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Technical Note 3.13

2005

Specification for Construction of a Granular Iron PRB using Trenching Methods

The following are general specifications for construction of a granular iron permeable reactive barrier (PRB) using various trenching methods. For specifications on biopolymer trenching method see TN 3.11. There are some details noted in the specifications that require project specific data. *This information is in [] brackets and in italics is provided as information in preparing the specification and is not intended to be incorporated in the completed specification.*

Description

The work described in this section consists of furnishing all labor, equipment, materials, and supervision for installation of a PRB using a trenching technique.

The trenching method for a PRB involves excavating of a trench and simultaneously filling the trench with a reactive material such as granular iron or a granular iron/sand mix. Common trenching methods include continuous trenching, unsupported excavation and supported excavation, such as hydraulic shores, trench box, slip box or cofferdam, etc.

The work shall include, but not be limited to, the following items:

1. Site preparation;
2. Supply of reactive material [*unless granular iron and/or sand is supplied by owner*];
3. Excavation of the trench;
4. Preparation of reactive material [*if required*];
5. Backfilling trench with reactive material;
6. Backfilling material on top of reactive material; and
7. Management of excavated trench spoils.

Qualifications

1. The Contractor shall provide written evidence of experience and competence in trench construction, especially in PRB applications.
2. The Contractor shall provide resumes of the following qualified field staff for the project:
   a. Quality Control Engineer – An on-site quality control engineer with several years experience in construction quality control and/or construction management.

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b. Operator(s) – The operator(s) for the excavation equipment shall have several years experience with clamshells, backhoe, chisels, and other excavation equipment proposed by the contractor.

Work Plan

1. The Contractor shall submit a detailed operating plan describing the proposed construction methods, equipment, and schedules. This shall include, but not be limited to, the Contractor's plan for each of the following:
   a. Listing of Supervisory Personnel: Name and experience of the various persons, their role and primary responsibilities.
   b. Construction Means and Methods: Listing of equipment and capabilities, construction steps, excavation, backfill placement, handling of trench spoil, utility crossings, work platform construction, maintenance and removal.
   c. Incorporated Materials: Certificates of compliance, test reports and/or catalog cuts and material safety data sheets (MSDS) provided by the manufacturers of the permanent materials that become a part of the final installation.
   d. Quality Control: The contractor shall provide a detailed quality control program covering all aspects of the installation, i.e. backfill placement controls, granular iron content, trench widths and depth, and corrective measures.
   e. Clean up: Site restoration, spoils disposal, etc.
   f. Schedule: Bar chart with starting and ending dates for major segments of the work, estimated production rates, days and hours of operation.

Drawings

State drawings showing PRB design. Items to include in drawings include:
- Limits of PRB including prominent site features (roadways, buildings, access, utilities, water bodies, etc.), location of existing and proposed monitoring wells.
- Profile of PRB showing existing grade, finished grade, high water table, general stratigraphy, granular iron requirements (weight percent for each section if applicable), confining units (if present), location and screened interval of existing and proposed monitoring wells.

Reactive Material Specification

Reactive material includes granular iron, and where used, sand that is mixed with the granular iron.

Granular Iron Specifications

1. The granular iron should consist of approved dry material free from oils, greases, or other foreign organic substances.
2. The granular iron shall be:
   - Connelly-GPM, Inc., 3154 S California Ave., Chicago, IL, 60608-5176
     Tel: 773.247.7231 Fax: 773.247.7239 Web: www.connellygpm.com
   - Product ETI-CC1004 (-8 to +50 US Standard Mesh Size)

[*The rate of degradation of VOCs by granular iron varies with iron suppliers and iron gradation. If site-specific treatability testing is undertaken, ETI recommends that the iron source used in the test be the same source used for the field installation, as the degradation rates determined will be specific to the iron source tested. The engineer may consider specifying the purchase of granular iron from that particular source. If a substitute product is proposed, the Contractor shall determine the degradation rates for site groundwater with an approved treatability test to determine the required flow-through thickness of granular iron. Substitutes are subject to approval.*]

3. Suppliers should be queried as to the buyback of reactive material, in the event excess material exists at the end of construction.
4. The gradation of granular iron should approximate the range specified in Table 1, and be approved.

Table 1: Granular Iron and Sand Gradation Requirements

Sieve Size		**Weight Percent Passing**
US Standard Mesh Number	**mm**	
Number 8	2.4	95 – 100
Number 16	1.2	75 – 90
Number 30	0.6	25 – 45
Number 50	0.3	0 – 10
Number 100	0.15	0 – 5

5. Granular iron should be transported and arrive on site at near ambient temperatures.
6. The granular iron shall not be directly exposed to moisture, mixing with foreign matter during production, shipment or storage.
7. The granular iron unloaded at site should be protected from contact with water at all times. Stored granular iron should be covered with impermeable sheets anchored or tied in place, if stored outdoors. Granular iron should not be stored directly on the ground surface.
8. Protective packaging should not be removed from granular iron until mixing or placement in the PRB. Unused portions of granular iron shall be returned to storage and protected in accordance with the above requirements.

Sand Materials for Reactive Mixture

1. The gradation of the sand shall approximate the grain size range specified in Table 1 and be similar in minerology to the native aquifer materials, and be approved.
2. Sand shall be free of stones, clay particles, debris, organic matter, and other foreign material.
3. Sand should be in as dry condition as possible prior to mixing with the granular iron.

Reactive Material Quality Control

Granular Iron

1. Grain size sieve analyses are to be completed on representative samples collected a minimum every [___] tons/kg [*typically up to 10 tests are sufficient*] during the production run in accordance with ASTM D 422, Particle Size Analysis of Soils (only the sieve portion of the test has to be completed). The results are to be within the range specified in Table 1.
2. All involved parties should reserve the right to visit the Manufacturer during the production run to visually inspect the manufacturing process and collect random samples at that time. The Manufacturer should provide reasonable assistance to obtain these samples.

Sand Material

1. Grain size sieve analyses are to be completed on representative samples collected a minimum every [___] tons/kg [*typically one to three tests are sufficient*] of sand delivered to the site in accordance with ASTM D 422, Particle Size Analysis of Soils (only the sieve portion of the test has to be completed).

Granular Iron/Sand Mixing [*If applicable*]

1. The granular iron and sand shall be mixed into a uniform mixture using suitable equipment. Satisfactory means, incorporating weighing, or metering shall be provided to assure the proper ratio of iron to sand is maintained. Equipment such as concrete trucks, mobile concrete mixers (e.g. Elkin Mixer), or stationary concrete mixers (e.g. pug mills) are suitable alternatives. [*The most common and accurate method to mix iron and sand is to pre-weigh sand in concrete trucks and add iron to the concrete trucks when they arrive on site. By using this method, the percent weight is easily determined since the weight of the sand and iron is known. The iron and sand is then mixed in the concrete trucks for a minimum of 10 minutes at high revolutions. Another method for mixing iron and sand is using a stationary or portable mixer such as an Elkin mixer or a pug mill. The Elkin mixer works in such a way that the sand and iron are added to separate open bins and the flow valves are adjusted to correctly add the quantities of sand and iron required in the mix. The iron and sand are then mixed with an auger on the discharge of the auger. Another method of mixing iron and sand would be to mix them by volume. This method involves using an excavator bucket or front end loader bucket of known volume and adding iron bags with a known volume to an empty concrete mixer or other similar machine to achieve the proper iron and sand mixture. All iron and sand mixtures should be verified using the magnetic separation test procedures (Attachment A) before the iron and sand mixture is placed in the trench.*]
2. All equipment should be clean of foreign materials (e.g. concrete mix, soil, stones, etc.).
3. The granular iron/sand mixture shall contain a minimum [___] percent granular iron by weight dry. [*The specification should specify whether the proportion of granular iron to be used in the mixture is given as a dry weight percent or volume percent. Weight percent*

based on trench width is preferred. This requires a determination of the expected in place bulk density of the granular iron and sand.]

4. The iron/sand ratio shall be based on the actual bulk densities for the granular iron and for the sand. A bulk density of 150 lbs/ft^3 (2,400 kg/m^3) shall be used for the granular iron and a bulk density of 100 lbs/ft^3 (1,605 kg/m^3) shall be used for the sand. [*Alternative bulk densities can be proposed by the Contractor and used if approved by the owners representatives.*]
5. *The ratio of granular iron to sand is dependent on the actual excavated width of the trench (Table 2). ETI's minimum recommended amount of iron in an iron/sand mixture is 20% iron by volume. The granular iron/sand ratio shall be based on dry weights. The following are examples of granular iron/sand ratios for a 2 ft (0.6 m) wide trench:*

Table 2: Examples of Required Iron Thicknesses and Mixtures

Excavated Trench Width	Required Iron Thickness	Percent Granular Iron by Volume	Percent Granular Iron by Weight [a]	Percent Sand by Weight [a]
2.0 ft (0.6 m)	0.4 ft (0.12 m)	20%	27%	73%
	1.0 ft (0.3 m)	50%	60%	40%
	2.0 ft (0.6 m)	100%	100%	0%

a - Based on estimated bulk densities of 150 lbs/ft^3 (0.075 ton/ft^3; 2,400 kg/m^3) for the granular iron and 100 lbs/ft^3 (0.050 ton/ft^3; 1,602 kg/m^3) for the sand. The actual bulk densities must be verified prior to construction.

6. The weights of sand and granular iron mixed in each batch shall be measured with approved methods and recorded.
7. The sand and granular iron shall be mixed to provide a uniform mixture. The uniformity of the mixture shall be determined with a magnetic granular iron separation test as described in Attachment A. The results of the magnetic separation test must be within __ [*2%*] or greater of the specified ratio.
8. [*If applicable*] If the granular iron/sand mixing is to occur off site, the mixing contractor must be made aware of granular iron handling and storage issues (i.e. keeping it covered and dry). The granular iron/sand mixture must be stored in a manner similar to the granular iron.
9. The granular iron and sand mixture may be stored prior to installation based on the moisture content of the mixture as specified in Table 3.

Table 3: Granular Iron –Sand Mixture Storage Times

Granular Iron-Sand Mixture Moisture Content (Weight Percent)	Granular Iron/Sand Mixture Maximum Recommended Storage Times (hr)
0 to 3	72
3 to 6	48
6 to 9	24
greater than 9	8

10. During transport and handling, care should be taken to minimize vertical drop and vibration of the finished product to prevent separation/segregation.
11. Quality control testing of the mixed sand and granular iron materials shall be conducted on every _____ [*100 cubic yards; 75* m^3] of material to verify compliance with the specifications.

Trench Excavation

1. The Contractor shall provide sufficient numbers and types of excavating equipment to complete the PRB trench to the final depth and complete the project within the schedule. The equipment is to be in good condition with no hydraulic leaks and have been decontaminated prior to mobilization to the site.
2. The Contractor shall maintain the stability of the trench excavation. The Contractor shall control surcharges from excavation and backfill equipment, soil stockpiles, backfill stockpiles, and any other surcharge loads that may affect trench stability.
3. The following tolerances shall apply to the PRB trench dimensions and construction. The tolerances may vary from the designed values if approved by the Owner's representative.
   a. The PRB shall be essentially vertical.
   b. The PRB shall be measured or surveyed to within _______ [*6-inches; 15 cm*] of the desired elevation.
   c. The PRB trench shall follow the designed alignment within _____[*1-foot; 30 cm*] of the designated centerline.
   d. [*If applicable*] The PRB shall be keyed in the underlying aquitard to a minimum depth of ____ [*4 inches; 10 cm*].
   e. Construction will not be permitted when severe weather conditions may compromise the quality of the work.
   f. [*If applicable*] Monitoring wells shall be installed to within _______ [*3-feet; 91 cm*] of the designated location.
4. In the event the excavated trench is wider than the design thickness (e.g. partial collapse has occurred), the Contractor may increase the ratio of the sand to granular iron to provide an equivalent granular iron flow-through thickness. The calculation of the granular iron/sand ratio shall be based on the minimum measured trench width in the section of concern. Any change must be approved and be no less than 20% by volume of granular iron. Cost for additional supply and placement of granular iron and sand materials and disposal of excess soil shall be the responsibility of the Contractor.

Backfilling of Reactive Material

1. The reactive material is typically placed to the historical high water table.

2. a) If the excavated trench is filled with water, the reactive material shall be placed into the trench via a tremie tube with a minimum diameter of 12-inches (30 cm) or other approved method. The base of the tremie tube shall be maintained a distance of not more than 4-ft (1.2 m) above the top of the placed mixture.
   b) If the excavated trench is dry or only small amount of groundwater is present, the backfilled can be placed by freefall, without using a tremie.
3. The Contractor shall excavate a sufficient length of trench to accommodate the slope of the mixture or provide means of preventing the placed mixture from reaching the excavation face.
4. Water from an approved source may be added to the backfill to assist in placement and/or as a dust control measure.
5. Samples of the granular iron/sand backfill are to be collected from the approximate mid depth of the trench a minimum every [___] ft/m along the trench. The granular iron fraction is to be determined using the magnetic separation test to verify compliance with the specifications.

Backfilling on Top of Reactive Material

1. After the trench has been filled with the reactive material, a geotextile may be place on top followed by clean native soil or sand, or depending on the site conditions, perhaps a lower conductivity material may be required.

Construction Quality Control

Granular Iron

1. Several samples of the granular iron should be collected during the construction. The production number (bag number) and location of placement in the PRB should be logged.

Sand

1. Several samples of sand should be collected during the construction. The source of the sand and location of placement in the PRB should be logged.

Granular Iron and Sand Mixture

1. The percent granular iron on a dry weight basis is to be determined with the Magnetic Separation Test as described in Attachment A. The testing should be completed on representative samples collected from the mixing device. The frequency of testing will depend on the potential variability of the mixing method. Typically more testing is completed in the early stages of the mixing and this frequency is reduced if the results are adequate. The percent granular iron must meet a minimum percent specified on a dry weight basis for the project.
2. Where the granular iron and sand is mixed in a batch process, the percent granular iron can be determined on a bulk basis. The mass of sand is to be determined by an approved method such as a truck scale, portable scale or bucket scale. The mass of wet sand must be corrected for moisture content, either with the moisture content determined with the

magnetic separation test of a moisture content test on the sand. This provides assurance that the correct tonnage of granular iron is emplaced.
3. The granular iron sand mixture shall not be stored for periods greater than specified in Table 3.

Trenching and Backfilling

1. Where the confining unit is bedrock, the bottom of the trench shall be verified by scraping the competent bedrock with the excavator bucket in the presence of the Site Owner's representative. Where the confining unit is soil, the bottom of the trench shall be verified by visual inspection of material excavated from the confining unit.
2. The final depth of the trench should be measured a minimum every 10 feet (3 m) along the length of the trench. The depth shall be measured on each side and the middle of the trench and referenced to a benchmark.
3. The mass of granular iron emplaced in the trench shall be recorded. The mass of granular iron emplaced shall be checked against the design mass on as short a trench section as possible (e.g. each panel or defined section, as it is difficult to determine the volume of backfill when a section is not completely filled).
4. Samples of the granular iron/sand backfill are to be collected from the approximate mid depth of the trench a minimum every [___] ft/m along the trench. The granular iron fraction is to be determined using the magnetic separation test to verify compliance with the specifications.

Health and Safety

1. The Contractor should ensure adequate protection for all on-site personnel and prepare and implement a complete site-specific Health and Safety Plan in accordance with all applicable federal, state, and local regulations. The plan should cover the Contractor, subcontractors, and visitors while on the site.
2. The granular iron material is a dust nuisance and adequate personal protective equipment should be worn at all times while handling or being in close proximity to granular iron material. MSDS data sheets are available from the manufacturer.
3. The contractor should be made aware that mixing of granular iron and sand might cause the temperature of the mixture to increase by several tens of degrees due to friction of the granular particles and oxidation of the granular iron.

Attachment A - Magnetic Separation Testing Procedure

[*Note: The Contractor or Site Owner's Representative, or both may complete this test.*]

1. Weigh the empty containers that the samples will be collected in.
2. Samples (about 250 to 1,000 g) of the iron-sand mixture are collected from the discharge of the mixing device (e.g. shoot of a concrete mixer) and/or from the backfilled material with excavation. The frequency and location of samples is dependent on the objectives of each project.

3. Weigh the sample (empty container and sample) and record the weight. Determine the net weight of the sample by subtracting the empty sample container weight. A suitable weighing device must be used.
4. Dry the sample. If cemented together during drying, lightly breakup, weigh and record the net weight.
5. Spread the sample out in a suitable container (e.g. bowl, pan, cardboard box, etc.).

6. Cover the magnet in a material (such as a plastic bag) to allow the magnetic material to be easily separated from the magnet.
7. Pass the magnet over the sample to remove the magnetic fraction. Care must be taken to minimize the trapping sand particles within the iron grains. The magnetic fraction is removed from the magnet and placed in a container.
8. Continue passing the magnet over the material until no more magnetic material is removed. Mixing of the non-magnetic fraction between passes may be required to obtain all the magnetic particles.
9. The magnetic fraction may contain some non-magnetic (sand) particles. Repeat Steps 5 to 8 should at least three more times to ensure the magnetic and non-magnetic fractions are completely separated. After each separation, the non-magnetic fraction should be added to the non-magnetic fraction from the previous separation.
10. Weight the magnetic and non-magnetic fractions are and weights recorded. The total net weight of the magnetic and non-magnetic fractions should be the same as the weight prior to separation.
11. The dry iron net weight percent is determined by:

$$\text{Dry Iron Net Weight Percent} = \frac{\text{Net Weight of Magnetic Material}}{\text{Total Net Weight of Dry Sample}} \times 100$$

Estimated time to complete the magnetic separation test is about 15 to 25 minutes, depending on how moist the iron/sand sample is.

<u>Equipment Required for Magnetic Separation Testing</u>

1. Sample containers
2. Balance/Scale (battery powered scale if electrical outlet is not available; approximately 500 grams required)
3. Hot plate, if electrical outlet available (or propane camping stove)
4. Frying pan (8 in or 10 in)
5. Large spoon (metal is better than plastic)
6. Disposable aluminum cookie sheet
7. Magnet
8. Ziplock bags
9. Sharpie Pen
10. Worksheets/Log Book

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Monitoring of Iron Permeable Reactive Barriers

Monitoring of a granular iron permeable reactive barrier (PRB) is typically completed by installing groundwater monitoring wells, collecting and analyzing groundwater samples from these wells. This technical note provides general guidelines for developing a monitoring well network, plan, and monitoring schedule based on site-specific objectives for groundwater remediation. There are many site-specific factors that need to be considered when developing a monitoring plan for a PRB and this technical note only provides a general guideline. Other available references or guidelines are provided by EPA (1998), Battelle (1999) and ITRC (1999).

Monitoring Well Network

Where the groundwater plume at the site is delineated and monitored over distinct depth intervals or zones, it is recommended that the PRB monitoring network follow the same pattern. The discussion in this technical note assumes only one zone hydrogeological unit and would be repeated for each significant hydrogeological unit

Continuous PRB

Transects of monitoring wells should be placed along the groundwater flow path, upgradient, within and downgradient of the PRB. The number of transects depend on site-specific objectives but transects are typically placed approximately every 100 ft (30 m) along the alignment or a minimum of three transects across the PRB. The upgradient well should be placed about 5 to 10 ft (1.5 to 3 m) upgradient and the downgradient well about 5 to 10 ft (1.5 to 3 m) downgradient. For hanging PRBs (not keyed into a confining unit), wells may be placed below the PRB on the upgradient or downgradient side to monitor for plume by-pass beneath the PRB.

If possible one or more monitoring wells should be placed within the PRB either during installation or after. The flow-through thickness of the PRB may dictate how many wells can physically be placed in the PRB. If only one well is placed in the PRB in each transect, this well should be placed as close to the downgradient side of the PRB as possible, typically about 6-inches (15 cm) from the downgradient side in excavation based construction. Wells placed in the upgradient portion of the PRB are useful for monitoring the long-term performance of the PRB as they will provide an early warning if conditions (e.g. permeability, reactivity) are changing within the PRB and allow time for corrective measures to be completed if required.

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Monitoring wells are placed at each end of the PRB to monitor for plume capture. If possible, these side gradient wells should be installed and sampled prior to PRB construction, to confirm they are indeed clean prior to PRB installation.

Funnel and Gate

Transects of monitoring wells should be placed along the groundwater flow path, upgradient, within and downgradient of the gate. Typically, only one transect per gate is installed unless the gate is relatively long (e.g. more than 50 ft; 15 m). The upgradient well should be placed about 5 to 10 ft (1.5 to 3 m) upgradient and the downgradient of the gate well about 5 to 10 ft (1.5 to 3 m) downgradient.

One or more monitoring wells should be placed within the gate. The flow-through thickness of the gate may dictate how many wells can physically be placed in the gate. If only one well is placed in the gate in each transect, this well should be placed close to the downgradient side of the PRB, typically about 6-inches (15 cm) from the downgradient side. Wells placed in the upgradient portion of the gate are useful for monitoring the long-term performance of the gate as they will provide an early warning if conditions (e.g. permeability, reactivity) are changing within the gate and allow time for corrective measured to be completed if required.

Monitoring wells are placed on the upgradient and downgradient side of each funnel section to monitor the head differential across the funnel sections. Monitoring wells are also placed at each end of the funnel and gate system to monitor for plume capture.

Installation of Monitoring Wells

Monitoring wells outside of the PRB can be installed with conventional techniques.

Wells within the PRB can be placed during construction with certain PRB construction techniques. If wells are installed during backfilling, care must be taken to ensure that the wells are not displaced as backfilling proceeds. For example, potential problems may occur if the well gets pushed against the wall of the excavation. Samples collected from the well will not be representative of groundwater in the PRB. Stiffer well materials (e.g. heavier schedule PVC or stainless steel) or frames may be required to maintain the position of the wells during backfilling. Typically, the wells are 2-inches (5 cm) in diameter.

Wells can be placed within the PRB after backfilling using conventional drilling techniques. It is important to know with relative certainty that the well screens are within the iron and have not been placed against or within the adjacent aquifer material. This typically is more of a concern for deeper well installations. In other words, measuring the plumbness (verticality) of the well is critical. A few degrees of deviation from vertical can result in several inches of horizontal deviation of the well screen at depth. If reactive material is displaced during well installation (e.g. hollow-stem augering) than the well annulus should be backfilled with the reactive mixture.

Groundwater Sample Collection and Analysis Plan

Sampling of wells close to or within the PRB requires special considerations in order to obtain representative samples. Purging and sampling large volumes of groundwater may result in groundwater from outside the PRB (i.e. the aquifer) being collected resulting in a non-representative sample. There are no set guidelines on the amount or rate at which groundwater should be purged or sampled. This must be determined on a case-by-case basis considering the thickness of the PRB, location of wells, groundwater flow velocity, and well configuration. Typically low flow sampling procedures have been utilized. Recently at some sites, diffusive bag samplers (Vroblesky and Hyde, 1997) have been used to collect samples for VOC analysis.

Standard sampling procedures can be used for wells installed in the aquifer upgradient and downgradient of the PRB, provided the purging and sampling will not influence groundwater flow through the PRB.

It is important to consider the fact that most PRBs are placed across an existing plume, not at the front edge of the plume. For this reason, monitoring wells placed in the aquifer downgradient of the PRB will continue to exhibit VOC concentrations for some time following PRB installation due to the time required to flush the downgradient aquifer and desorption of VOCs from the aquifer solids with treated groundwater from the PRB. This condition must be accounted for in the development of a monitoring plan for the PRB.

Monitoring the potential change in hydraulic performance of a PRB can be accomplished by measuring water levels in the vicinity of the PRB and by completing hydraulic testing on wells within the PRB. Water levels are used to compute hydraulic gradients, which after accounting for seasonal variations, can be used to monitor potential changes in the hydraulic conductivity of a PRB. Water levels can also be used to develop potentiometric maps to assess potential changes in flow through or adjacent to a PRB. Typically, slug tests are completed as it is the change in hydraulic conductivity over time that is typically of interest.

We note that coring and analysis of core material is not usually completed as part of a routine monitoring program.

If the PRB is to be located near a surface water body, it may be prudent to map any groundwater discharge points (seeps) and associated staining prior to PRB construction. These data may be useful to refute any subsequent perception of PRB effluent (i.e., iron in the effluent groundwater) causing staining at the point of discharge.

Table 1, lists the recommended parameters, monitoring frequency, and monitoring location for a groundwater monitoring program. This table is meant to be a guide and should be modified to suit site-specific needs.

References:

Battelle Inc., 2000. Design Guidance for Application of Permeable Reactive Barriers for Groundwater Remediation. Battelle Inc., March, USAF – AFRL Report A012.

Interstate Technology and Regulatory Cooperation Work Group, 1999. Regulatory Guidance for Permeable Reactive Barriers Designed to Remediate Chlorinated Solvents. 2nd Edition, December, www.itrcweb.org.

United States Environmental Protection Agency, 1998. Permeable Reactive Barrier Technologies for Contaminant Remediation. EPA 600/R-98/125, September, www.clu-in.org.

Vroblesky, D.A. and Hyde, H.T., 1997. Diffusion samplers as an inexpensive approach to monitoring VOCs in ground water. Ground Water Monitoring and Remediation, Vol. 17, No. 3, pp. 177-184.

Table 1: Guide for Monitoring Program

Parameter	**Monitoring Frequency**	**Monitoring Location**
Field Parameters • Water Level • pH • Groundwater Temperature • Redox Potential • Dissolved Oxygen	Quarterly for first two years. The frequency may be reduced based on operational stability.	Water level for all wells. Other parameters only for wells that are sampled.
Organic Analytes • VOCs (including possible breakdown compounds)	Quarterly to semi-annually for first two years. The frequency may be reduced based on operational stability.	All wells.
Inorganic Analytes • Calcium • Iron, Total • Magnesium • Manganese • Potassium • Silica • Sodium • Alkalinity • Chloride • Nitrate (as N) • Sulphate • Dissolved Organic Carbon • Total Dissolved Solids	Quarterly to semi-annually for first two years. The frequency may be reduced based on operational stability.	One or two representative transects.
Hydraulic Testing • Slug tests	Frequency site specific.	Select monitoring wells within the PRB.