraulic conductivity, *i.e.*, the extent to which water flows through subsurface materials; generally, target-zone

Table. Useful analytes for bioremediation evaluations.

Analyte	Analytical Method	Holding Time	Sample Volume	Use
Alkalinity	EPA 310.1 (field)	14 days	100 mL	CO_2 and HCO_3^- are produced by microbial respiration; an increase in alkalinity may indicate microbial activity; organic acid production (acetogenesis) also lowers the pH, which increases carbonate solubility
Chloride	EPA 325.3	28 days	100 mL	A conservative tracer; for chlorinated contaminants, an increase may indicate reductive dechlorination
Dissolved Oxygen	Field*	—	—	A major electron acceptor, high levels (>2 mg/L) indicate aerobic conditions, which persist until the dissolved oxygen is depleted
Manganese (dissolved)	EPA 6010B EPA 200.7 (field)**	180 days[†]	250 mL	An increase in dissolved manganese (Mn(II)) relative to background may indicate anaerobic Mn(IV)-reducing conditions
Iron (dissolved)	EPA 6010B EPA 200.7 (field)**	180 days[†]	250 mL	An increase in dissolved iron (Fe(II)) relative to background may indicate anaerobic Fe(III)-reducing conditions
Nitrate/ Nitrite (total)	EPA 353.2 (field)	28 days[†]	500 mL	A decrease in nitrate, relative to background, may indicate anaerobic nitrate-reducing conditions
pH	Field	—	—	Optimum range for ISB is 5–9
Phosphate (soluble)	EPA 365.1	28 days[†]	100 mL	Nutrient needed for microbial growth; may need to be added as an amendment to promote biodegradation
Oxidation-Reduction Potential (ORP)	Field*	—	—	Measurement of reducing or oxidizing environment may be indicative of real or potential biological activity; ORP values may be difficult to measure accurately
Sulfate	EPA 375.4 (field)	28 days	100 mL	A decrease in sulfate, relative to background, may indicate anaerobic sulfate-reducing conditions; may be accompanied by an increase in sulfide
Methane	GC-0019	14 days	40 mL	An increase in methane, relative to background, indicates reducing conditions, possibly methanogenesis (microbial production using carbon dioxide as an electron receptor)
Total Organic Carbon (TOC)	EPA 415.1	28 days[†]	100 mL	TOC may provide electron donors for biodegradation, thereby reducing the amount of electron donor amendment required; may affect retardation of contaminants due to sorption

* Obtaining meaningful measurements in the field may be difficult and may provide conflicting results.

** EPA 6010B is used for Resource Conservation and Recovery Act (RCRA) projects; EPA 200.7 is used for National Pollutant Discharge Elimination System (NPDES) (*i.e.,* Clean Water Act) projects.

[†] Holding time is based on the proper preservative added to the sample.

hydraulic conductivity values of 10^{-4} cm/s or greater are adequate for ISB

- effective porosity, *i.e.*, the percentage of interconnected pore space within a contained ISB treatment area; the higher, the better, because high porosity allows the treatment to reach all contaminated areas more directly
- hydraulic gradient, *i.e.*, the underground water head divided by the distance of travel; this parameter describes the residence time that the contaminants and ISB treatments have within the treatment site and their tendency to move in a particular direction
- groundwater flow velocity determines the chemical

transport velocity in the groundwater, and is often used to evaluate how fast the contaminant is moving and/or diffusing and to evaluate ISB relative to other treatment options

- depth to water and water depth profile within the contaminated system (along with the other variables noted above) describe the potential of the contaminant and ISB treatment to impact down-gradient receptors; contaminants and ISB treatments move much more rapidly through water than through rock or soil
- dispersion, advection and retardation describe the physical factors, including pore size distributions, pore geometry and composition of the subsurface matrix, that affect the spreading out or dilution of a contaminant plume and ISB treatment components such as microorganisms and supplemental nutrients
- the retardation coefficient and distribution or partition coefficients describe the equilibrium distribution of a chemical between solids and groundwater, and are important because they characterize the availability of contaminants and nutrients for ISB
- the distribution coefficient is usually described as a sorption isotherm, which relates the concentration of the chemical sorbed onto the soil to the concentration in solution at equilibrium; a compound with a high distribution coefficient will partition to a greater extent into surrounding soils.

Fate and transport

In developing an ISB strategy, it is important to understand the stoichiometry, kinetics and mass balance of site-specific contaminant biotransformation/degradation reactions. These parameters are usually defined in laboratory biotreatability screening and/or pilot-scale tests and are used to compare ISB with other remediation alternatives. They define the amount of amendment required to complete the desired bioreactions and define overall reaction rates. Since most bioremediation processes are metabolic, chemical reactions follow a stoichiometry influenced by site parameters and provide a scientific basis for ISB system design and operation.

Stoichiometry. Stoichiometric reaction equations are statements of the relative number of molecules or moles of reactants and products that participate in a reaction. For example:

$$5C + 4NO_3^- + 2H_2O \rightarrow 2N_2 + 4HCO_3^- + CO_2$$

On a purely stoichiometric basis, this generic reaction requires 5 moles of carbon to react with 4 moles of nitrate and 2 moles of water to produce 2 moles of nitrogen gas plus other products. The denitrification of each mole of nitrate to nitrogen gas requires 5/4 moles of carbon. In ISB field applications, numerous sinks exist that can react with or compete for the carbon. This increases the required amount of carbon amendment in excess of theoretical.

Many different carbon amendments can be used to stimulate denitrification in groundwater. Generally, the lower the carbon content, the more carbon amendment required. The sidebar highlights the stoichiometric reactions for some common nutrient amendments used in denitrification and other bioremediations, and shows the number of moles of amendment consumed in the reduction of one mole of nitrate to one-half mole of nitrogen gas.

Mass balance. Mass balances help identify problems with amendment distribution, amendment mixing, occurrence of unknown side reactions, and applicability of an amendment to a specific situation. Mass balances are usually determined in laboratory biotreatability testing and checked at the pilot scale before full-scale application by monitoring changes in amendment and contaminant concentrations.

Kinetics. Chemical kinetics, the reaction rates and mechanisms by which one chemical species is converted to another, can be used to estimate how long it will take to reduce a given contaminant concentration to a target cleanup level and to identify what amendments may be needed to enhance reaction rates. Knowledge of contaminant biotransformation reaction rates and mechanisms is desirable and sometimes crucial for designing and operating an ISB system and for determining whether an ISB system design will meet operating and economic constraints. Kinetic studies also provide estimates of contaminant electron-donor and -acceptor requirements and reaction half-life in terms that can affect the system design flowrates, donor/nutrient input rates, residence time in the subsurface flow field, and overall system layout *(6, 7)*.

Nutrient Amendments Used in Denitrification

Methanol:

$NO_3^- + 5/6\ CH_3OH \rightarrow 1/2\ N_2 + 5/6\ CO_2 + 7/6\ H_2O + OH^-$

Acetate:

$NO_3^- + 5/8\ CH_3COO^- \rightarrow 1/2\ N_2 + 5/4\ CO_2 + 1/8\ H_2O + 13/8\ OH^-$

Ethanol:

$NO_3^- + 5/12\ CH_3CH_2OH \rightarrow 1/2\ N_2 + 5/6\ CO_2 + 3/4\ H_2O + OH^-$

Acetone:

$NO_3^- + 5/16\ CH_3COCH_3 \rightarrow 1/2\ N_2 + + 15/16\ CO_2 + 7/16\ H_2O + OH^-$

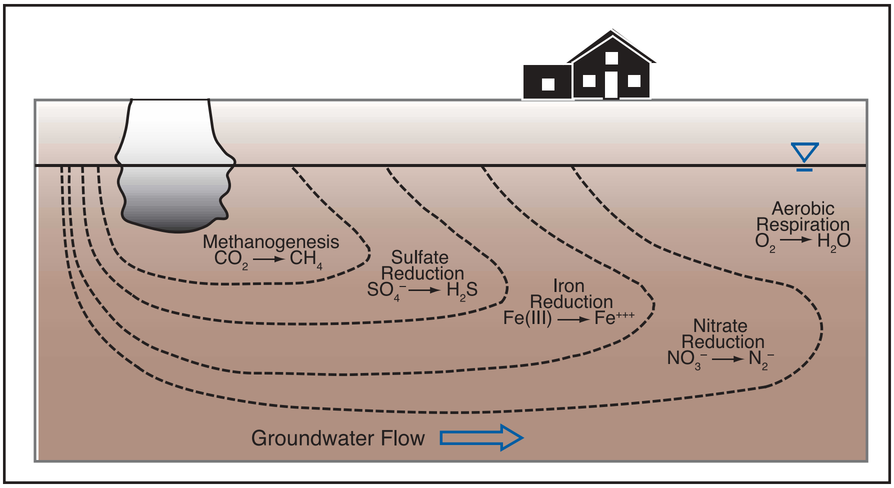
Sugar (sucrose):

$NO_3^- + 5/48\ C_{12}H_{22}O_{11} \rightarrow 1/2\ N_2 + 5/4\ CO_2 + 31/48\ H_2O + OH^-$

Receptors

An object, population, environment or location in a pollutant pathway is termed a receptor. Numerous mechanisms may transmit contaminated media from the source, or contaminated area, to a receptor.

Based on past and current chemical handling practices at the site, receptors and known or suspected environmental impacts of individual and combined contaminants need to be identified and characterized. This includes exposure rates, levels, food-chain and bioaccumulation factors, aquatic toxicity, and sensitive species. On-site and off-site exposure levels must be determined, measured or projected to establish the allowed contamination remediation time. Exposure estimates must include primary and secondary contaminants, contaminant degradation products, and biodegradation reaction products and their half-lives for incorporation into a risk assessment.



■ Figure 3. Idealized sequence of terminal electron acceptor processes.

Contaminant transformations

Transformation can be defined as a change in a contaminant's physical or chemical state through abiotic (*i.e.*, without living organisms) and/or biological processes.

Abiotic transformations. Many naturally occurring abiotic redox reactions are very slow, and many contaminated systems are in a state of redox disequilibrium. Abiotic transformations include redox, hydrolysis, elimination and volatilization reactions. Examples of abiotic redox and hydrolysis of carbon tetrachloride are:

Redox:

$$Fe^0 + CCl_4 + 2H_2O \rightarrow Fe^{++} + CH_2Cl_2 + 2OH^- + 2Cl^-$$

Hydrolysis:

$$CCl_4 + H_2O \rightarrow CCl_3OH + H^+ + Cl^-$$

Biotic transformations. Bacteria use chemical energy stored in thermodynamically unstable compounds to facilitate otherwise sluggish abiotic redox reactions, leading to more-rapid contaminant degradation. Essentially, all reactions responsible for contaminant degradation, including most natural attenuation of groundwater contaminants, are microbially mediated redox reactions.

Most natural environments contain a great diversity of microorganisms. Microbes normally present in the highest numbers are those best able to survive and multiply under site conditions. Some ubiquitous microbes, such as *Pseudomonas sp.*, can metabolize or transform a variety of organic and inorganic chemicals for growth.

ISB entails establishing optimal subsurface conditions by injecting nutrients and/or microbes to optimize specific microbial growth and redox reactions that result in accelerated contaminant transformation or degradation. Effective bioremediation systems harness key site microbes and/or augmented microbes to utilize the best metabolic processes and higher reaction kinetics required for contaminant degradation. Supplied nutrients and chemicals may serve various functions, but primarily are used for growth or as a source or sink of electrons in redox reactions. Redox reactions occur over a spectrum of environments ranging from oxygen-rich (aerobic) to anoxic (without oxygen).

Oxygen is an excellent electron acceptor. A hydrocarbon compound, such as benzene, can serve as an electron donor while oxygen serves as an electron acceptor. This is the basis of a classic aerobic respiration process. Microbes degrade benzene and produce carbon dioxide and water.

At the other end of the spectrum are anaerobic processes, in which organic contaminants, nitrate, sulfate, iron, manganese or carbon dioxide can function as electron acceptors. For example, anaerobic hydrogen-oxidizing bacteria can dechlorinate tetrachloroethylene (PCE) to trichloroethylene (TCE) with the release of a proton (H^+) and chloride ion. Under extreme reducing conditions, one would expect to observe the complete reductive dechlorination of PCE to ethane.

Microorganisms gain energy for growth by coupling redox reactions via electron transport systems. Figure 3 shows an idealized sequence of terminal-electron acceptor processes in the subsurface environment.

Additional contaminant degradation routes include:

- cometabolism — a process where a compound is degraded by an enzyme or cofactor produced by microorganisms for other purposes; a fortuitous reaction that does not benefit the microorganism
- assimilation — the incorporation of substances into microbial biomass; microbes require carbon, hydrogen, oxygen, nitrogen, and minor and trace nutrients for growth
- sequential transformations — contaminant transformations often involve a sequence of reactions with various intermediate degradation products appearing before the contaminant is completely mineralized.

Microbial characterization

Microbial characterization of the site is important because, in some cases, the microbes required for timely and cost-effective bioremediation are not present in sufficient numbers at the site. If enough key microbes are not present compared to other indigenous microbes, many of which will be stimulated by the addition of carbon sources, then microbial augmentation should be considered. Microbial augmentation can be done by producing and re-injecting more of the desired indigenous microbes or by introducing non-indigenous microbial species.

Problems can occur with the presence of indigenous, but environmentally undesirable microbes, such as *Morganella morganii* or *Citrobacter fruendii*. Even though these bacteria can be very effective in specific contaminant degradations, such as denitrification, they should not be stimulated if there is a chance that through stimulation they will impact on-site or off-site receptors.

Site characterization and ISB implementation

Good site characterization and field data alone are not sufficient to establish the suitability for implementation of ISB remediation technologies. The first section of Figure 1 guides the user through collection of data needed to develop the site conceptual model. It also helps identify general limitations to ISB that affect application feasibility. The last third of Figure 1 guides the user through ISB options of monitored natural attenuation (MNA) and ISB. A good reference for site characterization is the ASTM 1996 publication *(8)*.

Monitored natural attenuation

Evaluation of MNA as a remedial option requires an understanding of physical and biogeochemical conditions at a contaminated site, and quantification of relevant biogeochemical reactions to determine whether naturally occurring contaminant degradation processes can achieve remediation goals within the time constraints identified *(3, 9)*. If MNA is chosen as the final remedy, no treatment system is engineered or installed. However, the length of time over which monitoring is to be conducted must be considered with respect to impact on potential future receptors. The U.S. Environmental Protection Agency requires a rigorous technical assessment via multiple lines of evidence to determine MNA feasibility *(10)*.

In some cases, MNA may be an appropriate final remedial option or used in combination with or following ISB. MNA is typically approved for stable or shrinking plumes. Expanding plumes typically require additional remedial action to accelerate the degradation process.

ISB implementation

To stimulate the naturally occurring microbial population or bioaugmented ISB system, amendments are typically introduced into the contaminated subsurface to promote specific microbial activity that results in destruction of contaminant(s). ISB systems can be deployed for source reduction, dissolved-phase contaminant reduction, or as a biological barrier to contain a contaminant plume. Depending on the contaminant(s), site conditions and remediation goals, ISB processes can be designed based on reduction or oxidation of the contaminant, either directly, cometabolically or by a combination of reactions.

For established ISB applications, such as the destruction of petroleum hydrocarbons, laboratory and pilot-scale field testing may not be necessary. However, for innovative ISB technologies, laboratory biotreatability studies and field pilot testing are recommended. Biotreatability and pilot-scale testing should demonstrate that site contaminants can be transformed/degraded under field conditions, provide estimates of treatment times and capital and operating costs, and identify potential problems that may be encountered with a particular treatment at a specific site.

Biotreatability testing. Biotreatability studies provide specific information on subsurface microbiology, contaminant degradations and possible biodegradation reactions occurring naturally at the site, and it can help identify amendments needed to accelerate these reactions and enhance key microbial populations. These studies use groundwater samples and/or aquifer material and are commonly employed as microcosm studies, batch tests, and soil column studies evaluated over time.

Laboratory treatability studies are used to determine:

- naturally occurring biotransformation/degradation reactions in site samples

- the ability to control/enhance biotransformation/degradation rates under site conditions
- which microbial populations are stimulated and the potential benefits of bioaugmentation
- initial estimates of reaction kinetics, stoichiometry, mass balances and costs.

RABITT. A good example of biotreatability testing is the Reductive Anaerobic Biological *In Situ* Treatment Technology (RABITT) Technical Protocol. This protocol was developed because those responsible for implementing site cleanups often do not have a complete understanding of the reductive dechlorination process (dechlorination of PCE to ethane). This frequently resulted in uncertainty regarding the outcome of proposed remedial strategies even with laboratory and/or field data that strongly suggested a positive outcome.

The RABITT protocol presents detailed instructions for assessing the applicability of *in situ* enhanced biological reductive dechlorination at a specific site. It describes laboratory, microcosm and field test methods designed to evaluate the response of indigenous microorganisms to the addition of soluble electron-donating substrates used in the dechlorination process and the development of appropriate laboratory biotreatability tests. It also provides information used to develop site-specific contaminant transport/fate models and to design the injection formulation, enhancement strategy *(2, 11).*

Pilot-scale demonstration. Many ISB applications are site-specific, and a pilot-scale field demonstration may proceed without a laboratory biotreatability study if site conditions demonstrate that ISB is appropriate. Pilot-scale testing is typically conducted as a 1:100 to 1:10,000 scale model of the proposed biotreatment process. Pilot-scale testing allows for adjustment or modification of design parameters (*e.g.,* injection methods and rates, specific amendments, etc.) to accommodate site-specific circumstances and conditions prior to full-scale implementation.

Testing goals and objectives should be clearly defined, along with any other concerns, to provide site managers with enough information to make a decision about whether to implement the selected ISB technology. Topics of concern in pilot-scale testing include site selection, hydrogeologic evaluation, permitting and regulatory acceptance of the proposed treatment, delivery and mixing of amendments (*ex situ* or *in situ* mixing), system operation and maintenance requirements, contaminant and byproduct degradation monitoring, cost and performance evaluation, and determination of the potential for injection well or formation biofouling (plugging) and means to prevent it. An example of a

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pilot-scale test for chlorinated and recalcitrant compounds can be found in Ref. 12.

Full-scale implementation. Every remediation technology has certain limitations, and ISB is no different. If data collected during the site characterization, feasibility and biotreatability assessments are not favorable for ISB, then other technologies must be considered. An economic evaluation of all remediation technologies appropriate for the contaminated site is essential. Also, public and industry understanding of ISB systems is critical prior to implementation.

Before full-scale implementation is selected, ISB goals, including monitoring programs, cleanup levels, time constraints, and cost, should be clearly defined. If a pilot-scale field demonstration shows that ISB is effective for attaining remediation goals within an acceptable time frame, approval of a full-scale ISB project is greatly simplified. Full-scale permits are easily modified from pilot-scale field demonstration permits and full-scale design does not typically require considerably more engineering than the pilot-scale field demonstration.

Economics. An ITRC document entitled "Cost and Performance Reporting for *In Situ* Bioremediation Technologies" *(13)* describes a reporting methodology for obtaining comparable information regarding costs and performance associated with different ISB technologies. The Federal Remediation Technologies Roundtable (FRTR) has also developed a guidance document to evaluate the cost and performance of remediation technologies *(14).* The FRTR has compiled case studies from specific sites that have deployed enhanced ISB. To search the list of the numerous case studies, visit the FRTR website, www.frtr.gov. Ref. 15 is another good discussion of economic analysis.

Risks and liabilities. Risks and liabilities are always a major issue for any remediation system. Perceived risks involved with implementing ISB should be identified and resolved prior to selecting an ISB remediation system. These include:

- lack of knowledge of some parties involved
- contingency plans need to be prepared
- concerns that ISB is not universally accepted as a viable remediation technology
- risk of plume migration onto other properties during the course of *in situ* treatment.

Concluding thoughts

Standardized *in situ* biotreatment criteria, summarized here and presented in detail in ITRC's ISB guidance document *(1)* provides site managers and regulators accepted guidelines for evaluation of ISB treatments of contaminated groundwater. Application of these criteria will result in efficient and consistent decision-making processes that can be applied generically at any site and for any contaminant to evaluate ISB feasibility and effectiveness. CEP

The authors are members of the **Interstate Technology Regulatory Council's (ITRC)** In Situ **Bioremediation Team.** ITRC (www.itrcweb.org/) is a state-led coalition of 40 states, the District of Columbia, multiple federal partners, industry participants, and other stakeholders working together to achieve regulatory acceptance of environmental technologies.

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