

# Engineered Passive/Permeable Reactive Barriers as a Remedial Technology Solution for Contaminated Groundwater

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**Key Words:** reactive Barriers, permeable barriers, remedial technology, groundwater

**Abstract:** Technical uncertainties and lessons learned from engineered barrier installation case studies will be highlighted based upon a January 23-25, 2001, U.S. Department of Energy (DOE) sponsored permeable reactive barrier workshop in Salt Lake City, Utah. The workshop was by invitation only of national academic, federal agency, and contractor scientific and engineering experts. Their task consisted of developing engineering guidelines based upon their laboratory testing and field installation and operational experience with passive barriers. Conference session participants will gain an overview of lessons learned and installation guidelines for implementation of barriers that will provide valuable characterization-design-construction-monitoring and critical geochemical information that influence design decisions and implementability of these barrier.

## Introduction

Approximately 85% of the hazardous waste sites in the United States have contaminated ground water (EPA). The conventional approach for remediating contaminated ground water has been to extract the contaminated water, treat it above ground, and re-inject or discharge the clean water in a process known as "pump-and-treat." The recovered contaminants must be disposed of separately. Pump-and-treat technologies require considerable investment over an extended period, and it has been shown that these technologies often do not actually remove the source of the contamination. Current EPA and state regulatory agency policies and laws stress "permanent" remedies over simple containment methods.

Consequently, there is considerable interest in and effort being expended on alternative, innovative treatment technologies such as Permeable Reactive Barriers (PRBs) for remediation of contaminated ground water.

A PRB is a passive in situ treatment zone of reactive material that degrades or immobilizes contaminants as ground water flows through it. PRBs are installed as permanent, semi-permanent, or replaceable units across the path of a contaminant plume. Natural gradients transport contaminants through strategically placed treatment media. The media degrade, sorb, precipitate, or remove chlorinated solvents, metals, radionuclides, and other pollutants. These barriers may contain reactants for degrading volatile organics, chelators for immobilizing metals, nutrients and oxygen to enhance bioremediation, or other agents.

Numerous hazardous waste sites have significant concentrations of metals, halogenated organic compounds, and radionuclides that contaminate ground water. Traditional technologies, such as pump-and-treat, require an external energy source and their cost is high. Subsurface residuals frequently remain at undesirable levels. Thus, subsurface PRBs are being researched and deployed as a potential cost-effective alternative. Properly designed and installed PRBs are being considered by some remediation decision-makers as an innovative technology to reduce the levels of many residual contaminants to regulatory cleanup goals. These barriers are expected to have low maintenance costs, though the stability of aging barriers is still subject of considerable debate and study.

Choice of reactive media for PRBs is based on the specific organic or inorganic contaminant to be remediated. Most PRBs installed to date use zero-valent iron ( $\text{Fe}^0$ ) as the reactive media for converting contaminants to non-toxic or immobile species. For example,  $\text{Fe}^0$  can reductively dehalogenate hydrocarbons, such as converting trichloroethylene (TCE) to ethylene, and reductively precipitate anions and oxyanions, such as converting soluble  $\text{Cr}^{+6}$  oxides to insoluble  $\text{Cr}^{+3}$  hydroxides. The reactions that take place in the barriers are dependent on parameters such as pH, oxidation/reduction potential, concentrations, and kinetics. The hydrogeologic setting at the site is also critical—geologic materials must be relatively conductive and a relatively shallow aquitard must be present to contain the system.

Currently, most PRBs are installed in one of two basic configurations: funnel-and-gate or continuous trench, although other techniques using hydrofracturing and driving mandrels are also used. The funnel-and-gate system employs impermeable walls to direct the contaminant plume through a gate, or treatment zone, containing the reactive media. A continuous trench is installed across the entire path of the plume and is filled with reactive media.

## Barrier Design and Implementation Workshop

To support development of working guidelines for implementation of barriers and to address data gaps and future research needs the Department of Energy, Office of Science and Technology, Subsurface Contaminant Focus Area sponsored an invitational PRB workshop at the University of Utah, January 23-25, 2001. The primary task of the workshop was to evaluate specific concerns of barrier design and implementation via case study analysis and identify guidelines for the implementation of barriers. The workshop used a discussion format with approximately 30 subject matter expert participants from relevant and diverse backgrounds.

In the first portion of the workshop participants were divided into small working groups each consisting of 6 to 8 participants, a team leader, and a facilitator. Each group focused on one of three discussion topics: Hydrology, Geochemistry, or Performance Goals. During the second portion of the workshop the entire group discussed a fourth topic, Long-Term Performance. Each group team leader provided participants a list of case studies (selected by group leader and provided to participants in advance), objectives, a draft decision tree, and an outline of expected subtopics to be discussed. Although the primary task of the workshop was to develop working guidelines for design and implementation of barriers, the goal of the workshop included identification of data gaps and future research needs.

### **Hydrology Topics**

The hydrology group discussed how presently used characterization-design-construction-monitoring paradigm could be changed to ensure that the PRB technology is appropriately applied at a particular site. Specific questions discussed by the hydrology group included:

- How is the appropriate number of monitoring points and field hydraulic tests determined to adequately characterize a site where a PRB installation is planned?
- Are there new approaches that should be employed for hydrologic characterization?
- How important is it to characterize the spatial variability of the PRB?
- What is an appropriate scope for long-term hydraulic monitoring?

One specific case study evaluated by this group involved a site where the pre-construction hydrologic evaluation was inadequate, and where extensive post-construction evaluation was performed.

### **Geochemistry Topics**

The geochemistry group evaluated the state of the art (Are PRBs working? Is more research needed?) in PRB implementation from a geochemical perspective and identified the most critical geochemical issues that influence design decisions and implementation of PRBs. Specific questions that were discussed/debated included:

- What type of laboratory and field-testing is needed prior to construction?
- How well do reaction mechanisms need to be determined?
- What chemical measurements are important prior to and after construction?
- How useful is geochemical modeling?
- What reactive materials should be considered (advantages/disadvantages)?
- Can accurate predictions of longevity be made?
- Are any harmful byproducts likely?
- Can PRBs be rejuvenated with chemical injections?
- How does groundwater chemistry affect performance?

### **Performance Goal Topics**

The performance goals group discussions focused on the idea that reactive barriers may seem obvious, to contain the plume and, for the groundwater passing through the barrier, to reduce the contaminant concentrations to an acceptable level (i.e., MCL) over the lifetime of the barrier. This deterministic perspective works when there is a reasonable level of certainty that, indeed, the plume is captured by the reactive barrier system and that the measured concentrations at downstream monitoring points are representative. However, problems arise when there are long-term performance problems, heterogeneous conditions, unintended chemical reaction/transport pathways, background concentrations downstream of the barrier that are initially higher than the MCL, or when sampling isn't considered representative. The performance goals group approach included:

- Brief assessment of the current performance goals for PRBs
- Current analysis and monitoring methods that should be used with existing performance goals
- Alternative performance goals, including risk-based evaluations
- Research and development needs to better achieve performance goals
- A decision tree for the development of site-specific performance goals

Subsequently, performance group discussions then focused on the following questions:

- What preliminary design steps and criteria should be considered to evaluate primary PRB design alternatives (funnel and gate vs. continuous wall)?
- Are current designs well monitored, so that performance problems can be identified? What criteria should be used to suggest the detail and resolution to which a PRB should be monitored?

- What are significant mechanisms for failure that are not commonly planned for in conventional PRB designs? What alternative contaminant transport pathways are ignored?
- How can performance-monitoring strategies be employed as part of the PRB design - and how do these techniques affect constructability? Can performance monitoring be developed in such a way to permit routine evaluations - without impacting the performance and passive operation of the PRB?
- Is there a clear process for post-installation audits of the site characterization, design, and installation procedures?
- Are current designs adaptable, so the PRBs can be fixed if there are performance problems?
- Are the cost factors for reactive barrier designs well described?
- What optimization strategies should be used to generate high performance PRBs at the lowest possible cost?
- Should design criteria be risk-based or deterministic?
- What new modeling tools are available for testing the potential effects of heterogeneity?
- What types of modeling scenarios should be tested to address heterogeneity effects, changes in flow direction, effects of permeability reductions, and non-ideal reaction conditions?
- How can modeling be validated? Do existing field tests and field-scale barriers provide enough information to strengthen models used for design?

### **Long-Term Performance Topics**

Workshop participants then reconvened to discuss the overarching issue of long-term performance associated with PRBs plume capture and contaminant treatment over extended periods. That is, assuming the system initially performs as designed in terms of treatment and contaminant plume interception, how long can one expect remedial performance goals to be met before there is sufficient loss of reactivity and/or permeability, which results in excessive contaminant breakthrough beyond the established compliance points. The design of the barrier and nature of the reactive media in the context of site-specific hydrogeochemistry and microbial ecology have a direct influence on system lifetime.

Long-term performance group discussions included:

- Since PRB lifetime may be one or more decade, long-term performance will be case-specific, but should be considered at time scales of multiple years or greater. Agreed?
- If lifetime estimate is difficult to obtain (due to lack of data, models), are the methods clear to establish a critical lifetime when compared to other remediation alternatives? (Required lifetime obtained from cost analysis such that PRB costs are competitive with other low-cost alternatives). How long do they need to last?
- What are suitable design strategies to account for expected losses in performance? For instance, should a safety factor be applied for expected reactivity losses? Should a safety factor on capture area be applied for expected permeability reductions?
- What design strategies should be considered to allow greater flexibility in monitoring and addressing long-term performance problems over the period of operation?
- What is the current practice of assessing hydraulic conductivity of PRBs - and isolating effects of flow heterogeneity in getting better assessments for reactivity changes? Do these measures need to be improved?
- How should media sampling strategies be used to obtain good estimates on reactivity changes? Is sample disturbance a major problem?
- What are the most acceptable strategies for recovering performance (either from a reactivity or permeability standpoint) from PRBs (ultrasonics, chemical regeneration, etc.). What are the principal shortcomings?
- How does loading, groundwater chemistry (pH, ORP, major ion concentrations) and temperature affect rates and byproduct formation over time and thus, longevity?
- How does media selection impact permeability, reactivity and reaction mechanism and long-term performance?
- Will contaminants be released after the barrier becomes ineffective?
- What, if any, role is played by microorganisms vis a vis long-term performance?

### **Summary Synopsis**

Based upon workshop discussions it was concluded that PRBs have finite treatment capacity regardless of the nature of the reactive media or PRB design. The barrier life will be limited by the chemical characteristics of the barrier, the site geochemistry, hydrology, site microbiology and changes in the microbial ecology within and immediately surrounding the barrier. All these factors will cause changes in system performance over time, ultimately leading to decreased effectiveness of the remedial system. Long-term performance assessments evaluate these changes on a site-specific basis in an attempt to predict longevity of the system and develop contingency plans. These may include reactive media replacement or rejuvenation of the reactive media.

Reactions occurring within the barrier are responsible for contaminant destruction or immobilization, but also will eventually lead to decrease in reactivity and porosity of the system. Processes leading to decreased reaction rates within the barrier include consumption of reactive material, decreased reactive surface area from secondary precipitate formation, clogging and creation of preferential flowpaths through the reactive media.

Microbiological activity impacts are also important to understand and better predict how long these systems will remain effective in the subsurface. The presence of a large reservoir of iron and favorable pH and substrate availability conditions may favor the activity of iron and sulfate reducing bacteria and methanogens. This enhanced activity may favorably influence zero-valent iron reductive dehalogenation reactions through favorable impacts to the iron surface or through direct microbial transformations of the target compounds. However, this enhancement may come at the expense of faster precipitate buildup and potential biofouling of the permeable treatment zone.

Evaluations of improved monitoring methods are also important, both in terms of developing more effective and efficient ways to monitor performance, but also to minimize costs associated with long-term monitoring. Research involving long-term performance includes the development of better monitoring strategies.

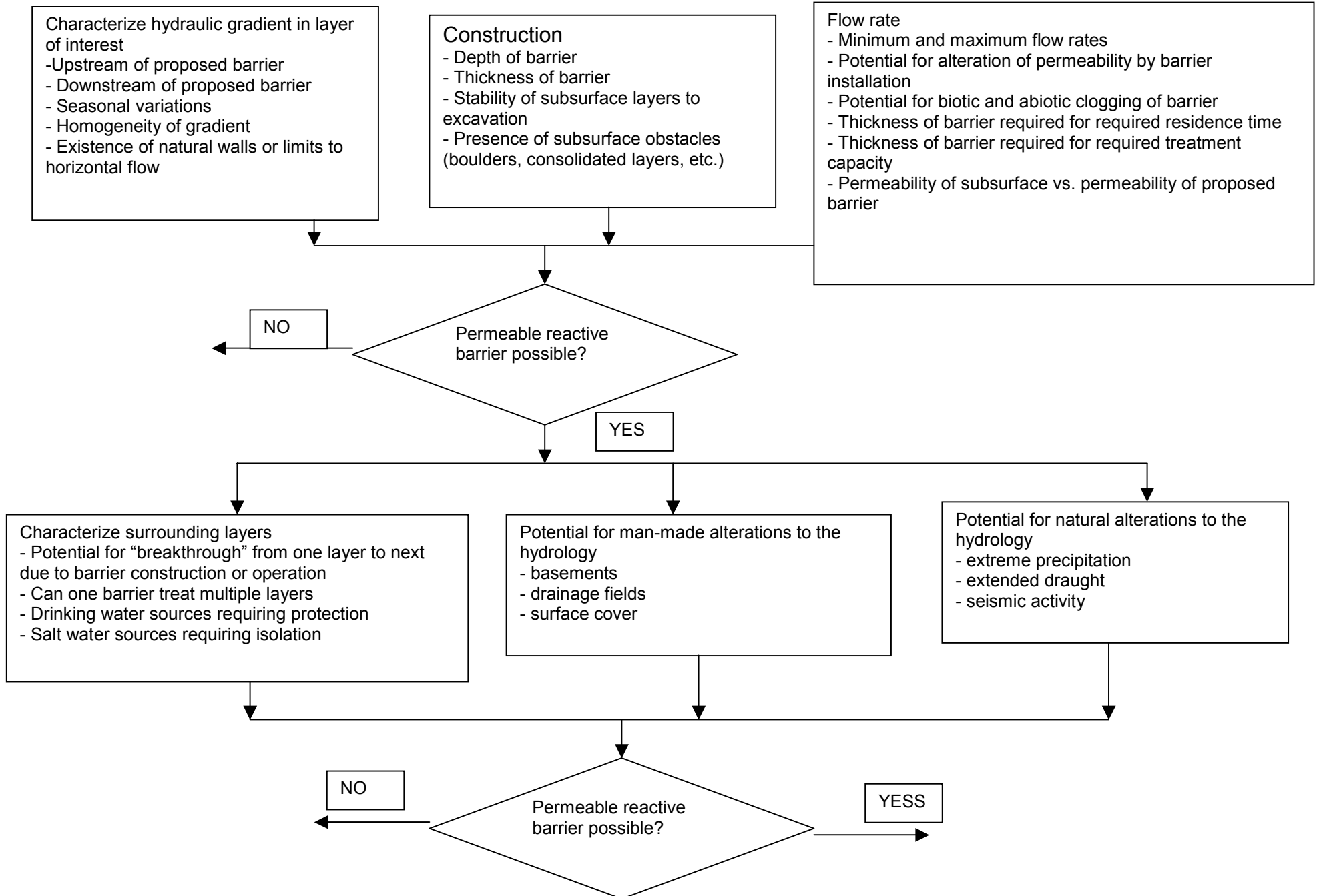
The difference between long-term performance and performance goals is a matter of both time and space. Performance goals are usually developed for the site as a whole and contingent upon plume and barrier location relative to compliance points and/or site boundaries. The performance goals can be a numeric, regulatory-driven targets and the system design may include remedial measures such as natural attenuation downgradient of the barrier location. The time horizon for sustaining performance goals will depend on site-specific factors related to chemical, physical and microbiological processes but also such things as the extent of source removal, source containment or expected lifetime of the source as a plume generator.

Long-term performance concerns are usually focused on the reactive media itself and its ability to function in terms of competing functions: reactivity and permeability. The objectives of long-term performance studies are: to provide insights for improved future system designs; models for predicting system longevity based on site-specific physical, biological and chemical parameters; improved monitoring strategies; and lower implementation costs for future installations. Long-term performance is focused upon obtaining this data while minimizing cost.

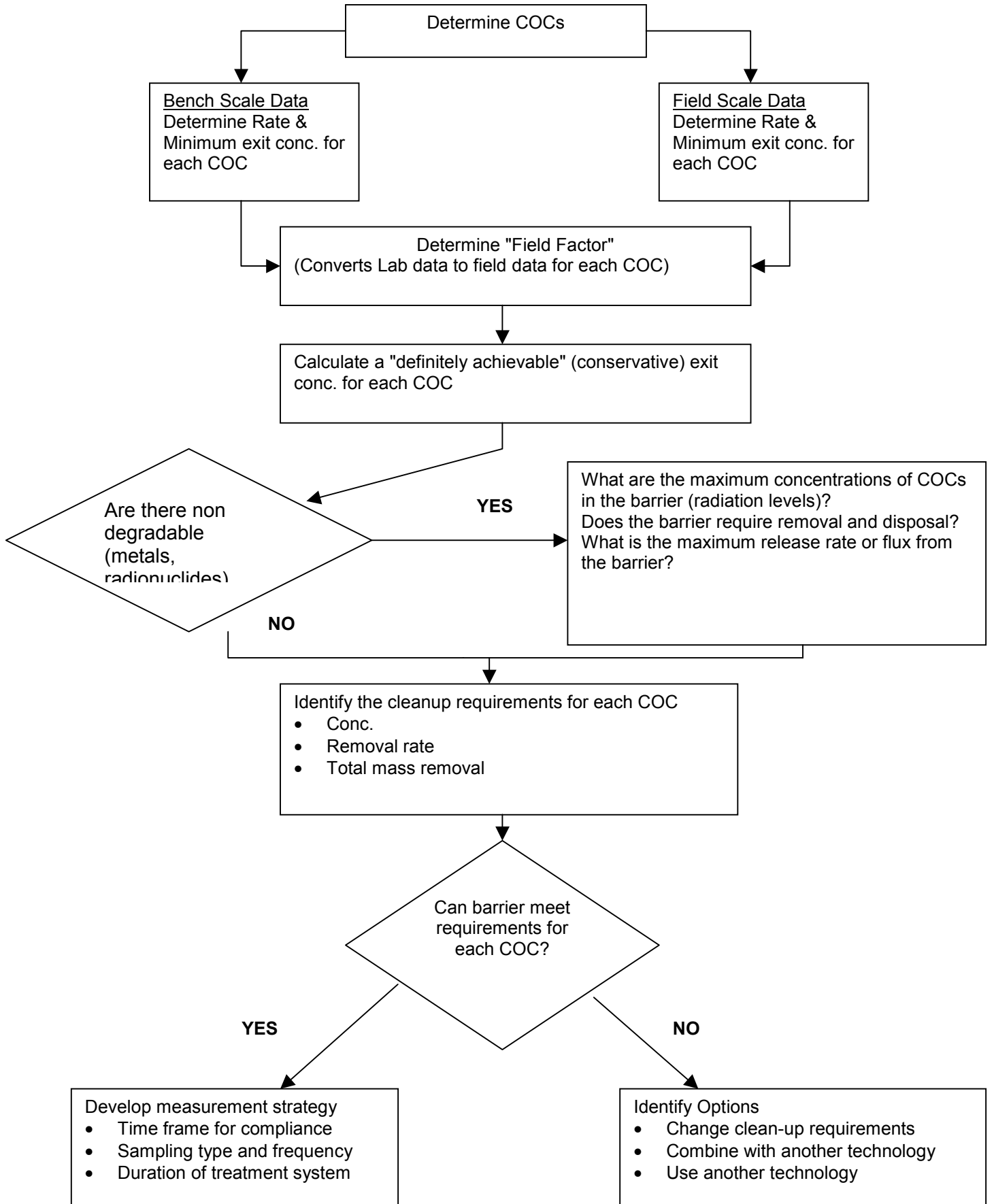
### **Decision Trees**

Decision Trees and other Tools were used at the Workshop to guide discussions and record results, key issues, and information gaps. Decision trees were different for each group and some groups used a universal decision tree. A decision tree matrix shows when pertinent questions should be asked, is flexible, and can be altered according to the team objectives; project management requirements, or other design and implementation considerations. Sample decision trees for each discussion group are appended.

Draft Decision Matrix  
**HYDROLOGY**



Draft Decision Matrix  
**PERFORMANCE GOALS**



Draft Decision Matrix:  
**GEOCHEMISTRY**

