7 Monitoring

A groundwater monitoring strategy for fractured rock sites takes into account lessons learned during site characterization, and informational needs, including those unique to fractured rock, to help ensure that the selected remedy strategy attains site-specific cleanup goals. Monitoring strategies consider the following:

- the purpose for monitoring (compliance, operational or performance monitoring)
- the need to monitor groundwater and other media that may be important in understanding the fate and transport of contaminants in groundwater (such as soil gas)
- design of a monitoring well network
- development of a comprehensive monitoring plan that ultimately informs the practitioner whether remedial activities are on track towards attainment of site-specific cleanup goals.

7.1 Types of Monitoring

Monitoring is the collection and analysis of data (physical, water elevation, chemical, and biological) over sufficient time, locations, frequency to evaluate performance criteria. Successful monitoring is not a snapshot in time but rather, it defines and establishes trends in the parameters of interest, which relate to clearly defined functional objectives. For more guidance, see GSMC-1, Section 5.5 (ITRC 2013) and GRO-1, Section 3.5 (ITRC 2016).

Monitoring can be organized into three general types: compliance monitoring, operational (process) monitoring, and progress/performance monitoring. These monitoring types can overlap, and data can be collected to satisfy the requirements for two or more of the monitoring types. For example, water elevation data can be collected to satisfy all three monitoring types. Monitoring systems can be used to refine the CSM and optimize the number of samples and analyses required to measure compliance, operational process, and performance (see IDSS-1, Chapter 5 (ITRC 2011).

- *Compliance monitoring* is the collection of data to evaluate compliance with regulatory requirements and protection of human health and the environment.
- *Operational monitoring* collects data to assess whether a remediation system is meeting or approaching its functional objectives (ITRC 2011). This data is also used to identify, adjust, modify, and optimize remedial system performance.
- *Progress/Performance monitoring* is used to assess the effectiveness of a remedial approach in achieving functional objectives (ITRC 2011). Multiple lines of evidence are used to measure the effect remediation has on COC concentrations or mass discharge and the completeness of treatment. Effective performance monitoring allows decision makers to evaluate the soundness of functional objectives, determine the value of the remediation program, and determine if alterations to the remedial approach are required. Communicating the results of performance monitoring to the project stakeholders may be an effective way to keep them apprised of site progress—and may be required in some circumstances.

7.2 Media to Monitor

Contaminants found in fractured rock may partition into several different phases. These partitioned phases may consist of sorption to the aquifer matrix, vapor, groundwater, and surface water. Additionally, many other parameters or chemicals may be present that signify the processes occurring within the fractured rock. Therefore, it is important to consider all relevant phases while monitoring.

- *Subsurface gas*. Monitoring vapor constituents in subsurface gas can provide information regarding the migration and degradation of contaminants. As contaminants move through fractured rock or degrade, they may partition into vapors (gases). The movement within the subsurface is controlled by the fracture network. Migration patterns may differ from groundwater flow patterns.
- *Groundwater*. Groundwater is the primary transport media for dissolved contaminants at most sites. Contaminant transport is affected by contaminant partitioning to solid and gaseous phases and aquifer hydrodynamics. Site-wide and regional/local groundwater elevation measurements, over time, provide insight on

well integrity and changes to groundwater flow, which can be either natural or influenced by structures. Additionally, monitoring groundwater general chemistry may provide insight on the flow, changes occurring to the impacted zone, transport within the fractured media, and the interconnectedness of fractures.

- *Surface water*. Monitoring surface water is an extension of monitoring groundwater. Surface water includes seeps, springs, lakes, ponds, and other bodies of water. Monitoring surface water may indicate where groundwater is discharging to the surface or how surface water is affecting groundwater. Changes in surface water geochemistry may indicate changes in the impacted zone or in the transport of contaminants. Depending on the hydrologic environment, changes in surface water flow may be influenced by the degree of interaction between surface water and groundwater. This interaction can vary temporally and spatially, responding to changing surface water flow conditions (for example, a stream shifting between gaining or losing conditions.)
- *Aquifer matrix materials*. Typically, groundwater or subsurface vapor monitoring data are used as indicators of changed conditions in the aquifer matrix materials.

7.3 Monitoring Network Design

The design of a groundwater monitoring network in fractured rock can differ from that in unconsolidated media environments. A key element of monitoring system design is understanding temporal variations in chemical and physical conditions, whether natural or artificial changes. For example, remedial actions may change water elevations, which may alter groundwater flow direction. Fractured rock data requirements include: rock type, fracture network, and hydrogeochemical zoning.

The presence of a discrete fracture systems can also affect well construction and placement decisions. It is essential that wells used to monitor potential receptors are placed appropriately in three dimensions, given the fracture geometry. For some purposes, particularly performance monitoring, only wells that are required to meet the objectives need to be monitored. Wells installed to define the plume may, in later project phases, be redundant.

Many factors influence the shape of the impacted zone, including original source distribution, geology, hydrology, and biologic/abiotic processes.

7.3.1 Informational Needs for Designing Monitoring Well Network

Certain site-specific information is needed to design monitoring well networks, including but not limited to the following:

Rock Types

The particular rock types at the site can impact the temporal fate and transport of contaminants, which informs placement of monitoring wells as part of the network. The rock type may influence the potential for matrix storage and/or matrix flow. For example, the primary porosity in a granite and a sandstone are vastly different leading to differing monitoring network design. In can be expected that the temporal variations may be greater in a sandstone than a granite and more monitoring wells may be necessary.

Fracture Network

The placement of monitoring wells should rely on the mapped fracture network developed during the site characterization. Fractures may be discontinuous, may have variable orientations and apertures, may interconnect with other fracture systems, or may vary in other ways. Because of these variations, simply placing wells in the network based on an assumed, symmetrical two-dimensional plume geometry may not be meaningful. Well placement should be guided by the CSM to target discrete fracture zones. In addition, consider seasonal variations that occur in flow directions during times of greater regional pumping due to fracture orientation.

Hydrogeochemical Zoning

Hydrogeochemical zoning at a fractured rock site can also affect the design of a monitoring well network. The portion of the CSM that describes the geochemistry can guide the locations and depths of the monitoring wells. For example, rocks with high metal sulfide mineral content, such as pyrite ($FeS2$), chalcopyrite ($CuFeS2$), sphalerite (ZnS), and galena (PbS), and cinnabar (HgS) can become oxidized and release metals into solution, thus generating acidity (as well as elevated aluminum, iron, and manganese). In this case, it may be desirable to monitor for pH and metals indirectly related to the contaminant release.

Other Media

Results from monitoring of other media such as vapor or surface water should be considered in the design of the monitoring well network. A subsurface gas survey indicating an area of elevated concentrations, that may not otherwise been included in the groundwater monitoring network, may suggest that an area is interconnected by fractures (although other causes such as utility conduits could be present). Guidance is available to assist in assessing subsurface gas (ITRC 2007, 2014;

USEPA 2002a). Surface water impacts may also suggest an interconnectivity of fractures from the release area to the surface water body and should be considered in designing the groundwater monitoring well network.

Potential Receptors

The presence of potential environmental or human receptors is a significant consideration when designing a monitoring well network. Monitoring wells should be placed to evaluate the potential for exposure to receptors. For example, in fractured rock environments the migration pathways may vary temporally under a pumping scenario. For long-term monitoring programs, periodic reevaluation of potential pathways to receptors may be necessary.

7.3.2 Monitoring Locations

As with unconsolidated media, the locations of boreholes for a monitoring well network are identified using a more complete CSM. Placing boreholes prior to completing a robust CSM may result in an inadequate monitoring well network. A poorly designed well network can result in a less than optimal remediation strategy and may increase the costs and time frame required for remediation. Because drilling in bedrock can be expensive, boreholes and monitoring wells installed during site characterization or during any treatability testing may also be monitored and sampled as part of the routine monitoring program.

Multiple lines of evidence from the site characterization should be considered in placing monitoring wells, such as:

- fracture network
- groundwater gradient and direction
- geochemistry

An understanding of the fracture network in bedrock is foundational to making decisions regarding well placement. Results from site characterization can be used to map the fracture network to understand whether fracturing is dominated by horizontal (commonly bedding planes), vertical fractures (common for sedimentary rock) or by diagonal/multidirectional fractures (common for crystalline rock).

Once the fracture network is understood, hydraulic information about groundwater gradient, velocity, and flow direction within the fracture network aids in monitoring well placement. These considerations are particularly important when designing a program to monitor an injection-based remedy. Injected fluids are typically devoid of contaminants and until the injected fluid has migrated past the monitoring points, thus the evaluation of remedial performance cannot be considered reliable. If groundwater flow is slow or is slow in some of the fractures intercepted by a monitoring well, then the impact of this “uncontaminated” injected fluid can continue to affect the sample chemistry for years.

Understanding the noncontaminant geochemistry may aid in proper monitoring well placement. For example, if the contaminated fractures have high salinity and other fractures have low salinity, then salinity can be used to place wells and well screens across the same portion of the fracture network responsible for the fate and transport of the contaminants. The geochemical fingerprint of the source area contaminants can include a variety of low cost parameters that may predict future contaminant transport flow paths.

The locations of monitoring points share similarities to those in unconsolidated media, including:

- source zone wells
- impacted zone wells (analogous to plume wells for unconsolidated media)
- distal portions and boundaries of the area of impact
- cross-gradient wells
- sentinel wells
- surface water

7.3.2.1 Source Zone Wells

The source zone may be associated with the presence of DNAPL or LNAPL found within fractures, but for non-NAPL contaminants, may be simply associated with high contaminant concentrations occurring in fractures near the release area. In general, the source zone is the area with free product present, the release area, or both. Source zone contamination may be encountered in fractures, but can also be present in the matrix porosity, and in some cases, may occur as matrix flow.

Monitoring well installation within a fractured rock source area should allow monitoring of the desired metrics, but not result in spreading contaminants. A contingency plan should be developed prior to drilling that addresses what actions are necessary in the event a conduit that is spreading contaminants is discovered. The placement of monitoring wells should not cause further migration of contaminants, such as coring through the fractured rock and establishing a preferential flow path for otherwise immobile contaminants to reach groundwater. Appropriate drilling methods may be considered on a case-by-case basis that will allow drilling but prevent establishing preferential flow paths. Drilling should not create pathways between contaminated and uncontaminated fractures that are otherwise not impacted or hydraulically connected. In the event a conduit is discovered, the conduit must be sealed.

The shortest possible well screens or isolated intervals should intersect the impacted fractures of interest. This practice is important not only for preventing preferential pathways, but also for screening wells to provide the best possible discrete-interval samples. An alternative to short screen wells is long-interval wells that are separated into multiple hydraulically isolated zones with either inflatable packers or Flute systems. Long-interval wells can be new wells or legacy wells that may be repurposed. Multiple-zone wells offer valuable information and operational opportunities if they are constructed and maintained without allowing cross contamination or cross flows between separate fractures and portions of the fracture network.

Placing individual wells with access to multiple isolated intervals requires a team effort for planning and coordination, as well as on-site expertise and decision making. Strings of removable inflatable packers (inflated with compressed gas or with water) or FLUTe liners are installed as soon as possible after drilling and well logging are completed. Information from logs (especially caliper, televiewer, combined temperature-resistivity-gamma, heat-pulse flowmeter as possible) and water samples during or immediately after drilling can guide the selection of zone intervals and packer placement locations. Multiple-zone isolation systems of packers or FLUTe liners are reliable if properly sized, installed, and monitored for air or water pressure. Multiple-zone isolation systems of packers or FLUTe liners can be: (1) permanent; or (2) modular and be modified in configuration, or replaced if needed; or (3) converted in place from temporary to permanent.

High-value information and operational opportunities from individual wells with access to multiple isolated intervals include:

- 1D vertical profiles per well (and collectively providing 3D information in a volume of interest when several such wells are used) for water sampling, hydraulic heads, and monitoring prior to, during, after in situ remediation
- 3D characterization to determine or estimate hydraulic parameter distributions of both fractures and rock matrix, and fracture connectivity (hydraulic tomography and hydraulic tests at individual zones, tracer tests using multiple wells +/- multiple configurations)
- operational opportunities during remediation such as 3D in situ remediation with many possible configurations for simultaneous injection, withdrawal, hydraulic control, and monitoring using multiple zones in multiple wells

Alternative configurations of multiple individual single-zone wells cannot realistically provide the information and operational opportunities of wells with access to multiple isolated intervals each. The cost and logistics are prohibitive for a cluster of perhaps 4 to10 or more individual wells for every individual well with access to multiple isolated intervals.

7.3.2.2 Impacted Zone Wells

While the formal definition of a contaminant plume may not apply to fractured rock, the distribution of contaminants downgradient from the source area may be referred to as the impacted zone. This term refers to continuous fractures and fracture sets hydraulically downgradient from the source area that exhibit elevated concentrations of dissolved contaminants. Monitoring wells that are intended to be placed in the impacted zone are best placed using the current CSM.

Vertical characterization of the contaminant distribution in the fractures may be necessary to design a protective monitoring well network. For this characterization, long-interval wells that are separated into multiple hydraulically isolated zones with either inflatable packers or FLUTe systems may be considered as an alternative to short screen wells. Long-interval wells can be new wells or legacy wells that may be repurposed. The zones of highest contamination in the rock/fractures that present risk to off-site or downgradient receptors may need to be monitored.

7.3.2.3 Distal Portions or boundaries of the Area of Impact

Multilevel monitoring points typically are placed at the cross-gradient, downgradient, and vertical boundaries of the contaminant distribution, and between these boundaries and possible receptors. The placement of each monitoring point should account for the fracture flow network developed as part of the CSM. These wells also may be placed strategically to provide evidence determine whether contamination is crossing a compliance boundary. This determination may require sampling of fractures that are known to carry contaminants off site towards receptors; sometimes these pathways can only be found through discrete fracture characterization and sampling.

Multilevel monitoring generally should also be performed at any other compliance boundaries specified in remedy decision documents. Results from these monitoring locations may directly demonstrate unacceptable expansion of the contaminants distribution and changes in groundwater flow directions.

7.3.2.4 Upgradient and Cross-Gradient Wells

Upgradient and cross gradient wells may be useful as part of the monitoring well network to understand whether contamination is coming on-site from an up gradient source, or whether the impacted zone is spreading laterally. As with placement of other wells within the network, an understanding of the fractured rock hydrogeology is necessary to making decisions for placement of these wells.

Monitoring the groundwater geochemistry should include well locations where interconnected fractures are hydraulically upgradient and cross-gradient with respect to the area of impact. Assumptions concerning the geochemical setting and naturally occurring changes in geochemistry affect interpretation of data from the area of impact, so these assumptions should be tested and evaluated with other parts of the CSM.

As part of this evaluation, multiple monitoring points should be used to determine the variability of geochemical conditions outside the area of impact. Data concerning the movement of electron acceptors, donors, and any contaminants are used to determine whether the observed differences in geochemical parameter concentrations within the area of impact are due to contaminant transformation processes rather than natural variations in the background geochemical conditions. The locations cross-gradient to the area of impact help to evaluate changes in the area of impact geochemistry with time as groundwater migrates through uncontaminated fractured rock. Changes in geochemistry within the area of impact may not be directly related to attenuation of the contaminants, so geochemical changes outside this area generally should be assessed and compared to geochemical changes taking place within the area of impact. If upgradient and cross-gradient monitoring points show geochemical changes similar to changes in the area of impact, such changes may not be attributed solely to contaminant related processes (degradation) and may not serve as supporting evidence for degradation processes.

At some sites, monitoring groundwater elevations at locations in addition to those used for the monitoring chemical parameters may be needed to determine hydraulic gradients between hydraulically connected fractures. At these sites, appropriate locations for placing piezometers often include positions that are upgradient and cross-gradient to the area of impact, as well as in zones above and below the area of impact. Piezometers are usually spaced across the site so that groundwater elevation measurement errors are relatively small compared to the difference in groundwater elevations between piezometers.

7.3.2.5 Sentinel Wells

Sentinel wells may be installed to protect a potential sensitive receptor, or for a beneficial use. Monitoring wells for the monitoring network that are intended to be used as sentinel wells are best placed based on the current CSM—after gaining an understanding of the fractured rock hydrogeology.

7.3.2.6 Surface Water

Where surface water/groundwater interactions may be an important migration pathway, surface water bodies may need to be monitored as part of an effective monitoring system. At some sites, the CSM may include the potential connection between fracture systems and surface water bodies such as springs, rivers, ponds, or lakes. When considering monitoring in surface water bodies, be aware of seasonal hydrology that affects flow in these features.

7.3.3 Monitoring Well Design Considerations

Drilling into fractured rock is expensive compared to unconsolidated media so information gained from each drilling location should be optimized. This approach includes the optimal use of core holes drilled during site characterization. The monitoring network for a fractured rock site must be planned effectively and use as many of the existing boreholes and characterization data as possible. Because of the heterogeneous and anisotropic nature of fractured rock sites (for example, fracture orientation and discontinuities), there is inherent uncertainty about the fate and transport of contaminants. Therefore, the design of the monitoring network should be periodically reevaluated.

Monitoring well design considerations specific to fractured rock sites include selecting screen (or open borehole) lengths and positions that target transmissive fractures or zones, as well as evaluating flow conditions, evaluating potential hydraulic cross connections, and selecting appropriate well dimensions. Decisions regarding screen or open borehole lengths and depths of sampling intervals are based on the findings made during site characterization and remediation as described in the CSM.

Where the bedrock has adequate strength and competency, monitoring wells may be constructed as an open borehole. This approach can be more cost effective than placing filter pack and screen in the targeted zone. Using open boreholes provides flexibility in altering the well in the future by allowing for future deepening of the well, use of packers, and other options. Where open boreholes are used, well casing placement is essential to hydraulically isolate the targeted (open borehole) zone and eliminate the potential for cross-connections.

In some cases, existing wells that were not originally designed as monitoring wells are incorporated into monitoring systems. Prior to use, these wells should be assessed as to their potential for cross-connections of hydraulically distinct zones, using the appropriate characterization tools.

Discrete interval monitoring systems enable the monitoring of multiple depth zones in one borehole. These systems can reduce the high cost of drilling in bedrock. As when using open boreholes, care must be taken to eliminate or minimize cross-connections of hydraulically distinct zones. Discrete interval sampling technologies are described in Section 5.5.

The design of any monitoring well network at a fractured rock site should consider the potential for mobilizing contaminants or causing otherwise undesirable hydraulic cross connections. For example, otherwise immobile NAPL encountered in a bedding plane of a shale unit could be mobilized vertically through installation of a borehole that connects the impacted bedding plane to fractures or other bedding planes at other depths. As another example, a borehole drilled through an uncemented sandstone, where matrix flow provides the transport pathway for contaminants, could provide a pathway for vertical migration into otherwise unaffected fractures at other depths in the rock. The CSM should be used to design monitoring wells that minimize potential cross-connection

As at any site, the sampling interval or open borehole length for a given well is sized to obtain samples or take hydraulic measurements from the interval (set of hydraulically connected fractures) of interest. Fractured rock sites are unique in that the target monitoring interval is defined by fracture location, density, or orientation, as well as contaminant loading or geochemistry. The target intervals are based on the CSM, and factors to consider in determining screen interval length include the following:

- Match screen interval length to bedrock type, fracture density, continuity, or secondary porosity. In addition, consider geochemical values such as conductivity, contaminants, redox parameter and temperature.
- Interval depth and length are typically designed to target comparable intervals based on the CSM (such as sets of hydraulically connected fractures, or for a single fracture).
- Isolated intervals are matched to geochemistry to monitor fracture zones with a particular geochemical signature. Because attenuation of some contaminants is highly sensitive to the geochemical environment, it is often desirable to accurately identify and discretely sample locations in the area of impact where a particular geochemical condition prevails.

The design of the borehole and casing diameter are important considerations at fractured rock sites because of the potential need to isolate discrete zones. Well and borehole dimensions are driven by planned use of well casing and down hole packers, installation of discrete interval monitoring systems, and depth of the well.

7.4 Monitoring to Evaluate the Remedy

Starting with an end in mind is critical to effectively implementing a monitoring strategy. The USEPA guidance "*Groundwater Remedy Completion Strategy: Moving Forward with an End in Mind*", Section 6, describes four elements to an effective remedy evaluation (USEPA 2014):

- remedy operation
- remedy progress toward groundwater RAOs and associated clean up levels
- remedy attainment of RAOs and cleanup levels
- other site factors

The process outlined by USEPA is applicable to fractured rock sites as well as porous media sites and should be reviewed carefully before evaluating the performance of a site remedy.

USEPA further explains:

The evaluation of engineering, operating and monitoring components of a remedy should indicate whether the system is functioning adequately to achieve the RAO and associated cleanup levels and if remedy operation can be improved to reduce the remedial time frame.

7.5 Example of a Remediation Monitoring Strategy

USEPA's remedy evaluation structure has proven effective in the field. The case study for the Former Industrial Site in Greenville, South Carolina illustrates development of a remediation monitoring strategy. Table 7-1 summarizes the remedy evaluation structure for the site. Saprolitic overburden (both saturated and unsaturated) was also impacted and the subject of several phases of remediation. This discussion is focused only on the fractured rock zone.

Table 7-1. Remedy evaluation structure for the Former Industrial Site in Greenville, SC

Absolute Objective	SMART Functional Objective	Selected Remedy Component		Evaluation Questions	Metrics
Protect human health and the environment	Eliminate DNAPL and reduce groundwater VOC concentrations to MCLs within 15 years, to eliminate ongoing source of VOCS to plume area.	Source area in-situ chemical oxidation with potassium permanganate, injected as a solid slurry into water-bearing fracture zones.	Remedy Process Monitoring	Was permanganate reagent successfully injected in the target fracture zones, or was injection inhibited?	Comparison of actual injection rates, pressures, and volumes relative to design developed based upon preinjection CSM, as modified during implementation based upon field observations (distribution of water-bearing fractures) during drilling.
				Was the permanganate reagent mass injected commensurate with the matrix and contaminant oxidant demand?	
				Was there preferential flow into certain fractures?	
				Was reagent successfully distributed in the designed area of influence?	Visual observation (purple color) and geochemical characteristics (particularly oxidation-reduction potential) of groundwater in the treatment area.
				Is there evidence that injected reagent was preferentially directed away from the target treatment zone (i.e., daylighting, diversion to utility trenches, etc.), or towards downgradient areas?	Visual observations and geochemical characteristics of downgradient, sidegradient, and upgradient monitoring wells, and visual observations of surface, utilities, and other locations in the treatment area.
				Is there evidence of displacement of contaminants away from the source area as a result of injection?	Groundwater monitoring for contaminants outside the treatment area and comparison to pre-treatment data.
			Remedy Performance Monitoring	Do groundwater samples indicate sustained presence of permanganate?	Visual observation (purple color), geochemical characteristics (particularly oxidation-reduction potential), and contaminant concentrations in groundwater in the treatment area.
				Is there evidence of contaminant rebound?	
				Are contaminant concentrations decreasing as anticipated?	
				Does it appear that progress is being made towards the absolute objectives?	
			Remedy Attainment Evaluation	Are absolute and functional objectives achieved?	Contaminant concentrations in groundwater in the source and plume area.

Absolute Objective	SMART Functional Objective	Selected Remedy Component		Evaluation Questions	Metrics
Mitigate offsite migration of contaminants and potential impact to surface and groundwater resources	Reduce dissolved and sorbed-phase contaminant mass to MCLs within 15 years, to eliminate further offsite migration and potential surface water discharge.	In-situ chemical reduction utilizing granular zero valent iron, injected as a solid slurry into water-bearing fracture zones.	Remedy Process Monitoring	Was ZVI reagent successfully injected in the target fracture zones, or was injection inhibited?	Comparison of actual injection rates, pressures, and volumes relative to design developed based upon preinjection CSM, as modified during implementation based upon field observations (distribution of water-bearing fractures) during drilling.
				Was the ZVI reagent mass injected commensurate with groundwater reductant demand?	
				Was there preferential flow into certain fractures?	
				Was the reagent successfully distributed in the designed radius of influence?	Geochemical characteristics (particularly oxidationreduction potential) of groundwater in the treatment area, and contaminant concentrations downgradient of each barrier.
				Is there evidence that injected reagent was preferentially directed away from the target treatment zone (i.e., daylighting, diversion to utility trenches, etc.)?	Visual observations and geochemical characteristics of downgradient, sidegradient, and upgradient monitoring wells, and visual observations of surface, utilities, and other locations in the treatment area.
				Is there evidence of displacement of contaminants away from the treatment area as a result of injection?	Groundwater monitoring for contaminants outside the treatment area and comparison to pre-treatment data.
			Remedy Performance Monitoring	Do groundwater samples indicate sustained reactivity of ZVI?	Geochemical characteristics (particularly oxidationreduction potential), and contaminant concentrations in groundwater in the treatment area.
				Is there evidence of contaminant rebound?	
				Are contaminant concentrations decreasing as anticipated?	
				Does it appear that progress is being made towards the absolute objectives?	
			Remedy Attainment Evaluation	Are absolute and functional objectives achieved?	Contaminant concentrations in groundwater in the source and plume area.

7.5.1 Identification of Media to Monitor

The relevant media to monitor at this site are groundwater and surface water. Groundwater is the primary transport medium for contaminants, reagent, and geochemical conditions. The downgradient margin of the impacted zone is bounded by a perennial stream; thus surface water is a relevant media to monitor. Only the source area is overlain or adjacent to a building. The vadose zone in the source area (comprised of approximately 55 ft of dense saprolite) was remediated by other technologies, and postremediation indoor air monitoring confirmed there were no unacceptable risks, thus further vapor monitoring was not required.

7.5.2 Monitoring Network Design

Previous site investigations determined that the bedrock aquifer consists of a partially weathered rock zone at the interface between the rock and the overlying saprolite, which grades into competent bedrock over an approximately 10-foot interval. At some locations, the partially weathered rock and fractured interval is much thicker, approaching 100 feet. Fractures in the bedrock are predominantly subhorizontal. Water-bearing fracture zones could be readily identified and distinguished from mechanical fractures in bedrock cores by dark red to brown (oxidized iron) staining on the fracture surfaces. The crystalline rock is a metamorphic gneiss, with little matrix porosity.

An extensive network of 15 monitoring wells in the source area and 37 monitoring wells in the impacted zone and adjacent areas (including upgradient, cross gradient, and sentinel wells) provide a dense groundwater network of locations for data collection in both the saprolite and the bedrock (see site map in the full case study). The network includes wells with screens that intersect the saprolite interface and partially weathered rock interval, and deeper wells with screens only in the fractured bedrock interval. The preremedy well network was augmented during the remedy with additional locations just upgradient and downgradient of individual ZVI barriers to specifically monitor remedy progress. Additional wells on the cross-gradient margins of the impacted zone area were also installed to confirm the treatment area boundaries. Periodic surface water sampling is conducted, typically at up to four stations adjacent to the downgradient margin of the impacted zone.

7.5.3 Process Monitoring Strategy

The process monitoring plan focused on factors relevant to confirming that the field construction of the remedy matched the design of the remedy as closely as possible. Process monitoring of the injections in both the source and impacted zone centered primarily on the reagent distribution:

1. A design identifying specific well locations, injection depth intervals, and reagent volumes was developed based upon the CSM and site characterization data available prior to remedy implementation.
2. Each injection well was cored during drilling. This process allowed well-by-well evaluation of the fracture distribution, with ongoing updates to the CSM. This allowed adaptation of the remedy design to the observed fracture distribution at each location.
3. The amount of reagent injected at each targeted injection depth interval was monitored during injection. In some cases, multiple attempts were required to deliver the design reagent volume. In other instances, the target reagent volume could not be delivered, in which case the reagent was redistributed among other injection intervals in the same boring.

In the source area, the permanganate reagent colors the groundwater a distinct purple. Sampling of adjacent monitoring wells during injection visually confirmed distribution of permanganate during injection. The ZVI does not color the groundwater, so additional borings were needed after the initial field pilot tests to confirm the ZVI distribution.

7.5.4 Performance and Remedy Attainment Monitoring Strategy

Performance monitoring includes quarterly sampling for contaminants of concern and other analytes and parameters (such as redox, color, and manganese dioxide) used to evaluate the ongoing performance of the remedy and to identify locations that may require augmentation with additional reagent. The reagent is monitored quarterly. Monitoring locations include all the monitoring wells within, and adjacent to, the source and impacted zone treatment areas. This monitoring includes wells located cross-gradient of the treatment areas and downgradient sentinel wells.

In the source area, performance monitoring includes observations of color and presence of manganese dioxide, which are relevant to the long-term persistence of permanganate. The oxidation-reduction potential is a relevant parameter collected as part of low-flow sampling. The expected outcome is that permanganate is distributed throughout the source area and persists for several years. The permanganate was found to rapidly dissipate in some of the monitoring wells, and permanganate did not appear to reach other monitoring wells within the source area (allowing time for advection and diffusion of the reagent away from the initial emplacement zone). In response, additional injection around those locations was conducted to augment and optimize the remedy. In the impacted zone, the performance monitoring relies primarily on contaminant concentrations in groundwater downgradient of each ZVI barrier. The VOC data are compared with other groundwater characteristics that are associated with the ZVI, including oxidation-reduction potential and pH.

The initial remedial design was based in part on a modeling effort using REMChlor and PREMChlor. One output from these models includes a prediction of the contaminant concentrations at specific locations defined by the user. Thus, in addition to demonstrating steady progress towards the functional objectives, based upon declining contaminant concentrations, the remedy progress is also being compared with the REMChlor model predictions. Although reductions in contaminant concentrations are apparent, and the impacted zone appears to be contracting, the available period of post-remedy data is insufficient for a meaningful comparison. However, a strategy has been proposed to confirm long-term progress towards the objective. This strategy compares the modeled and measured contaminant concentration data, on a well-by-well basis, in order to identify locations or portions of the impacted area in which the remedy may require additional injection.