NAVFAC
Naval Facilities Engineering Command
EXWC Engineering & Expeditionary Warfare Center

ENVIRONMENTAL RESTORATION

IN SITU CHEMICAL REDUCTION: STATE-OF-THE-PRACTICE AND NEW ADVANCES

Introduction

This fact sheet describes the state-of-the-practice and new advances for in situ chemical reduction (ISCR). This remediation approach involves the use of various reactants to promote the chemical reduction of contaminants. As shown in Table 1, reactants can include engineered reductants (solid or soluble) and naturally-occurring minerals that are formed through biotic or abiotic reactions.

These reductants can be used to treat source areas and/or plumes contaminated by a variety of inorganic and organic contaminants. This fact sheet focuses primarily on the application of zerovalent iron [ZVI] for treatment of chlorinated solvents. This focus was selected as chlorinated solvents are the most prevalent groundwater contaminants at Navy sites and ZVI is the most common ISCR amendment used to treat them.

Background

ISCR development began in the early 1990s when granular ZVI or cast iron was applied in permeable reactive barriers (PRBs) to treat contaminated groundwater. In the late 1990s, methods were developed for producing microscale ZVI (mZVI) and high-reactivity nanoscale ZVI (nZVI). Those advancements led to a number of field demonstrations using mZVI and nZVI for treatment of chlorinated solvent source areas. At the same time, research demonstrated that naturally-occurring iron-based minerals (e.g., magnetite and iron sulfide) can serve as natural reductants for sustaining long-term, abiotic treatment of chlorinated solvents. However, these natural reductants are less reactive than ZVI, and often are not present in aquifers at concentrations high enough to contain migrating chlorinated solvent plumes.

The chlorinated solvents most commonly addressed by ISCR are tetrachloroethene (PCE) and trichloroethene (TCE). Degradation of PCE or TCE by ZVI occurs abiotically primarily via the beta elimination pathway. Figure 1 shows the beta elimination pathway for TCE where acetylene is produced as the product. This pathway avoids production of toxic intermediates, such as cis-1,2-dichloroethene (cDCE) or vinyl chloride (VC), which are typical daughter products of biological reductive dechlorination. This is considered as an advantage for remedial approaches using ZVI treatment. However, some chlorinated solvent contaminants, such

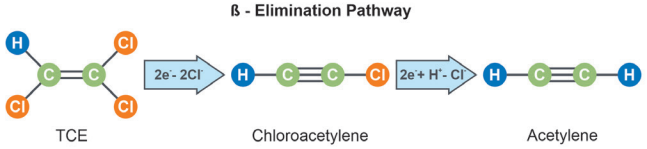

Figure 1. Beta Elimination Pathway for TCE (Courtesy of Battelle)

Table 1. Summary of ISCR Amendments

Reductant	Reductant Type	Reductant Type
Zerovalent metal (e.g., ZVI)	Engineered solid	Chlorinated solvents, explosives, metals
Iron sulfide, magnetite*, green rust*	Naturally-occurring or engineered solid	
Sodium dithionite	Soluble	Chlorinated solvents, explosives
Calcium polysulfide	Soluble	Metals

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as 1,2,3-trichloropropane (TCP) or 1,2-dichloroethane (1,2-DCA), are less reactive or not reactive with ZVI. Note that the former can be degraded by zerovalent zinc (ZVZ), a stronger reductant than ZVI (Salter et al., 2012; ESTCP-201628). A detailed list of chlorinated solvents that are treatable by ZVI is provided in the SERDP/ESTCP EnviroWiki Zerovalent Iron Permeable Reactive Barrier Webpage.

Recent Advances in Amendment Composition

Recent advances in ZVI amendment composition were developed to improve reactive longevity and mobility of mZVI and nZVI in the subsurface.

ZVI in groundwater corrodes continuously via reaction with water, both under oxic and anoxic conditions. This process acts to passivate the ZVI surface and reduce its reactivity and capacity over time. While the reactivity of granular ZVI can last multiple decades depending on aquifer geochemistry, the reactive longevity of mZVI and nZVI is shorter due to their smaller particle diameters and higher reactive surface areas. Conventional unmodified nZVI, in particular, is highly reactive in water and therefore has reactive longevity on the order of weeks to months. Mobility of injected unmodified nZVI in aquifers can be challenged by filtration onto the aquifer matrix and nZVI particle agglomeration.

Three significant advancements to improve ZVI selectivity, longevity, and mobility are described below.

- *Sulfidation* of ZVI (S-ZVI) is one of the more prominent advances in ISCR amendments. Sulfidation is a process where ZVI is chemically modified by reducing sulfur compounds (e.g., dithionite), forming an FeS layer on the surface of ZVI particles. The FeS layer reduces the extent of Fe(0) reaction with water by inhibiting Fe(0) corrosion. The FeS layer also enhances TCE dechlorination rates due to its hydrophobic tendency to sorb contaminants and its conductivity, which enhances electron transfer from Fe(0) to sorbed contaminants. As a result, sulfidation improves the selectivity of ZVI for dechlorination over corrosion and extends ZVI reactive longevity. The most significant enhancement in dechlorination rates has been observed for TCE compared to other chlorinated ethenes. To date, most of the sulfidation research has focused on nZVI materials (Fan et al., 2017a). Recently, two S-mZVI products consisting of fine ZVI particles (i.e., < 2 µm) have been developed and are commercially available.
- Activated carbon is another notable amendment development where a sorptive material acts as a carrier for ZVI. With carbon-ZVI composite amendments, contaminants are first sorbed to the activated carbon and then degraded by ZVI. The sorptive material also inhibits Fe(0) corrosion by shielding its exposure to water, thereby increasing the longevity of ZVI. Commercial products are available and have been applied at a number of sites for treatment of chlorinated solvents in both source areas and plumes (Fan et al., 2017b).
- Food-grade biodegradable *organic polymers* such as carboxylmethyl cellulose (CMC) are commonly used in preparation of commercial nZVI, S-nZVI, and S-mZVI formulations to modify the surface charge of the particles, limit particle-particle attraction, reduce agglomeration, and thereby improve injectability and mobility in the subsurface. However, the performance of CMC and other polymers with nZVI is an active area of research and understanding of their success at field scale is still evolving.

These newly developed materials have similar or slightly lower unit cost compared to conventional nZVI, which is more expensive than mZVI or granular ZVI on a unit mass basis. However, the cost-effectiveness is expected to increase given the enhanced selectivity and longevity.

Recent Advances in Delivery Methods

ZVI can be placed into the subsurface by a variety of methods, including excavation and backfill, trenching, soil mixing, direct push technology (DPT) injection (mZVI and nZVI), and hydraulic/gravity feed delivery to conventional injection wells (nZVI). The delivery method is specific to ZVI particle size, treatment scenario (source or plume treatment), and subsurface lithology.

Most of the early ISCR applications were PRBs for plume treatment, which primarily used excavation or trenching for placement of granular ZVI (ITRC, 2011; NAVFAC, 1998). The development of mZVI enabled injection with DPT, which is more flexible and less costly compared to excavation and trenching. Trenched PRBs and DPT injection of mZVI typically involves use of guar gum, a biodegradable polymer, as a carrier to suspend ZVI during injection. Permanent injection wells are only suitable for polymer-stabilized nZVI or S-nZVI that are intended to pass through the well screen and filter pack into the formation.

Recent advancements in delivery methods provide novel ways to overcome the challenges encountered by conventional delivery methods to treat low-permeability formations or obstructed areas in the subsurface.

- **Direct-Push Technology Jet injection (DPT-JI):** DPT-JI is an injection method that combines high-pressure jetting (10,000 pounds per square inch [psi]) and controlled hydraulic fracturing for emplacing amendments into low-permeability geologic matrices where remediation is limited due to poor contact between amendments and solvents trapped in the matrix. The major benefit of DPT-JI resides in its ability to allow controlled delivery of amendments in fractures, and avoidance of short-ciruciting to the ground surface. Figure 2 shows the horizontal orientation of the fractures for emplacement of ZVI with DPT-JI. DPT-JI has a higher injection efficiency than conventional hydraulic fracturing and can deliver a greater quantity of amendment than DPT. The technology has been used successfully to deliver mZVI for full-scale remediation of a chlorinated solvent source area in clay till (Ross et al., 2018).

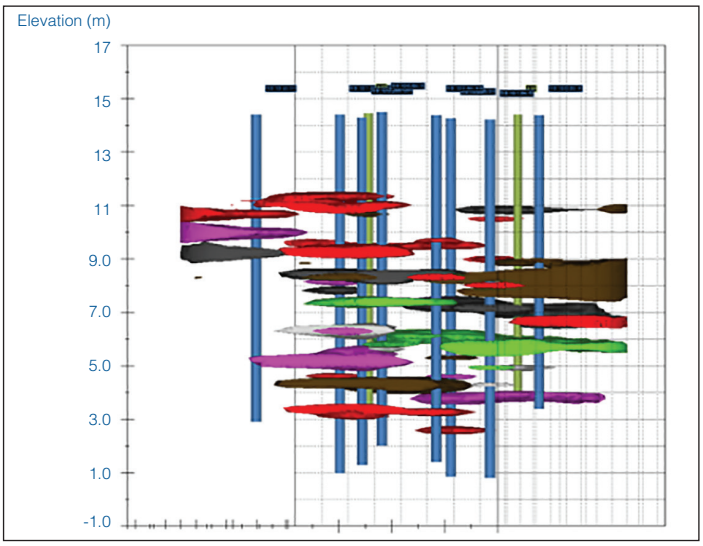

Figure 2. DPT-JI Fractures Mapping (Courtesy of Geosyntec)

- **Horizontal Wells:** Horizontal wells are a mature technology for a variety of remediation applications, but they have not been used widely for delivering ISCR amendments. The main advantage of horizontal wells is that the technology allows access to contamination located in obstructed subsurface areas (e.g., under a building or utility lines), which can be difficult to access with conventional vertical wells. Similar to fracturing, horizontal wells can be filled with reactive amendments to create a horizontal treatment zone at a target depth interval. A field demonstration of granular ZVI-based PRB delivered by horizontal well technology has recently been conducted under the funding of Environmental Security Technology Certification Program (ESTCP ER-201631).

- **ElectroKinetics (EK):** EK involves application of low voltage direct electrical currents in low-permeability geologic matrices to facilitate distribution of ionic and charged particle reactive amendments. The rate that dissolved ionic amendments move through the hydrogeological formation is driven by the electrical field and independent of the formation's permeability. Most of the EK field applications to date are coupled with bioremediation (ESTCP ER-201325) or chemical oxidation (ESTCP-201626). In principle, EK could be utilized for ISCR; however, due to pore size restriction, it is anticipated that only polymer-stabilized nZVI may be transported by EK in low-permeability formations. nZVI delivery via EK is an emerging research topic.

ZVI can be applied as a standalone technology, but combinations with other in situ technologies are also common to take advantage of the synergy between technologies. The following are some of the technologies that can be combined with ZVI treatment.

- **Bioremediation:** Bioremediation is the most common in situ technology coupled with ZVI. ZVI creates strongly reducing geochemical conditions that are favorable for biological reductive dechlorination. In addition, ZVI may act as an electron donor that can transmit electrons either directly (via ZVI-microbe contact (Tang et al., 2019)) or indirectly (via hydrogen production from ZVI corrosion (Bruton et al., 2015)) to microorganisms to carry out reductive dechlorination. Coupling ZVI with bioremediation is a mature remedial approach widely used to treat chlorinated solvents, including the compounds that may be less reactive or not reactive with ZVI alone, such as cDCE,

Table 2. ZVI Treatment Applications and Delivery Methods

ZVI Type	Size (µm)	Application	Delivery
Granular ZVI	> 300	Source and Plume	Trenching, soil mixing, and direct injection
mZVI	0.1 to 300	Source and Plume	Direct injection and soil mixing
nZVI	< 0.1	Source	Direct injection and injection wells
Oil/ZVI	Micro- to nanoscale	Source	Direct injection

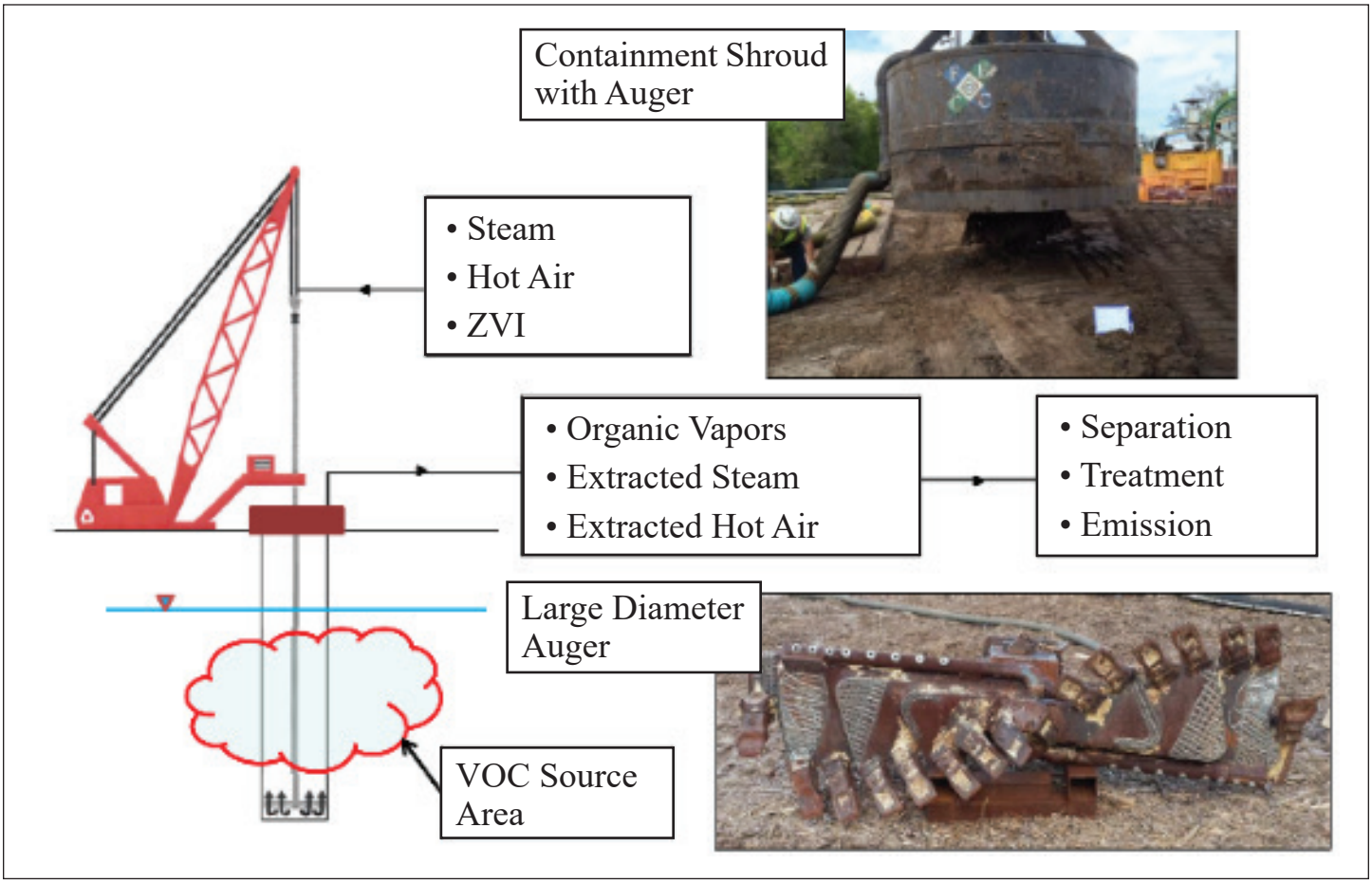

Figure 3. Combined Steam and ZVI Injection (Courtesy of Geosyntec)

VC, or 1,2-DCA. It should be noted that ZVI is typically coapplied with a biodegradable carrier (e.g., emulsified oil or guar gum), which can stimulate biodegradation. Guar gum may initially inhibit ZVI reactivity, which recovers over time as guar gum is biodegraded. Additionally, commercial products, such as ZVI-organic carbon composites and emulsified-ZVI (E-ZVI), are commonly used to promote both biotic and abiotic degradation as well as source treatment in the case of E-ZVI (ESTCP-200431). These products can include ZVI, organic carbon, biodegradable carriers, electron acceptors, and nutrients.

- **Thermal Remediation:** In situ thermal remediation (ISTR) is a common source treatment technology. ISTR volatilizes chlorinated solvents by increasing subsurface temperature, which subsequently enhances abiotic dechlorination rates. As shown in Figure 3, granular ZVI can be added as a polishing reagent, during or following ISTR, to enhance treatment of residual contamination remaining after ISTR (Johnson et al., 2009). An example of this combined technology involves in situ injection of steam followed by ZVI via direct soil mixing, which is commercially available and has been successfully applied for source treatment (Johnson et al., 2009).
- **In Situ Stabilization/Solidification (ISS):** ISS is a mature remediation and ground stabilization technology that has been widely used for source containment. ISS involves mixing cement (e.g., Portland or slag) into the target treatment zone, with cement dosages typically ranging from 8 to 15% depending on soil type and moisture content. Primary objectives of ISS include achieving geotechnical stability to allow future construction and to prevent contaminant leaching to the underlying groundwater. A growing body of academic research indicates that ZVI can be applied in combination with ISS to destroy contamination, significantly reduce or eliminate leaching of contamination from source areas, and achieve a soil bearing capacity sufficient to support construction post-remediation.

- **ZVI-Clay Soil Mixing:** ZVI-clay is a mature technology that involves soil-mixing delivery of ZVI and bentonite to achieve treatment and sequestration of chlorinated solvent source zones. Bentonite in the mix can reduce contaminant mass flux by reducing the permeability of the treatment zone by 2 to 3 orders of magnitude. This technology has been successfully applied at multiple Department of Defense (DoD) sites (Olson et al., 2017; Popovic et al., 2018). While often highly effective at achieving contaminant destruction, this technology suffers from the limitation that, unlike ISS, does not achieve ground stabilization and may result in weaker bearing capacity / unconfined compressive strength in the treatment zone. Consequently, the treated ground may not be suitable for future construction and other land uses.

Considerations for Selecting ISCR

As described in the discussion above, ISCR with ZVI is applicable across a wide range of site conditions. In general, the following factors should be considered when selecting ZVI to remediate a contaminated site.

- **Contaminants:** The primary contaminants of concern or risk drivers should be degradable by ZVI or ZVI-based technologies with reasonable rates.
- **Geochemistry:** ZVI remedies can be implemented successfully in both oxic and anoxic aquifers. Groundwater that contains high concentrations of inorganic electron acceptors such as nitrate, however, may not be suitable for ZVI remedies due to the well-known passivation effect of nitrate on ZVI reactivity. Sulfate is more prevalent in groundwater than nitrate, but the effects of sulfate on ZVI dechlorination reactivity have been reported to vary by the sulfate concentration, type of ZVI, and contaminant. The presence of high concentrations of carbonate and silica in groundwater may also passivate ZVI over the long term. Additionally, the creation of anoxic conditions by ZVI may lead to an unintended consequence of mobilizing certain reduced metals downgradient of the target treatment zone. As such, potential secondary groundwater quality issues should be evaluated when considering ISCR.
- **Implementability:** Lithology, hydrogeology (i.e., unconsolidated deposits versus competent bedrock), depth, and subsurface accessibility of the target treatment zone affect the implementability of ZVI. Given the broad size range of ZVI amendments and recent advances in amendment delivery technologies (e.g., DPT-JI), implementability is less constrained. However, contamination depth is still a major limiting factor. Contamination deeper than 75 feet (ft) below ground surface (bgs) is generally considered difficult to treat with conventional DPT injection. Hydraulic or pneumatic fracturing can be effective at deeper depth but only up to 150 ft bgs (NAVFAC, 2013).
- **Performance Objectives:** As with evaluating all remedial technologies, performance objectives and the time frames to meet the objectives are important considerations when determining if ISCR is the best option for remediation. Granular ZVI or mZVI are generally considered suitable for long-term treatment because of its suitable lifespan. In contrast, nZVI achieves faster treatment but lacks long-term effectiveness due to its high surface area and high reactivity with water.
- **Cost:** Capital costs typically include amendment, equipment mobilization, and installation, which is ultimately determined by treatment scenario and performance objective. The cost for amendments is usually < 20% of the overall project cost. Cost considerations should also include potential costs for reapplication (particularly for source area applications), which is affected by the long-term effectiveness of the treatment. Detailed descriptions of individual cost elements for various prior ISCR applications have been provided in previous guidance documents and technical reports (ITRC, 2011; NAVFAC, 2005; Olson et al., 2017).

Design and Implementation

The design and implementation of ISCR applications, in most cases, are specific to the type of ZVI selected and the corresponding delivery method. However, the fundamental principles for design are similar across all ISCR remedial approaches. Detailed design processes, considerations for various ISCR amendments, and implementation methods are described in several guidance documents published by ITRC and NAVFAC (ITRC, 2011; NAVFAC, 2013). The steps highlighted in Figure 4 should be followed for a robust ISCR design.

ISCR implementation presented here mainly pertains to DPT injection as it is the most commonly used ISCR delivery method. Typically, the ZVI injection slurry is prepared on site with potable water in a mixing tank. For mZVI-based products, the injection slurry typically contains 25% to 35% solid by weight, which is suspended by adding guar gum in the slurry. The mZVI slurry is most commonly injected using a DPT rig equipped with an injection rod and a pressure-activated injection tip allowing for horizontal placement by either top-down or bottom-up approaches. Top-down is preferred but clogging might occur during implementation. To prevent clogging, a small volume of

Figure 4. ISCR Step-by-Step Design Process

1 Site Characterization

Objective: Inform conceptual design and application approach, establish treatment objectives, and evaluate site-specific factors that may impact remedial design and implementation.

Task: Characterize nature, extent, and migration pathway of contamination as well as lithology and hydrogeology, microbiology, geochemistry, and site-specific infrastructure. Consider high resolution site characterization as appropriate.

2 Bench Treatability Test

Objective: Acquire site-specific design parameters, such as treatment rates.

Task: Conduct batch and/or flow-through column tests using the target ZVI to soil loading in the field (typically 0.5%–2% for injection or mixing of mZVI) and monitor degradation over an extended number of pore volumes. The ZVI loading should be adjusted lower for nZVI injection and higher for granular ZVI in trenched PRBs.

3 Pilot Test

Objective: Evaluate field implementability, such as injection tooling, amendment injectability and distribution (i.e., radius of influence [ROI]) for injection; geotechnical constructability and engineering parameters for soil mixing and trenched PRB.

Task (injection): Conduct injection at one or two points with amendment and evaluate ROI by soil and/or groundwater sampling and analysis of indicators of ZVI impact. Typical ROI for designing DPT injection is 5 to 7.5 feet (NAVFAC, 2013). Larger ROI can be acheived by DPT-JI.

4 Full-Scale Implementation Plan

Objective: Specify dimensions of treatment zone, treatment area layout, total quantity of required amendment and other reagents, and implementation procedures.

Task: Determine the treatment zone size based on the conceptual site model, treatment goal, and site-specific treatment rate derived from column tests. A safety factor should be applied to total amendment quantity to account for continuous corrosion of ZVI by water, gradual loss of ZVI reactivity and nonuniform amendment distribution during placement (e.g., injection).

chase water can be used to clear the injection tool between injections. If enhanced bioremediation is also being applied, a dechlorinating bacterial culture can be bioaugmented along with the mZVI slurry. For nZVI, the slurry concentration is typically much lower (2 to 10 grams per liter [g/L]) than with mZVI. Guar gum is not needed for nZVI injection, but stabilizers such as CMC are commonly used to prevent nZVI particle agglomeration and improve delivery. Typically, water used for nZVI injection needs to be deoxygenated prior to mixing with nZVI in order to minimize nZVI oxidation by and dissolved oxygen. Detailed information regarding ISCR implementation, including other application methods, can be found in several previous guidance documents (ITRC, 2011; NAVFAC, 2013).

ISCR Monitoring

ISCR monitoring includes process monitoring and performance monitoring. A detailed monitoring plan should be developed as part of the implementation plan.

- **Process monitoring:** Process monitoring mainly applies to injection-based ISCR and includes monitoring for pressure, volume, and flow rate during injection all of which can be affected by the geology of the target treatment zone. Injection pressure indicates the resistance of the formation to accept fluid. Higher injection pressures (100 to 500 psi) are expected for injecting a mZVI slurry by DPT, which is more concentrated and viscous, than a nZVI slurry. An initial high-pressure spike followed by steady lower pressure indicates creation of fractures. Monitoring volume and flow rate provides real-time indication of injection progress. Once the injection is complete, soil cores should be collected to verify distribution of ZVI (i.e., ROI). ZVI distribution in cores can be verified through a combination of visual inspection, magnetic susceptibility measurement, and total iron analysis. Additional evidence for distribution may be obtained from wells near the injection points by monitoring groundwater geochemical parameters indicative of ZVI, including oxidation-reduction potential (ORP), pH, and conductivity.
- **Performance monitoring:** Performance monitoring should be designed to adequately assess the long-term effectiveness of ISCR and may include monitoring trends upgradient, within, and downgradient of the treatment zone for the following parameters:
  - o Contaminant concentrations, including parent and degradation products;
  - o Aqueous geochemical indicators (e.g., ORP, total organic carbon [TOC], pH, sulfate, and ferrous iron);
  - o Mass flux reductions;
  - o Compound-specific isotope analysis, molecular biological techniques (e.g., next generation sequencing); and
  - o Biogeochemical and reactivity characterizations of aquifer materials.
  - o The tools listed above have been applied in several recent projects to evaluate the long-term performance of ISCR (Olson et al. 2017; Popovic et al. 2018).

Lessons Learned

ZVI-based remediation is a mature in situ remediation technology for treating chlorinated solvents. Vast amounts of knowledge and experience have been accumulated through developing and implementing this technology.

- Properties and reactivity of ZVI can vary significantly among different ZVI products, especially for granular/mZVI. Apart from size difference, different raw material sources, impurity or additives, and production methods also affect product reactivity. Product consistency can even vary from batch to batch. Therefore, it is recommended to request quality control documents from the supplier when sourcing the product. These documents should include the characterization of the physical properties and reactivity of the product.
- mZVI is the most common injectable ZVI product used in the remediation market today, as it offers an attractive balance between reactivity, longevity, and cost. Guar gum is typically used as a carrier during injection of mZVI. Although guar biodegrades in the subsurface, its degradation can be slow, and research indicates that guar temporarily passivates the mZVI surface.
- nZVI only represents a small market share in field applications despite extensive research interests over the last two decades. Injection of nZVI has been limited primarily to pilot-scale applications and lacks long-term monitoring data to support performance assessment. The field effectiveness of nZVI has been limited by its poor distribution and lack of longevity. Recent advances in sulfidation could potentially improve both aspects for nZVI application.
- Batch treatability tests are a useful and cost-effective way to screen reactivity of different ZVI products. At a minimum, batch studies should be performed to measure the extent of treatment and reaction kinetics. Flow-through column tests that simulate groundwater flow in the field are preferred as they provide more robust design information

and assessment of long-term performance under site-specific geochemical conditions. Typically, column tests generate faster dechlorination rates than batch tests because of the higher solid to liquid ratio used in columns.

- Pilot tests are typically recommended if DPT injection is the selected implementation approach to evaluate amendment injectability into the subsurface and identify appropriate injection tooling, approach, and parameters (e.g., injection volume).
- The best practices for ISCR implementation were established based on numerous projects conducted over a wide range of site conditions. Documents by ITRC and NAVFAC (ITRC, 2011; NAVFAC, 2013) can be used as guidance.
- Treatment effectiveness over the long term has been evaluated at a number of PRB sites for plume treatment and several ZVI soil mixing sites for source treatment. Most of these project sites used granular ZVI. At these sites, abiotic processes and ZVI-stimulated biotic processes contributed to contaminant degradation. Additionally, ZVI transformation to reactive Fe(II) minerals may result in secondary abiotic degradation. Therefore, long-term monitoring plans should include assessing secondary treatment by biotic and abiotic processes.
- Long-term treatment effects of ISCR can be negatively impacted by ZVI passivation due to corrosion of Fe(0) and subsequent geochemical precipitation (e.g., siderite). Certain constituents, such as nitrate or silica, also strongly passivate ZVI. The degree of passivation varies depending on the site-specific geochemical conditions, and in the case for PRBs, can have significant effects on performance by reducing the hydraulic conductivity of the barrier and altering the direction of groundwater flow. Biogeochemical conditions within and around the treatment area should be evaluated prior to design.

Case Study – Naval Support Facility Indian Head, Site 17, Maryland

Introduction. Site 17 is in the southeast portion of the Naval Support Facility (NSF) Indian Head facility, which is located on the Potomac River and Mattawoman Creek, less than 30 miles south of Washington, D.C. The site covers approximately 3.5 acres and was used for disposal of rocket motor casings, shipping containers, drums, and various metal parts from the 1960s until early 1980.

Site Characteristics. Soil at Site 17 consists of fill material (surface to approximately 10 to 12 ft bgs), a silty clay layer that is approximately 10 ft thick, and a clay layer with depths greater than 25 ft bgs. Shallow groundwater (5 to 15 ft bgs) generally flows toward Mattawoman Creek at an estimated velocity between 43 and 400 ft per year. TCE is the primary contaminant of concern with initial, maximum concentrations of 490,000 micrograms per liter (µg/L) and 870,000 µg/L in the upper and lower surficial aquifers, respectively. Such high concentrations indicated the potential presence of DNAPL. Reductive dechlorination daughter products, including cDCE and VC, were also present at significant but much lower concentrations than TCE, indicating that some degree of natural dechlorination had occurred in the target treatment zone prior to remedy implementation.

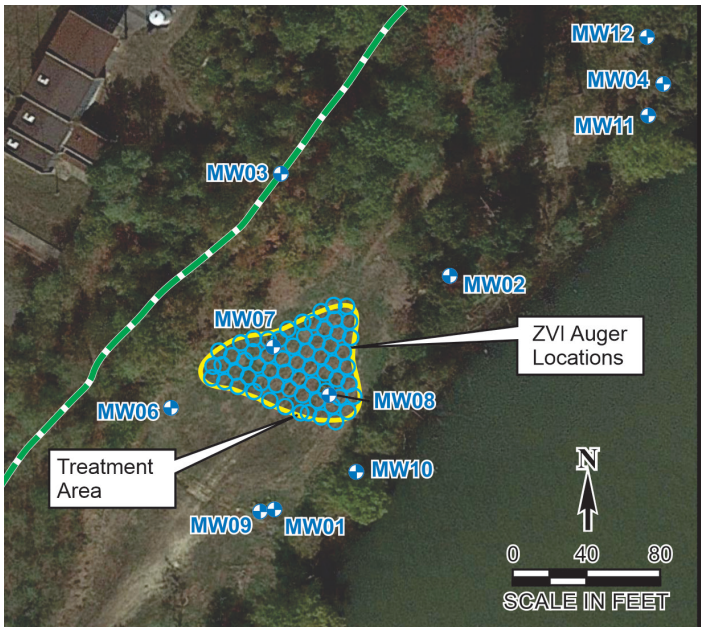

Figure 5. Layout of ZVI Soil Mixing Zone (Courtesy of ESTCP)

Remediation. In 2012, ZVI soil mixing was conducted in the area where most of the contamination mass resided (TCE concentration > 1,000 µg/L). The target treatment zone covered approximately 3,500 square ft of surface area and contained a volume of approximately 1,300 cubic yards (see Figure 5). Soil mixing was conducted using 9-ft augers, and 70 mixing columns were developed using a bentonite slurry to facilitate drilling. The ratio of ZVI to soil mass was at 1%. Between 875 and 1,050 pounds of granular ZVI was mixed at each soil column.

Evaluation of Treatment Performance. Contaminant concentrations were significantly reduced in all of the source wells within the soil mixing zone. Within four years of implementation, concentrations of TCE, cDCE, and VC in portions of the source zone all decreased by 99% to levels slightly greater than maximum contaminant levels, and no rebound has been observed. Long-term performance evaluation was further conducted in 2016 at Site 17, which

Figure 6. Processing Soil Cores Collected by Cryogenic Coring (Courtesy of ESTCP)

was funded by ESTCP (ER-201587). Cryogenic coring, a novel soil coring technique, was used to collect frozen soil cores from within the mixing zone and downgradient locations (see Figure 6). The frozen cores were processed in the laboratory to characterize soil contaminant concentration, degradation products, as well as ZVI content, reactivity, and microbiological parameters. The results indicated effective source treatment and long-term efficacy. The highest soil TCE concentration within the mixing zone decreased from 510 milligrams per kilogram (mg/kg) to 0.3 mg/kg. The reactivity testing also confirmed that reactive ZVI is still present and capable of reacting with chlorinated ethenes.

Resources

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