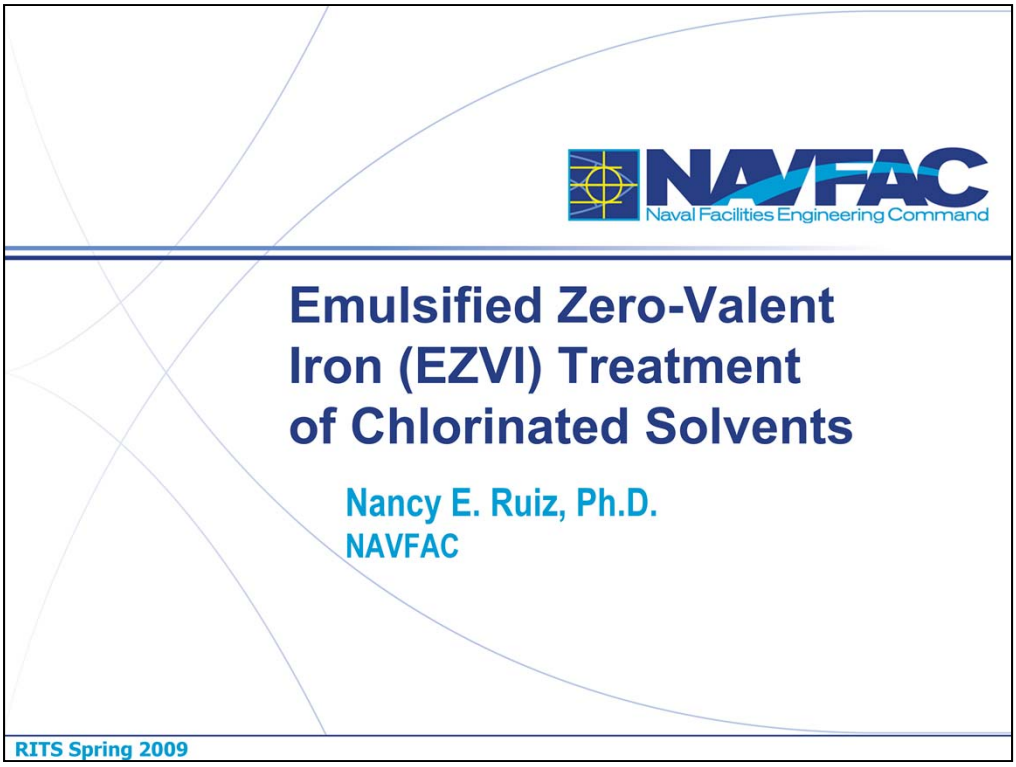

NAVFAC
Naval Facilities Engineering Command
Emulsified Zero-Valent Iron (EZVI) Treatment of Chlorinated Solvents
Nancy E. Ruiz, Ph.D.
NAVFAC
RITS Spring 2009

Past RITS Presentations on ZVI and Bioremediation

- Permeable Reactive Walls (Spring 1998)
- Advances if Permeable Barrier Technologies (Spring 2002)
- In Situ Treatment of Chlorinated Solvents Using ZVI Technologies (Spring 2005)
- Enhanced Bioremediation Technologies (Spring 2000)
- Advancements in In Situ Bioremediation (Spring 2001)
- Bio – State of the Practice (Fall 2007)

Key Points

- EZVI combines degradation capabilities of two common remediation technologies
  - Zero-valent iron (ZVI)
  - Biodegradation
- EZVI both sequesters and degrades chlorinated volatile organic compounds (CVOCs)
- Microscale and nanoscale iron are suitable for EZVI
- The ZVI provides rapid and immediate degradation and the vegetable oil component of the EZVI emulsion droplet can provide more long-term biodegradation
- Multiple injection technology options are available for application

Presentation Overview

- **Technology Overview**
- **Technology Implementation**
- **Case Studies**
- **Other Applications**
- **Cost**
- **Summary**

- **ZVI**
  - Chemistry, Applications, Limitations
- **nZVI and mZVI**
  - Reactivity, Applications, Advantages, Limitations
- **EZVI**
  - Theory, Chemistry, Applications, Advantages, Limitations
- **Application Methods**
  - History
  - Advantages, Limitations

ZVI

- ZVI is a strong reducing agent
- ZVI is an accepted technology for degradation of dissolved CVOCs such as PCE and TCE to ethene, as well as metals and pesticides
- ZVI role in degradation:

$$Fe^{0} \rightarrow Fe^{+2} + 2e^{-}$$

$$2H_2O \rightarrow 2H^{+} + 2OH^{-}$$

$$2H^{+} + 2e^{-} \rightarrow H_{2(g)}$$

$$X\text{-}Cl + H^{+} + 2e^{-} \rightarrow X\text{-}H + Cl^{-}$$

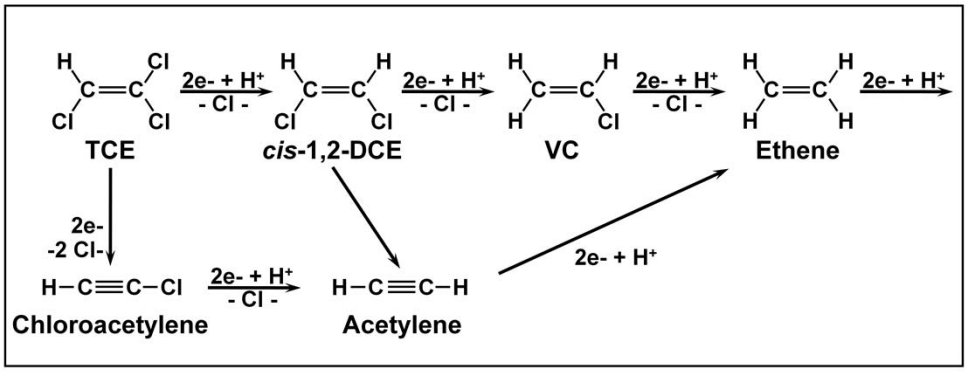
$$C_2HCl_3 + 3H^{+} + 6e^{-} \rightarrow C_2H_4 + 3Cl^{-}$$

Essentials for ANY ZVI Treatment

- Highly reduced conditions (-300+ mV)
- Active iron surface
- Contact of iron surface with contaminant
  - Surface-mediated reaction

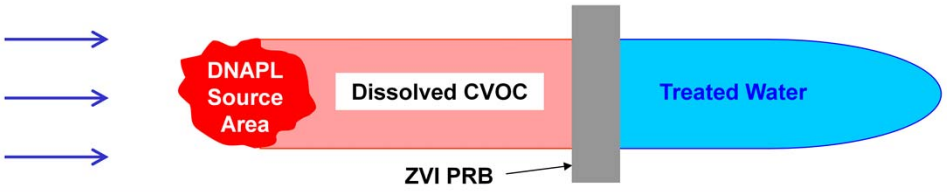
ZVI Chemistry

- Multiple pathways for chlorinated ethene degradation by ZVI
- Surface-mediated reaction but basic chemistry the same regardless of particle size (granular, micro- or nano-scale ZVI)



Common Use of ZVI in Permeable Reactive Barriers (PRBs)

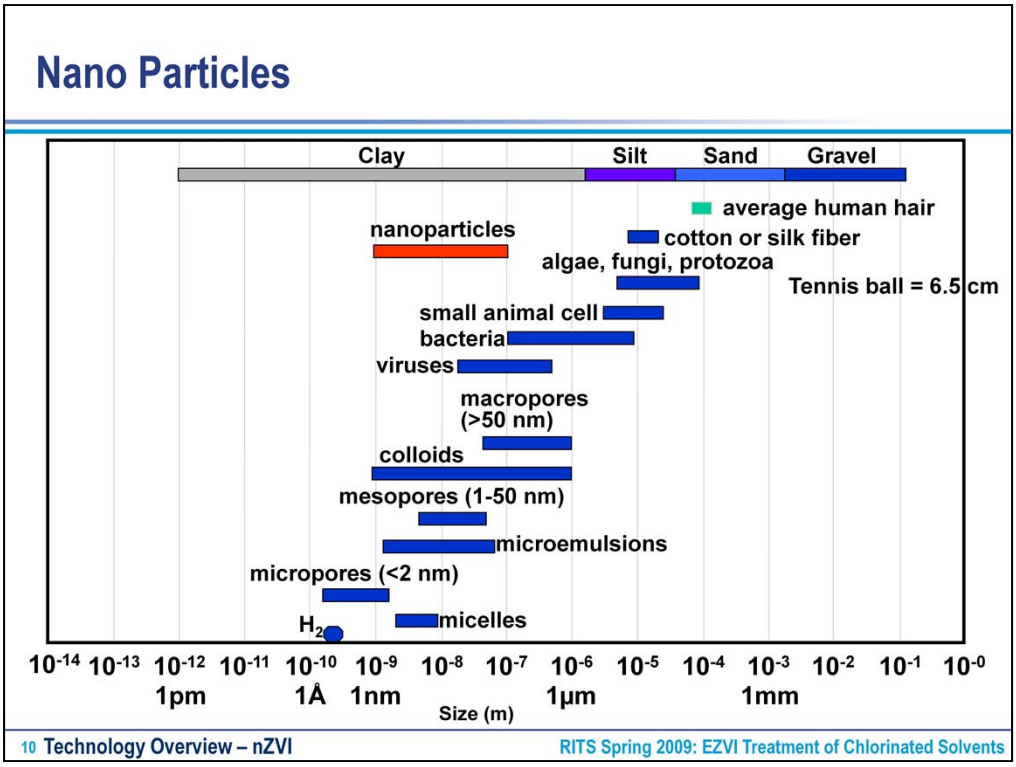
- ZVI (granular) PRBs are effective in treating dissolved CVOCs but:
  - Are dependent on dissolution and transport of CVOCs; and ∴
  - Do little to reduce the clean up time and long-term monitoring costs
- ZVI needs to be in the presence of water to promote reductive dehalogenation
- Injection of ZVI into a DNAPL source zone will only treat the dissolved phase at the edges of the DNAPL



Nanoscale and Microscale ZVI (nZVI and mZVI)

- nZVI particle sizes typically range from 50 to 300 nanometers (nm)
- Surface area of nZVI 30 times greater than granular iron per unit volume (up to 33.5 m^2/g)
- mZVI particle sizes typically range from 1,000 to 3,000 (up to 40,000) nm or 1 to 3 µm
- Large surface area of mZVI and very large surface area of nZVI equals large number of reactive sites for degradation to occur
- 10 to 1,000 times more reactive than granular iron
- However, basically the same chemistry

To get an idea of the surface area of the nano scale iron (50 nm) versus a powdered iron on the mm scale (large micro scale iron), it would take approximately 5,800 kg of the powdered iron to have the surface area equal to a football field. It would only take 0.3kg of the nano scale iron to have a surface area equivalent to the area of the same ball field

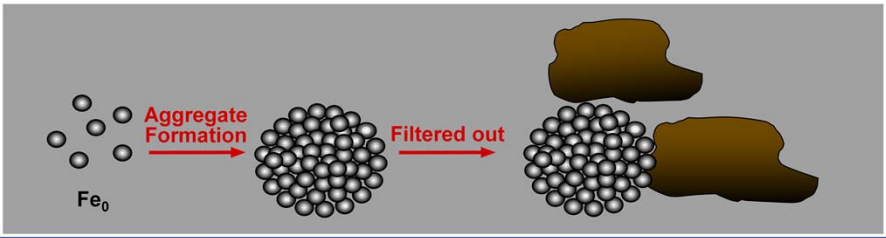


Average human hair is 80 um or 10,000 times the size of many nanoparticles

A tennis ball for scale – 6.5 cm

nZVI Properties

- Theoretically, nZVI particles are able to travel with groundwater and be transported downgradient of the point of injection
- In reality, magnetic and colloidal properties of nZVI may result in aggregation during storage, handling and once injected into the subsurface
- nZVI can be filtered out by soil such that much of what is injected remains very close to the point of injection



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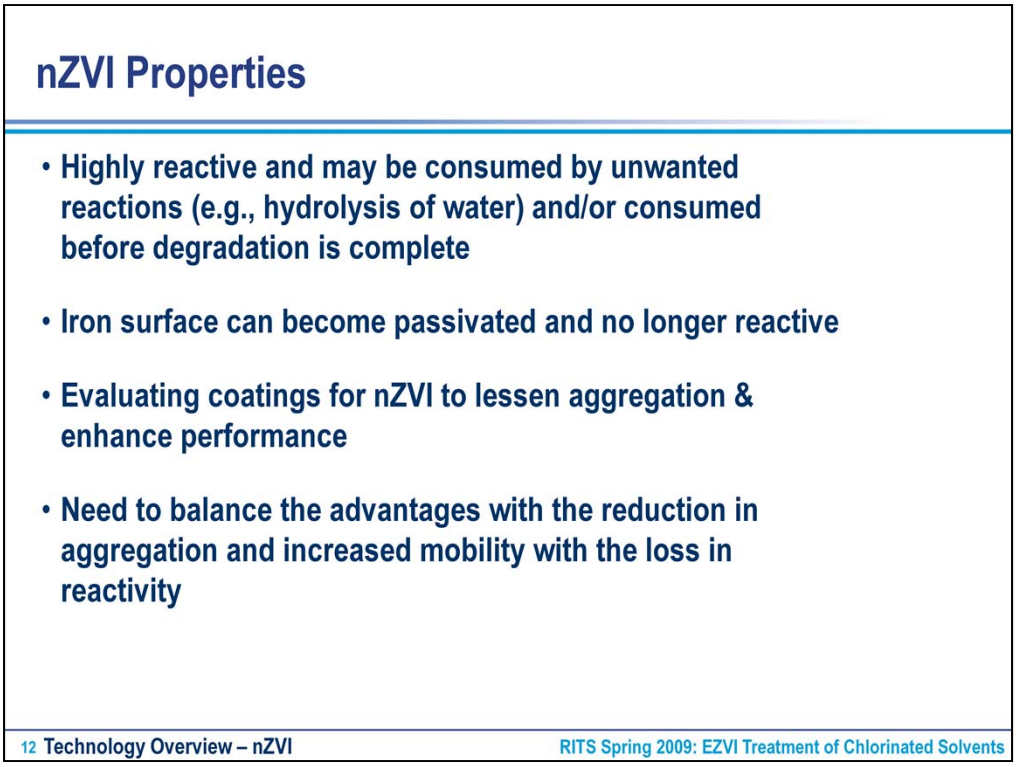
Theoretically, nZVI particles may be able to travel in suspension in groundwater due to very small size and be transported downgradient of the point of injection groundwater flow

In reality, magnetic and colloidal properties of nZVI may result in aggregation during storage, handling and once injected into the subsurface and nZVI can be filtered out by soil such that much of what is injected remains very close to the point of injection



Highly reactive and may be consumed by unwanted reactions (e.g., hydrolysis of water) and/or consumed before degradation complete and iron surface can become passivated

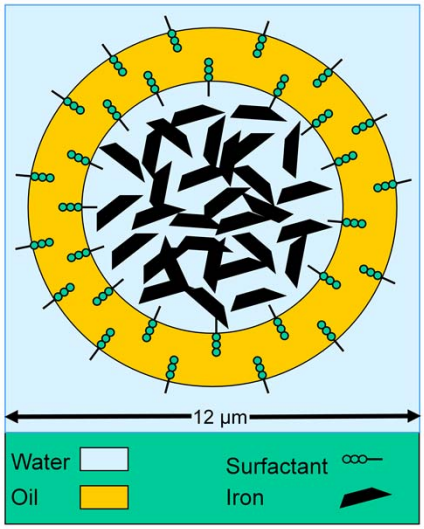
- Stabilizers tend to provide both steric and electronic means of intra-cluster repulsion

Balance the enhancement of mobility with loss of reactivity

- Some portion of active nZVI surface occupied by stabilizer attachments

EZVI

- EZVI consists of emulsion droplets containing iron particles in water surrounded by an oil-liquid membrane
- EZVI is composed of food-grade surfactant, biodegradable vegetable oil, water, and ZVI (nano- or micro-scale iron)



Yellow = oil layer stabilized by the surfactant in water

Water contained within the emulsion droplet and iron contained within the interior water

Note in diagram – iron particles inside droplet - if using micro scale iron would have 10s of particles; if using nano scale iron would have 1000s of iron particles in a droplet

Image of EZVI and DNAPL Contact

- Since exterior oil membrane of emulsion droplets have hydrophobic properties similar to DNAPL, the emulsion is miscible with the DNAPL

DNAPL
dyed red

DNAPL
with nano-scale ZVI

DNAPL
with EZVI

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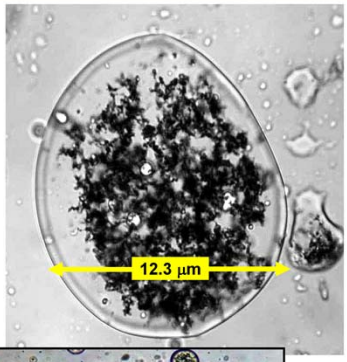
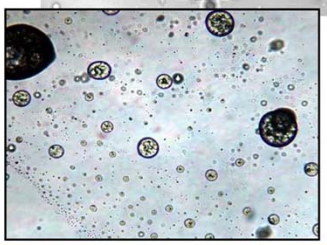
Since exterior oil membrane of emulsion droplets have hydrophobic properties similar to DNAPL, the emulsion is miscible with the DNAPL

EZVI (cont.)

- VOCs in DNAPL diffuse through the oil membrane and are degraded in the presence of the ZVI in the interior aqueous phase
- In addition to abiotic degradation due to iron, EZVI contains vegetable oil and surfactant which will act as a long-term electron donor and promote anaerobic biodegradation





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The continuous degradation of the VOCs drives the diffusion gradient so VOCs continue to diffuse and degrade.

In this photo the EZVI was made with nZVI and there are 1000s of particles in this one 12 um droplet

Lower photo shows EZVI droplets suspended in water – the EZVI was made with water dyed green with food coloring and although hard to tell in the photo it was obvious that the interior of the droplets were green (water)

EZVI Laboratory Testing Summary

- **Lab tests conducted to evaluate treatment of near saturation dissolved phase concentrations (1,000 ppm) and DNAPL (10 x saturation) using:**
  - **Controls (active and sterile)**
  - **Vegetable oil & surfactant (emulsion)**
  - **Nano-scale zero-valent iron (nZVI)**
  - **Emulsified zero-valent iron (EZVI)**
- **Monitor VOCs, DHG and chloride in the water phase of each reactor**

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Controls

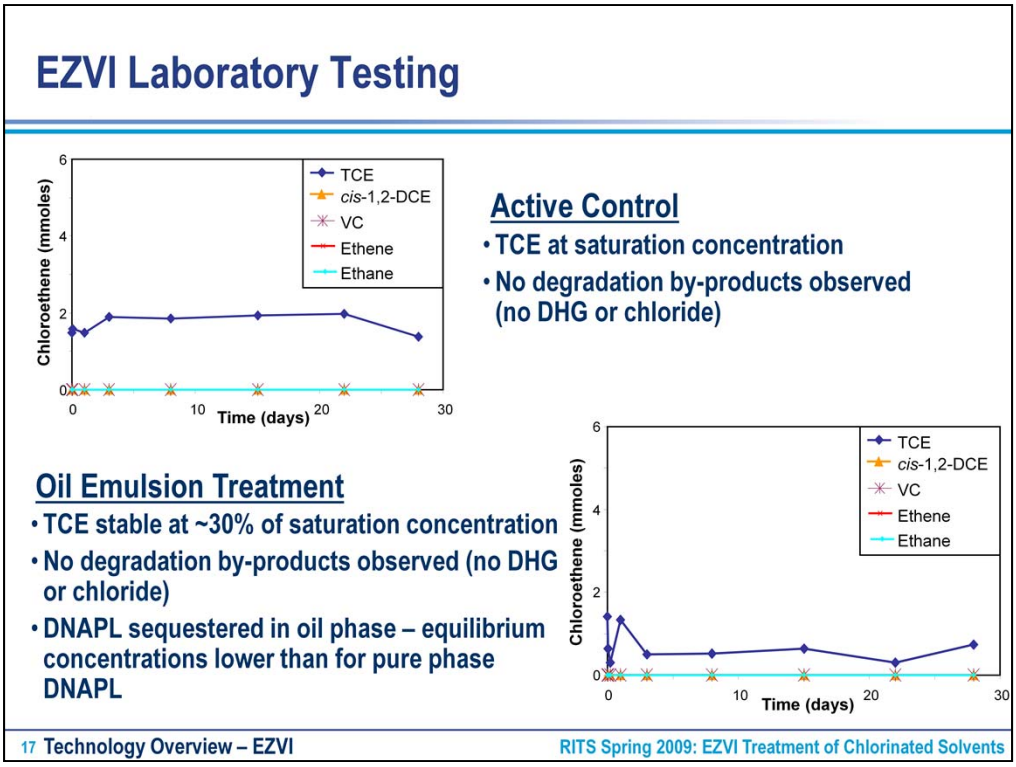
Oil emulsion treatments – oil, surfactant and water in the same amounts as the EZVI treatments but without any nZVI

nZVI treatments – same amount of nZVI as the EZVI treatments without the oil or surfactant

EZVI treatments

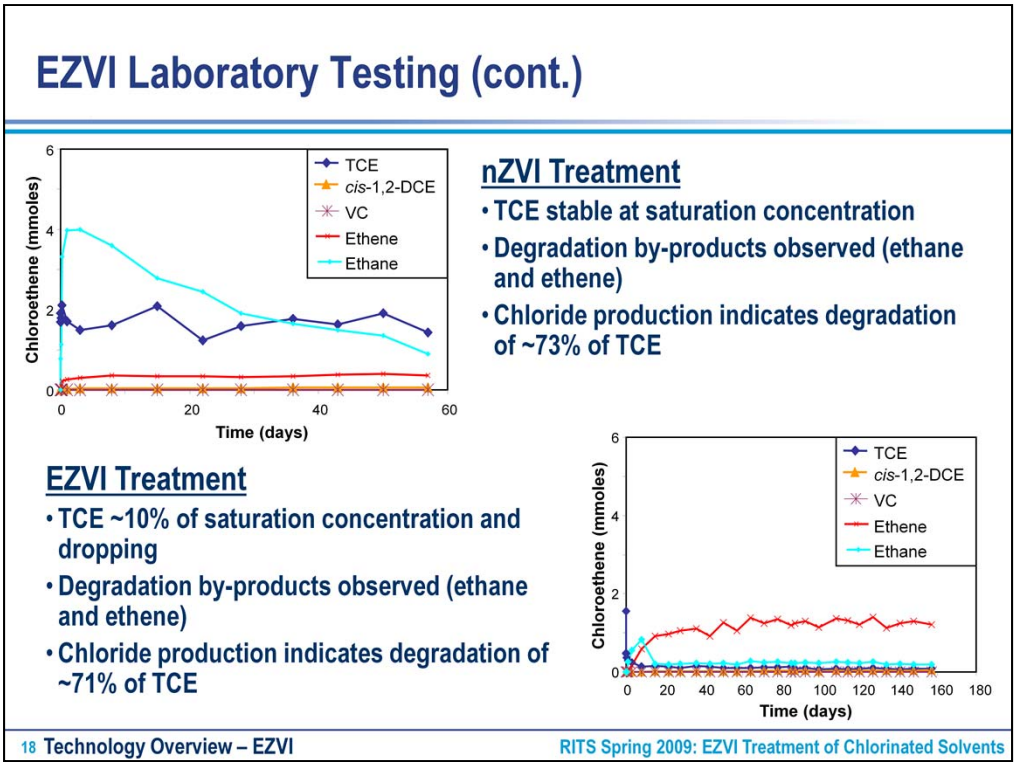
All results shown are from samples taken from the water in the reactors

For these tests there is a separate DNAPL phase present and sampling started once TCE DNAPL was in equilibrium with the water (water in reactors saturated with TCE).



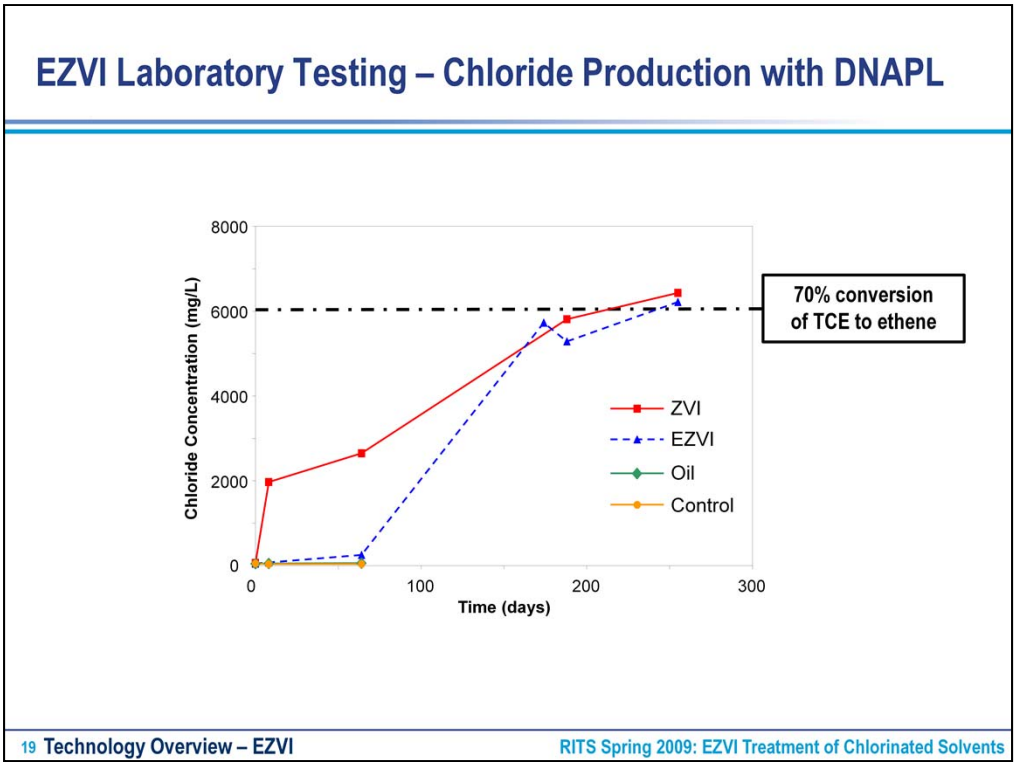
Active control – as expected we see no change in concentration in the active control = concentration in mmoles steady around 2 which is TCE saturation concentration = in all these tests there was a separate DNAPL phase present

Oil emulsion treatment = EZVI without the iron (surfactant, veg oil and water emulsified) = here we see that the steady TCE concentration is lower than saturation - around 1.5 mmoles, no degradation by-products evident but the DNAPL has been sequestered into the oil phase



For the nZVI treatment – only nZVI added, same amount of nZVI as added in the EZVI treatment. The TCE is stable at the saturation concentration of around 2 mmoles but there are degradation by –products present – so degradation is occurring (~70% of TCE degraded) but the concentration in the water doesn't change because still a separate phase present.

For EZVI treatment – we see TCE concentrations at only 10% of the saturation concentrations, degradation products form and ~70% of the TCE degraded based on the chloride data – so here we see significant decrease in the concentration in the water- if this was your field site you would see reduction in flux off the source here but not in the nZVI treatment.



Same end point for amount of degradation that occurs but the EZVI treatment is apparently delayed a bit but this is due to the chloride being produced within the EZVI droplets and having to diffuse back out of the drops before being seen in the water in the reactors.

Conclusions of EZVI Laboratory Testing

- Veg oil emulsion decreases TCE concentration due to sequestration (no degradation)
- nZVI reduces mass of TCE due to treatment but no decrease in aqueous concentration of TCE if DNAPL present (no effect on mass flux)
- EZVI benefits from sequestration due to oil plus degradation due to nZVI
  - Significant decrease in aqueous concentrations (drop in mass flux) greater than with just the oil; and
  - Reduction in mass of TCE

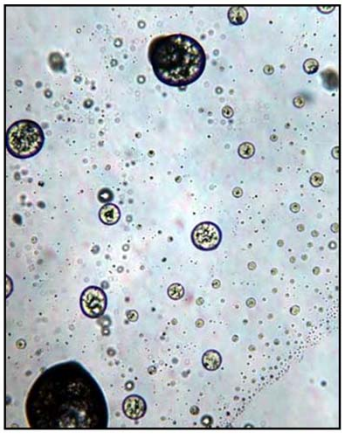
Impacts of biodegradation not significant in these tests which utilized synthetic groundwater and no soil (expect to see biodegradation with emulsion and EZVI)

EZVI Application Methods

- Injection
  - Direct injection
  - Pneumatic injection
  - Pressure pulse injection
  - Hydraulic fracturing
- Large diameter auger mixing
- EZVI is a fairly viscous fluid and can be difficult to emplace in the target treatment interval

Application History

- NASA holds the patent for EZVI
- Technology has been successfully commercialized by NASA and has been licensed to 6 companies
- EZVI awarded Invention of The Year and Commercial Invention of The Year by NASA and the Federal Government, and was inducted into the Space Technology Hall of Fame



Application History

State - Location	Year	Volume (gal)	Size of Iron	Primary Contaminant	Soil Type	Injection Method
Central FL - LC34	2002	670	nano	TCE	sand and sandy silt	pressure pulse
TN	2004	1,000	nano and then micro	PCE, TCE	residuum	direct injection
Central FL	2005	62,000	mix - nano and micro	TCE	sand	pneumatic
Southern FL	2005	2,300	mix - nano and micro	TCE	sand	pneumatic
Southern AR	2005	800	mix - nano and micro	EDB	clay	pneumatic
SC	2005	1,400	micro	PCE,TCE,TCA	saprolite	direct injection
IL	2005-2006	920	micro	PCE	clayey silt	pneumatic
OH	2005-2006	1,840	micro	PCE	sandy silt	pneumatic
SC - Parris Island	2006	750	nano	PCE	sandy silt, clay and peat	direct injection and pneumatic
Central FL	2006	6,000	micro and a mix of nano and micro	TCE	sand	direct injection
MA	2006	600	mix - nano and micro	PCE, TCE	fractured bedrock	gravity flow
TX	2006	1,840	micro	CT	sandy silt	pneumatic
NC	2006	1,800	micro	TCE	residuum	direct injection
LA	2006 & 2008	2,300	micro	CT	silty vadose zone	pneumatic
Central FL	2007(planned)	3,000	mix - nano and micro	TCE	sandy	direct push hybrid
IL	2007-2008	10,800	micro	TCE	clayey silt	pneumatic

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Injected at over 16 sites to date.

Earliest in 2002 and some sites planned for 2009 and ‘10.

Largest volume injected to date was 62,000 gal at Patrick Air Force Base – one of the case studies to follow.

Has been used at sandy sites, clayey sites and even in fractured bedrock.

Has even been applied in the vadose zone – the idea being that the EZVI has water within the droplet so that the ZVI will have the water it needs to degrade the contaminants - no data available on that site so don’t know how it worked.

Most applications are with micro iron. Many have been done with pneumatic injection.

EZVI Advantages and Limitations

Advantages

- *In situ* treatment of DNAPL source areas is possible thereby shortening time for closure
- Immediate degradation provided by ZVI
- Significant decrease in mass flux due to VOCs partitioning into oil
- Long-term biodegradation provided by oil, bioaugmentation can enhance biodegradation
- Complete reduction to non-toxic end products possible
- ZVI provides treatment of chemicals which may inhibit biodegradation (e.g., Freon)
- Minimal labor and waste disposal

Limitations

- Not generally cost-effective for dispersed plumes
- Cost of nZVI material itself can be high – can use mZVI instead
- Due to viscosity can be hard to inject and difficult to get EZVI to target treatment zone
- Well-characterized source zone needed

Presentation Overview

- Technology Overview
- Technology Implementation
  - Conceptual Site Model (CSM)
  - Site Characterization
  - Design
  - Performance Monitoring
- Case Studies
- Other Applications
- Cost
- Summary

Conceptual Site Model

- Developed based on the results of site characterization
- Necessary to determine applicability of EZVI and appropriate design parameters for implementation
- Design of EZVI application may be inappropriate or insufficient if the conceptual model is incorrect or incomplete

Factors that Need to be Determined for Applicability of EZVI

- **Site Characteristics**
  - Hydrogeology
  - Geology and depth of target treatment interval
  - Geochemistry
  - Contaminant type and distribution (source zone delineation)
- **Site Constraints**
  - Site access restrictions
- **Remedial Objectives**
  - Regulatory requirements
  - Other remedial objectives

Site Characterization

- **Additional characterization in the target treatment area may be necessary:**
  - **Geology of targeted treatment zone**
  - **Horizontal and vertical distribution of contamination**
  - **Groundwater flow characteristics**
  - **Presence of underground obstacles**
  - **Presence of indigenous microorganisms**
    - Consider bioaugmentation when injecting EZVI to boost the biodegradation component

Choosing Injection Technologies

Site Characteristic			Injection Technology to Consider			
			Direct Injection	Pneumatic Injection	Pressure Pulse Injection	Large Diameter Augers
Geology		homogeneous				
		heterogeneous				
		homogeneous				
		heterogeneous				
		highly fractured				
		few fractures				
Depth	0-10 ft					
	10-50 ft					
	50-100 ft					
	>100 ft					
Size	<0.5 acres					
	0.5 to 1 acre					
	>1 Acre					

Consider

Use caution

Probably not applicable or may be very expensive to use

Design and Remediation Management Considerations

- The EZVI application should be implemented in the source zone or area of highest contaminant concentrations
- Consideration of bioaugmentation to enhance complete degradation
- Other elements of design include:
  - Extent of treatment necessary (volume)
  - Dosage of EZVI (may be much greater than stoichiometric ratio Fe/TCE = 1.3/1; safety factor and ability to distribute effectively)
  - Injection method
  - Radius of influence to determine location and number of injection points (located in source area)
- Consider injecting maximum of 30% of available pore space and no less than 10% so that it can be properly distributed throughout target treatment area

nZVI / mZVI Issues = EZVI Issues

- Iron Surface Passivation
  - Minimize storage time of nZVI / EZVI
- Significant variability of properties of nZVI and mZVI
  - Therefore, all EZVI is not the same
  - Obtain QA/QC documentation from manufacturer or test iron and even EZVI prior to use

Performance Monitoring

- **Compliance Monitoring**
  - **Regulatory monitoring requirements**
  - **Groundwater samples upgradient and downgradient of treatment zone**
- **Performance Monitoring**
  - **Used to determine short-term and long-term effectiveness of treatment technology**
  - **Groundwater samples include:**
    - Contaminant levels
    - TOC, ORP, pH
    - Manganese, iron, chloride, sulfate
    - Dissolved hydrocarbon gases (e.g., ethene, ethane, methane)
  - **Soil samples include**
    - Contaminant levels
    - Visual confirmation of EZVI presence

Soil and Groundwater Samples

- Look for presence of EZVI in cores to evaluate distribution; can also analyze soil for VOCs to evaluate performance
- Sample groundwater and evaluate changes in field parameters, concentrations etc…

Presentation Overview

- Technology Overview
- Technology Implementation
- Case Studies
  1. Launch Complex (LC) 34
  2. ESTCP – Parris Island, SC
  3. Patrick Air Force Base, FL
- Other Applications
- Cost
- Summary

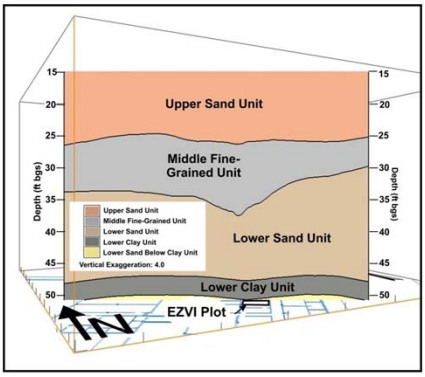
Case Study #1 – Launch Complex 34

- Demonstration conducted at NASA's LC34, Cape Canaveral, FL
- Launch Complex 34 was used as a launch site for Saturn rockets from 1960 to 1968

Launch Complex 34

- **Pilot test area was inside of a building and was 15 ft by 10 ft**
- **Performance evaluation based on GW mass flux and TCE mass in pre- and post-treatment soil cores**
- **Monitored changes in CVOCs in:**
  - **Groundwater**
    - 5 depth intervals, 2 upgradient and 2 downgradient wells; and
  - **Soil cores**
    - 8 depth intervals, 6 locations

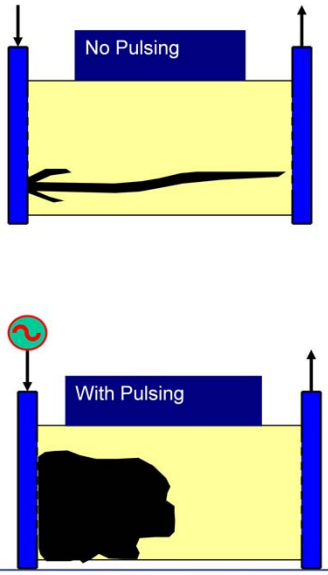
Site Geology and Contaminant Distribution



Technology Implementation

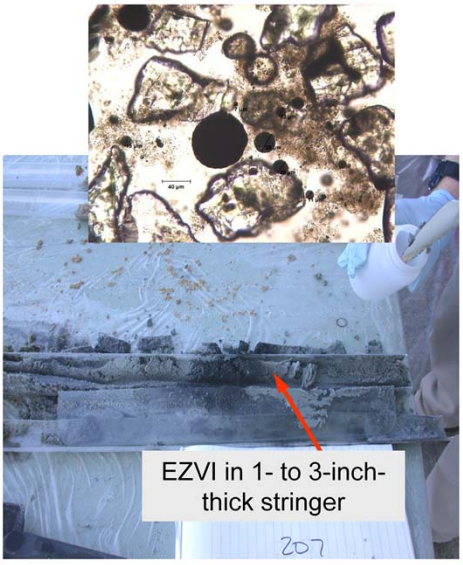
- EZVI injected in 8 injection wells using pressure pulse technology
- Injection wells along edge of plot directed inwards
- Injection wells in center were fully screened
- Injection at 2 discrete depth intervals in each well

EZVI Injection Setup within Pilot Test Area



Results – Soil

- **Soil Core Samples:**
  - **Stated objective of 50% removal of total TCE**
  - **Significant reduction of TCE (>80%) where EZVI was present**
  - **EZVI migrates to shallow intervals**
  - **Average reduction of 58%**



Results – Groundwater

- **Groundwater Samples:**
  - Significant reduction (60 to 100%) of TCE in target depths
  - Reduction of 56% in the Mass Flux
  - 18 months after injection, groundwater concentrations indicate that long term degradation due to bioremediation is ongoing
  - Elevated *cis*-1,2-DCE and vinyl chloride (VC) suggest biodegradation due to oil as an electron donor may also be significant

Results – Injection Technology

- EZVI was found in soil cores within 5 feet of the injection wells at 10 to 26 ft bgs – well above target injection depth of 16 to 24 ft bgs
- Evidence of upward movement of EZVI although EZVI is well dispersed in sediments

Recommendations and Follow-on Work

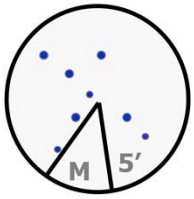
- Promising results at LC34, but needed to determine:
  - How to control placement of EZVI in subsurface
  - Evaluate the contribution of the abiotic and biological components of the degradation
- ESTCP project to evaluate contribution of abiotic and biological components and further evaluate EZVI (Case Study #2)

Follow-on Work – Injection Testing

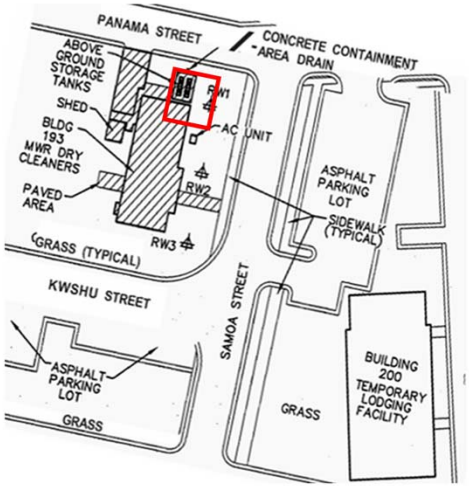
- Evaluation of four different injection techniques to improve ability to deliver EZVI to source zone
  - Direct injection
  - Pneumatic injection
  - Hydraulic fracturing/injection
  - Pressure pulse technology with different injection tools

Follow-on Work – Injection Testing (cont.)

- All four technologies were able to inject EZVI without damaging the emulsion structure
- Pneumatic and direct injections had the best control over placing EZVI in target treatment interval
- Pneumatic had best radius of influence and mixing — felt that with more volume to inject could have gotten greater than the target 5 ft



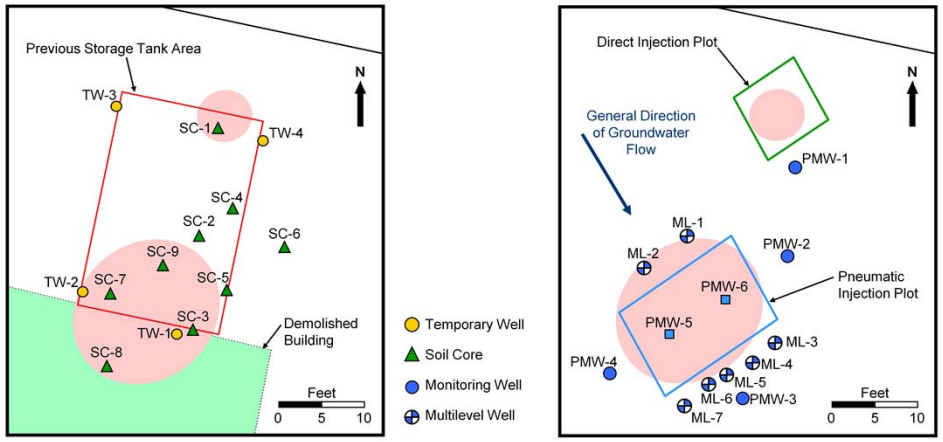
Case Study #2 – ESTCP – Parris Island SC

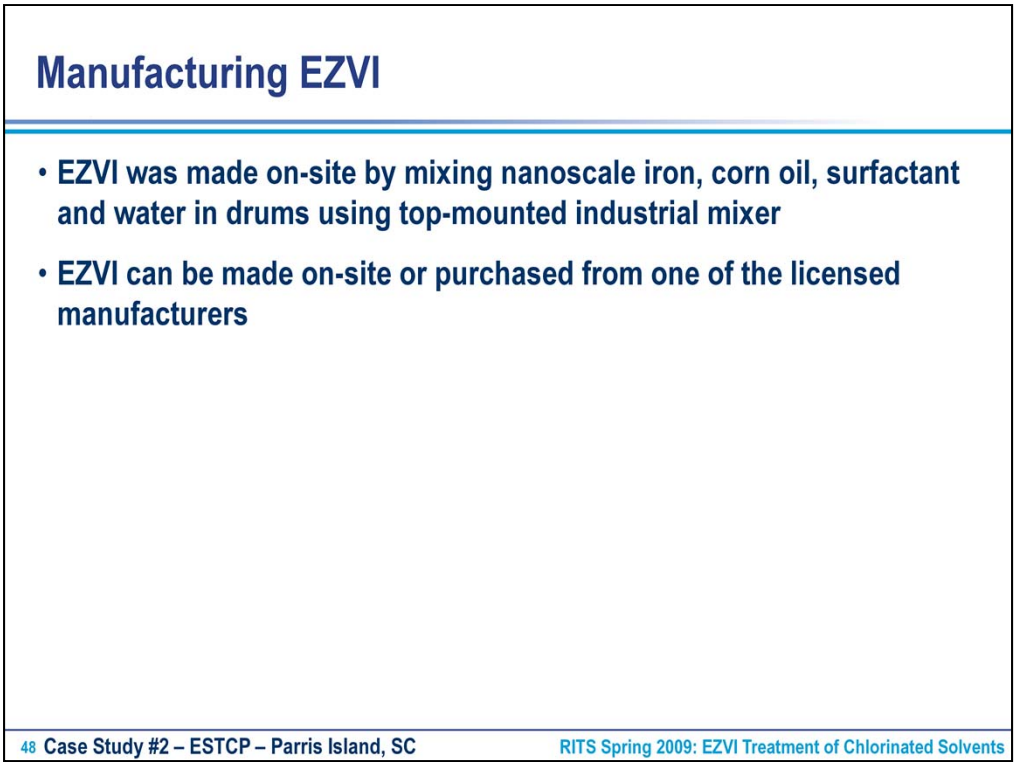


- Environmental Securities Technology Certification Program (ESTCP) project ER-0431
- Site 45, Parris Island MCRD, SC
- Former dry cleaning facility
- Buildings have been torn down
- Source areas located around former aboveground and belowground storage tanks

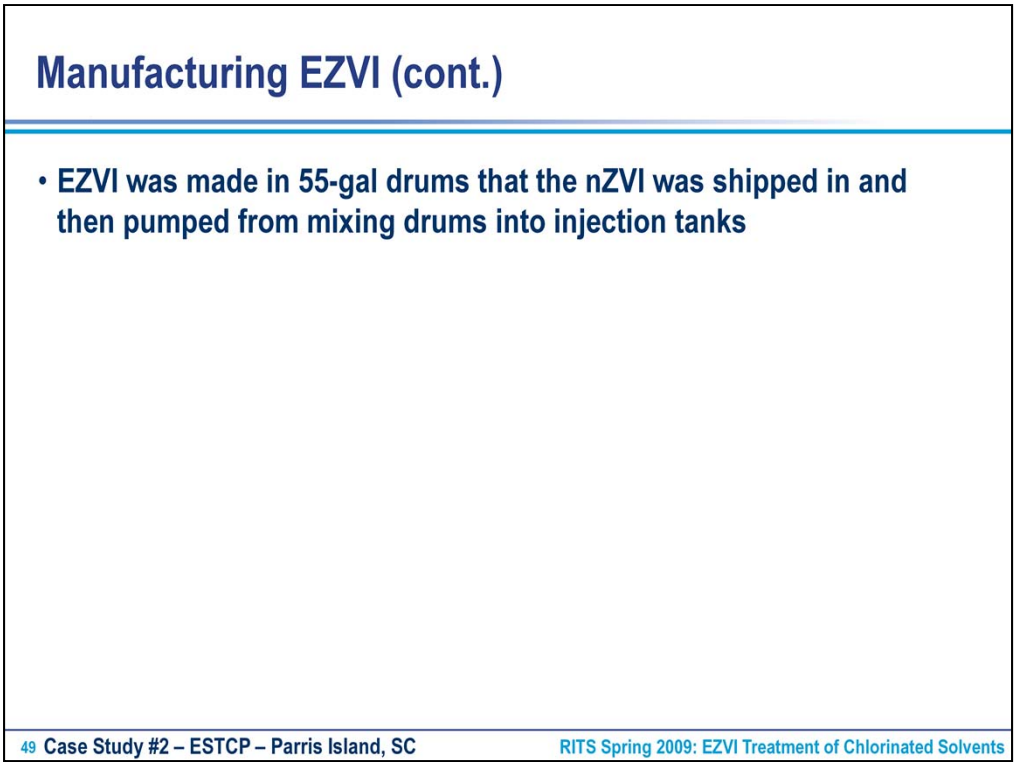
Site Geology and Contaminant Distribution

- Well-characterized site with number of wells, soil cores and cone penetrometer testing (CPT)/ membrane interface probe (MIP) borings
- Wells installed in July 2006 to target the source areas

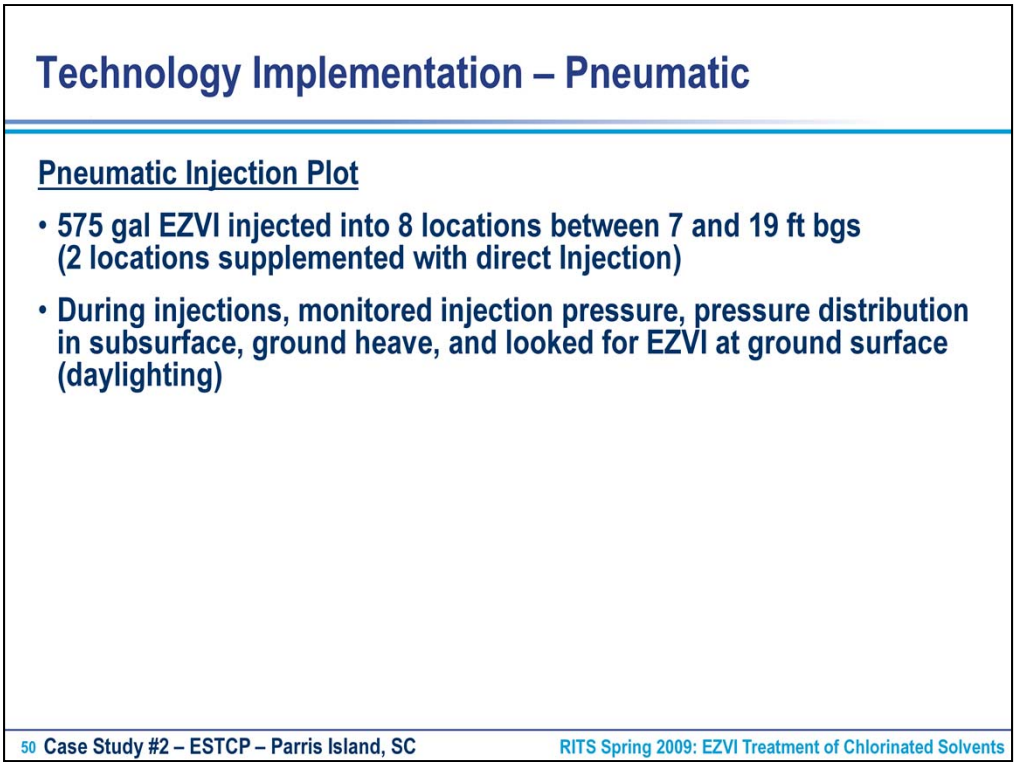




EZVI can be made on site or purchased from one of the licensed manufacturers info at NASA's web site.

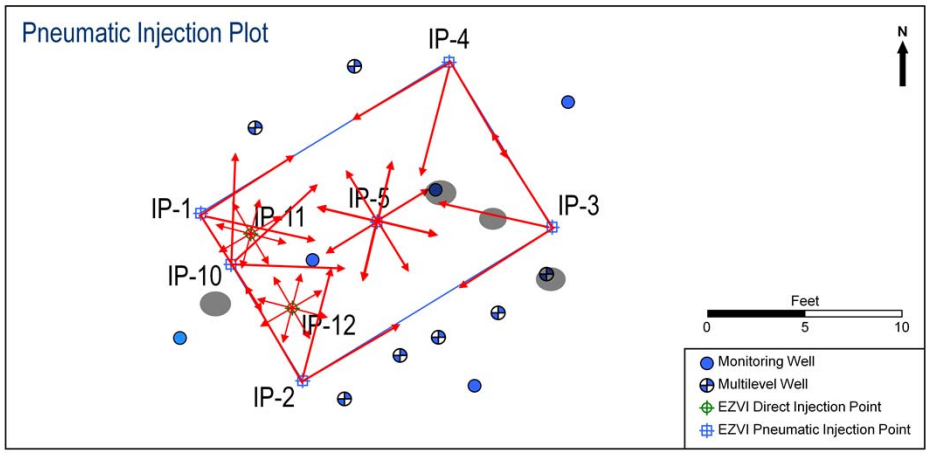


EZVI can be made on site or purchased from one of the licensed manufacturers info at NASA's web site.



Used tilt meters and stadia rod to look for ground heave to give us an idea of the radius of influence of the injection and the direction of the injection

Pneumatic Injection Plot

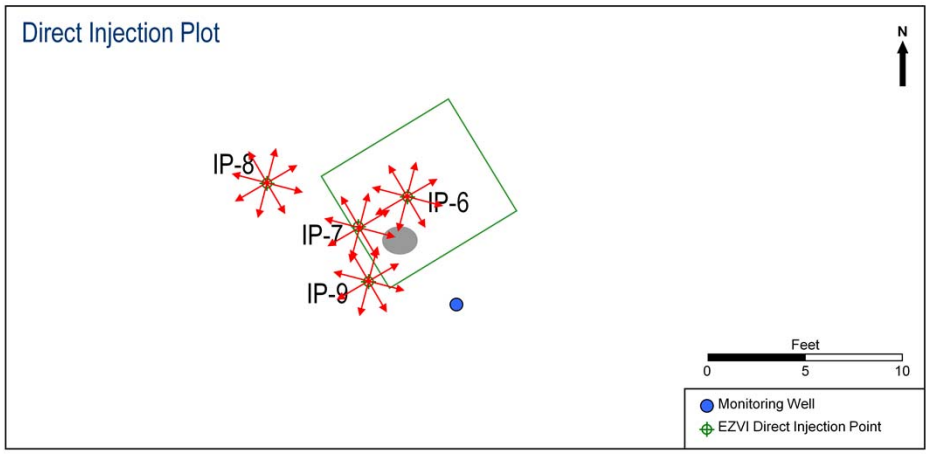


Technology Implementation – Direct Push

Direct Injection Plot

- 150 gal EZVI injected into 4 locations between 6 and 12 ft bgs
- During injections, monitored injection pressure and looked for EZVI at ground surface (daylighting)

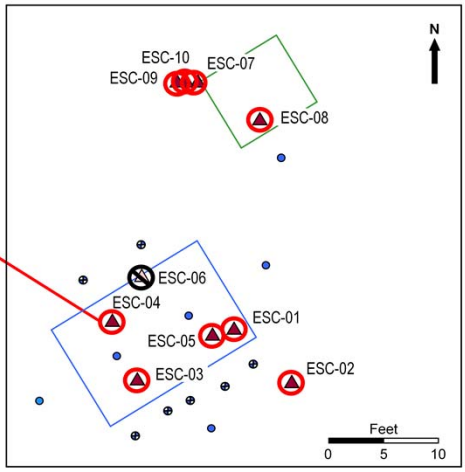
Technology Implementation – Direct Push



Soil Cores – Distribution

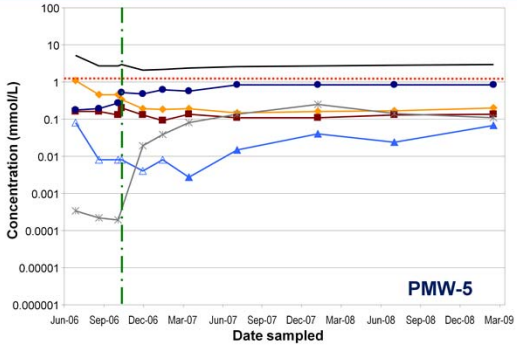
- Cores collected to evaluate ability of injection technologies to distribute EZVI evenly over target treatment intervals

Sand Saturated with EZVI

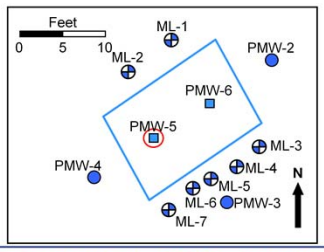


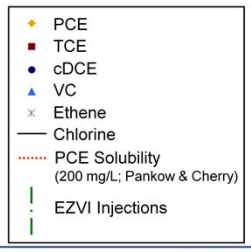
- EZVI in all cores but one (ESC-06)

Results – Groundwater VOC Trends: Wells with DNAPL in Pneumatic Injection Plot



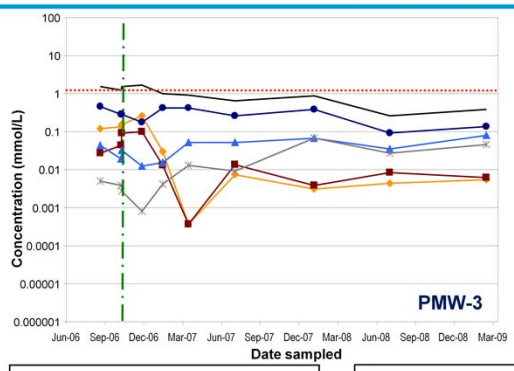
- PMW-5 shows continued presence of DNAPL although significant production of ethene in PMW-5 indicates that degradation is ongoing in the area



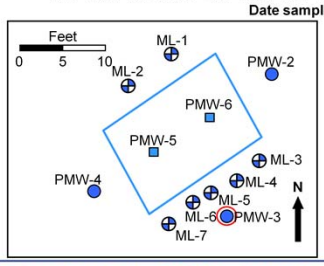


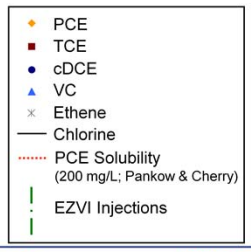
Open symbol indicates non-detects

Results – Groundwater VOC Trends: Downgradient Well from Pneumatic Injection Plot

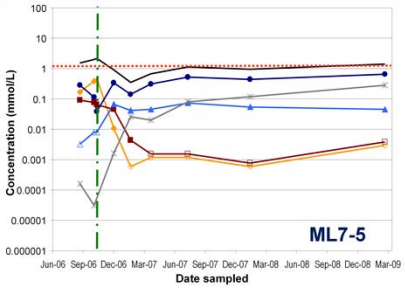


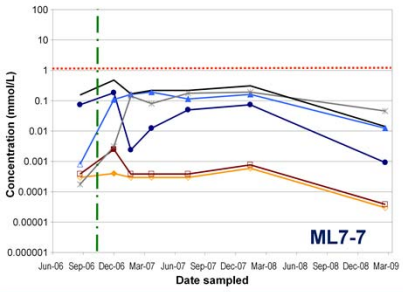
- In general, downgradient wells show decrease in PCE/TCE with increase in degradation products including significant increases in ethene



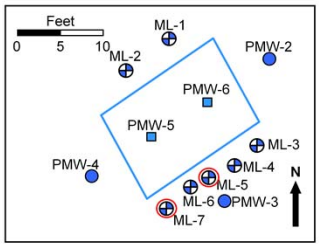


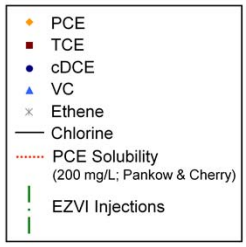
Results – Groundwater VOC Trends: Downgradient wells in Pneumatic Injection Plot





- Downgradient wells show decrease in PCE/TCE with increase in degradation products including significant increases in ethene





Open symbol indicates non-detects

Results – Injection Technology

- EZVI daylighted in both Pneumatic and Direct Injection test plots
  - Pneumatic Injection Plot
    - Daylighting around ML-3 pad, downgradient of plot and from old MIP locations
  - Direct Injection Plot
    - Daylighting possibly from old soil core location

)

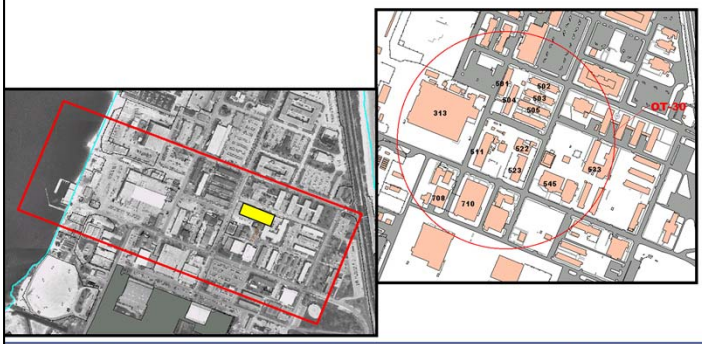
Summary and Conclusions

- In general, downgradient wells show decrease in PCE/TCE with increase in degradation products including significant increases in ethene
- Upgradient wells and PMW-5 show continued presence of DNAPL although significant production of ethene in PMW-5 indicates that degradation is ongoing in the area
- DNAPL now being pumped from some wells where DNAPL was previously absent, indicating that some of the DNAPL is mobile
- Difficulty in getting EZVI evenly distributed in this small area due to shallow application and short-circuiting up existing boreholes

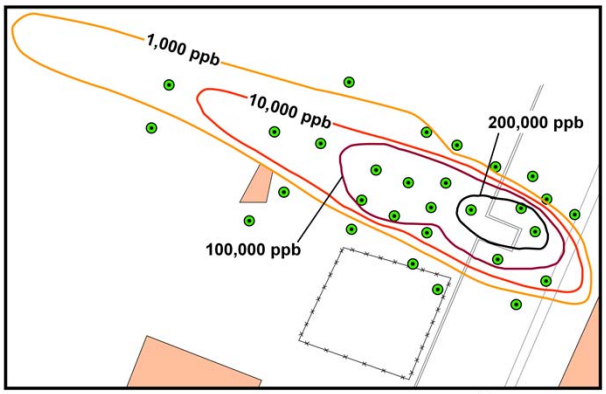
NOTE – this level of monitoring is for a demonstration – normally would target larger area and be more flexible in where and how much you inject in areas since not trying to get as detailed a snapshot of performance – next case study in point

Case Study #3 – Patrick Air Force Base, Florida

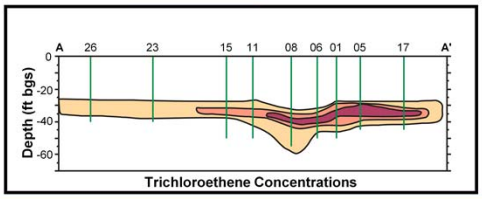
- Two apparent source areas, one near Building 533 and one at Building 313
- Past operations (1940s through the 1960s) resulted in releases of trichloroethene (TCE)
- TCE and its breakdown products 1,2-Dichloroethene (DCE) and VC affect groundwater in an area about 600 feet wide by 1,500 feet long

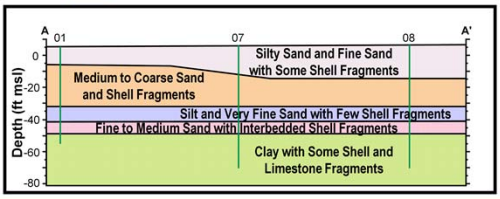


Baseline Concentrations



- TCE, *cis*-DCE, VC in groundwater
- TCE up to 350 ppm
- Focus remediation on source area





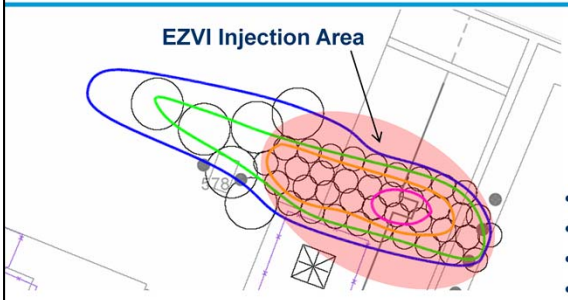
Approach

- Inject EZVI in source area
- Inject straight vegetable oil in plume area downgradient of source as electron donor
- Co-injection of KB-1 (dechlorinating bacteria) in the source area and in plume

Approach (cont.)

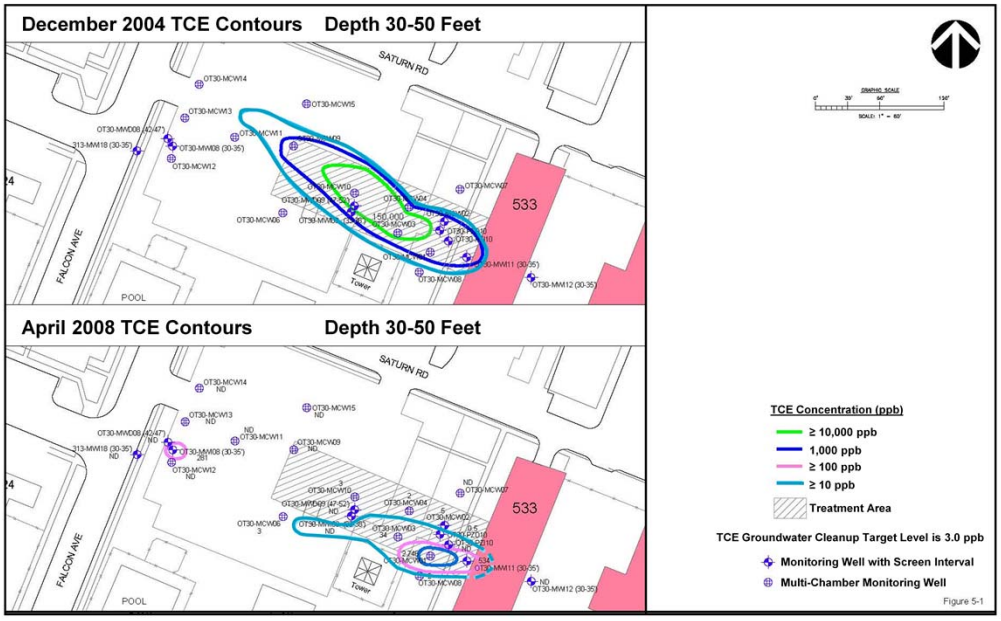
- EZVI injected with pneumatic fracturing/pneumatic injection process in the 100 ppm TCE contour, between 25 and 45 ft bgs (~5,400 ft^2)
- Radius of influence (ROI) = 7 ft (36 injection points)
- KB-1 injection after EZVI injection – direct push rig injecting the KB-1 a couple of days following EZVI injection with pneumatic injection rig

Injection Design



- N_2 used to fluidize formation
- N_2 used as a carrier fluid
- Co-Injection process

- Bottom up injections
- 1 ft. intervals
- 4 injections/interval at most points
- 2 injection/interval at perimeter points



65 Case Study #3 – Patrick AFB, Florida RITS Spring 2009: EZVI Treatment of Chlorinated Solvents

Lessons Learned

- **Shipping/Handling EZVI:**
  - Tanker truck shipment is effective for large volume sites
  - On-site storage tanks need to be considered
  - If planning to hold EZVI for > 10 days should have stirring capability to offset separation/compaction/viscosity issues (only in large volume containers 5,000 gallons and larger)
- **Injection of EZVI:**
  - Inconsistency of product viscosity caused variation in pumping times, nitrogen requirements and potentially impact on ROI
  - Daylighting due to improperly abandoned wells or unknown well locations

Presentation Overview

- Technology Overview
- Technology Implementation
- Case Studies
- Other Applications
  - Modified EZVI Applications
  - Leveraging EZVI Applications
- Cost
- Summary

Modified EZVI Applications

- mZVI versus nZVI to make EZVI
  - Both work well although the mZVI EZVI is less stable over longer period of time and this must be taken into account if transporting pre-made EZVI to site for injection versus making on site
- Co-injection of ZVI and vegetable oil
  - Some groups have been experimenting with co-injection of nZVI and emulsified vegetable oil (EVO) rather than mixing two at surface
- Different emulsification techniques
  - Research into using different surfactants, different mechanical emulsification techniques to make a less viscous EZVI which will be theoretically be easier to emplace in subsurface

Leveraging EZVI Applications

- Co-injection or follow-on injection of bacteria to enhance biodegradation component of EZVI
- Applications for co-mingled plumes or sources where either ZVI or bioremediation on its own wouldn't work
  - Metals (abiotic)
  - VOCs (abiotic and biological)
  - Perchlorate (biologic degradation)

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Cost Analysis

The primary factors affecting treatment costs include:

- High reagent cost (e.g., nZVI versus mZVI)
- Size of the contaminated zone
  - Incentive to reduce source footprint through more-detailed characterization
- Field implementation restrictions such as drilling and infrastructure
- Monitoring requirements
- Cleanup goals

Costs for nZVI

Iron Powder	Nano Iron
$1/lb	$25/lb
~ 1 m^2/kg	~ 25,000 m^2/kg
~ 1 m^2/dollar	~ 1,000 m^2/dollar

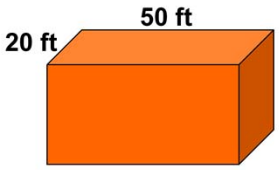
Data for actual remediation costs is scarce…

Cost of EZVI

- Cost of nZVI and to lesser extent mZVI is what drives cost of EZVI
- Cost of other ingredients are minimal (up to $6/gal)
- The cost of manufacturing the EZVI can be higher if you need large volumes that can't easily be made on site
  - ~$10/gallon if made on site for mZVI EZVI
  - $27/gallon for nZVI EZVI made on site

Iron Product	Cost
Nanoscale ZVI	$26-$34/lb, depending on quantity
Microscale ZVI (40,000 nm)	$1-$1.70/lb
Microscale ZVI (up to 3,000 nm)	$4/lb
Granular Iron (comparison only, can't use to make EZVI)	$0.40/lb

EZVI Cost Scenario



10,000 cf impacted by DNAPL

30% porosity = 3,000 cf

TREAT 10% to 30% of porosity =

300 to 900 cf EVZI

EZVI (on-site, gal) 2,250 to 6,750

Small mZVI ($10/gal) = $22,500 to $ 67,500

nZVI ($25/gal) = $56,250 to $168,750

If large volume of EZVI required – Negotiate Costs!

Cost of Injection

- Dependent on site geology, size of treatment area
- Rough costs for injection with pneumatic could be around $650/injection lift (targeting roughly 10 ft radius of influence over a 4 ft depth interval)
- Direct Injection methods costs are approximately $255/injection point (assumes five injection points a day)

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Summary and Conclusions

- Emulsified Zero-Valent Iron (EZVI) both sequesters and degrades CVOCs
- Microscale and nanoscale iron are suitable for EZVI
- The vegetable oil component of the EZVI emulsion droplet can provide a bio-polishing of the site
- Multiple injection technology options are available

Additional Information Resources

- NASA-Kennedy Space Center's information on EZVI
  - Technology description
  - Laboratory Studies
  - Case Studies
  - Licensed vendors
- Fact Sheet on ESTCP Project ER-0431
- Fact Sheet on SERDP Project ER-1487