Probabilistic Design and Construction Verification of a Permeable Reactive Barrier at an Industrial Site in Virginia

By

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Presentation Outline

RTDF Permeable Reactive Barrier Meeting
Washington DC – Nov 6-7, 2002

- Industrial Facility in VA
  - 1,200' Long Iron PRB, 5' down to 44' deep
  - Constructed by Azimuth Controlled Vertical Hydraulic Fracturing Technology
  - Completed July '02
- PRB Probabilistic Design
  - Chlorinated Compounds Degradation in presence of Zero Valent Iron
  - Probabilistic Design Methodology
  - Input Parameters, Analysis & Results
- Construction Verification Techniques
  - Active Resistivity Imaging Technology
  - PRB Thickness by Inclined Profiling
  - Hydraulic Pulse Tests to quantify PRB Hydraulic Impact

Golder Sierra changes its name to: GeoSierra

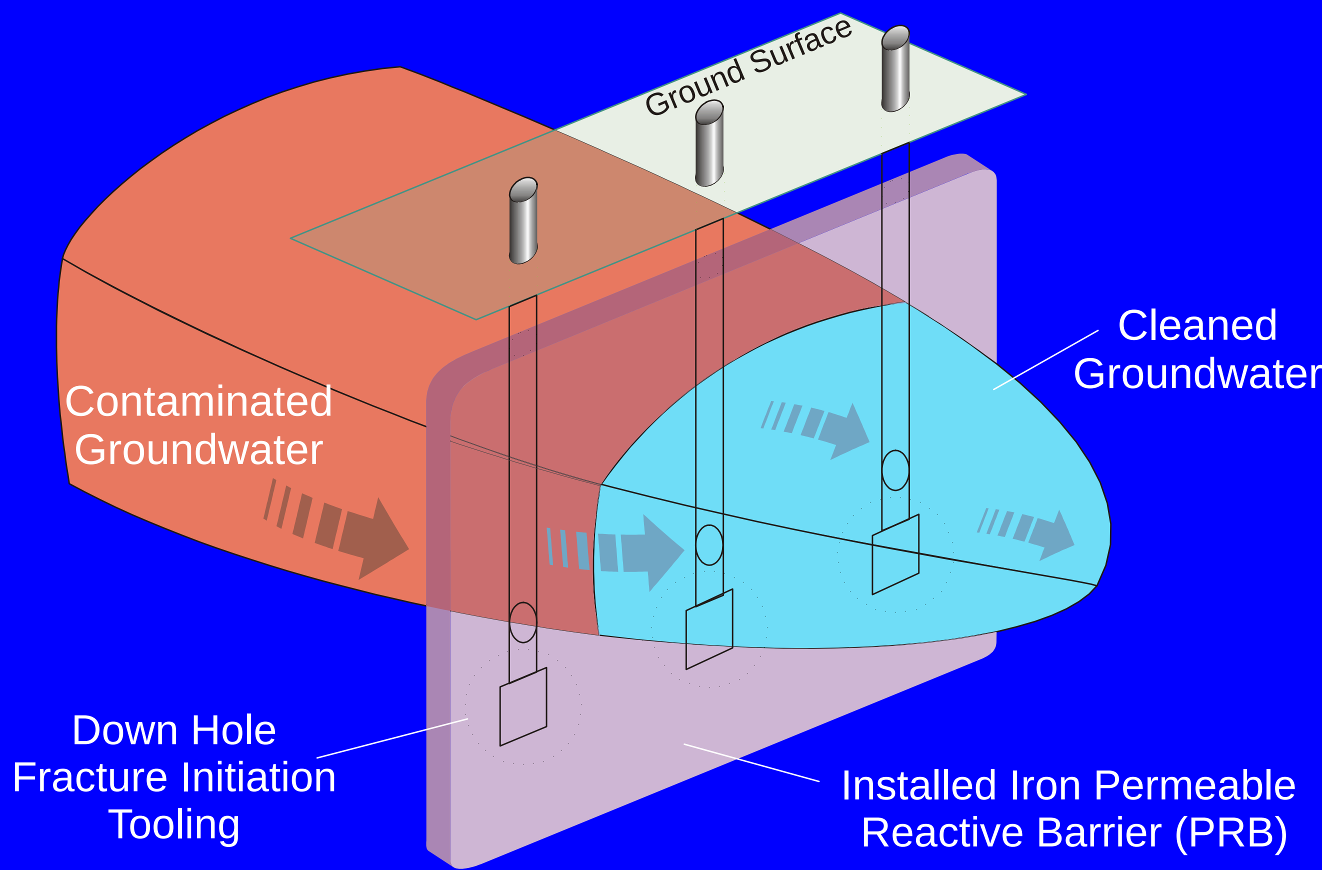
- Golder Sierra changed its name to GeoSierra as of August 1, 2002
- Both Web Sites will be viewable:
  - www.goldersierra.com
  - www.geosierra.com
- Name change is to distinguish specialized Design/Build services and expanded products and services
- No change in Management or Ownership

Arrowhead Superfund Site
Montross, VA

Construction of Iron PRB
Azimuth Controlled Vertical Hydrofracturing

RTDF02.ppt

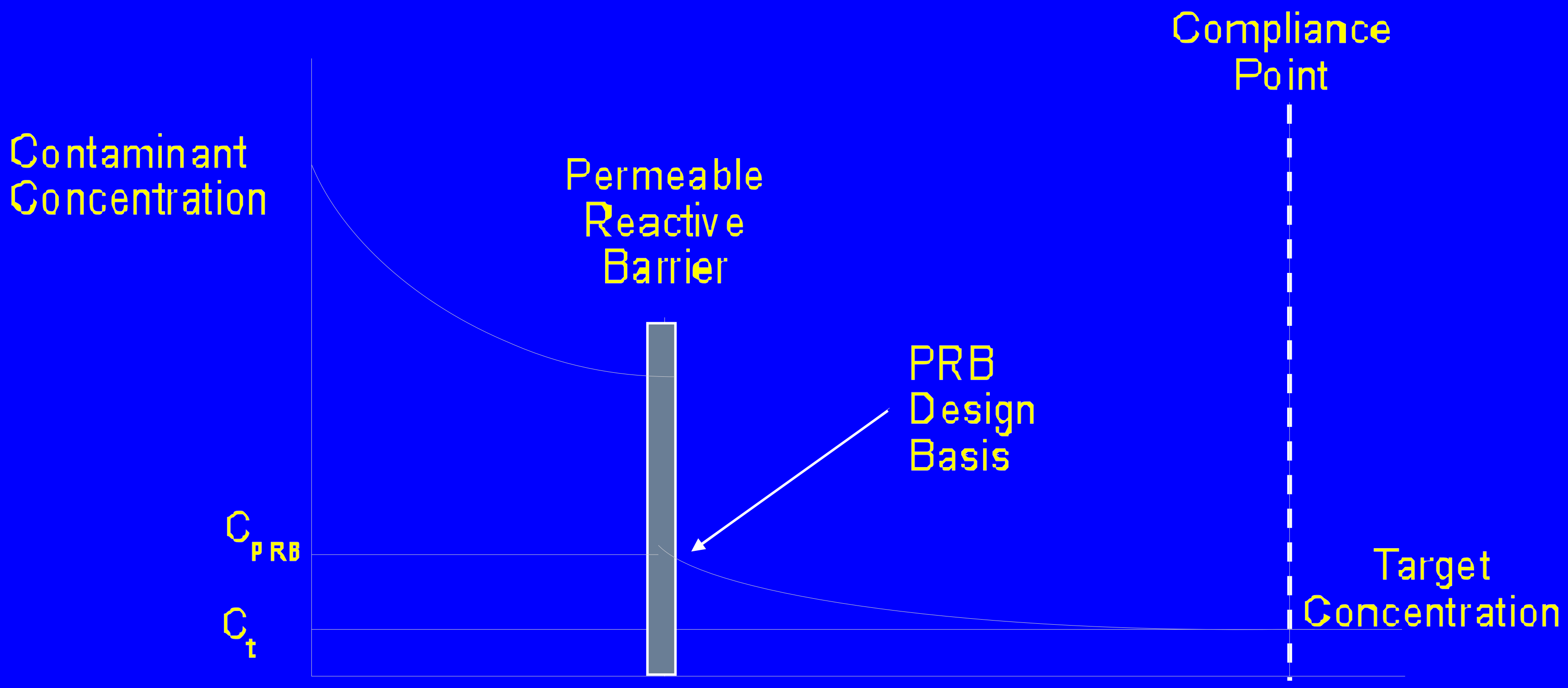
Azimuth Controlled Vertical Hydrofracturing Installed Iron Permeable Reactive Barrier



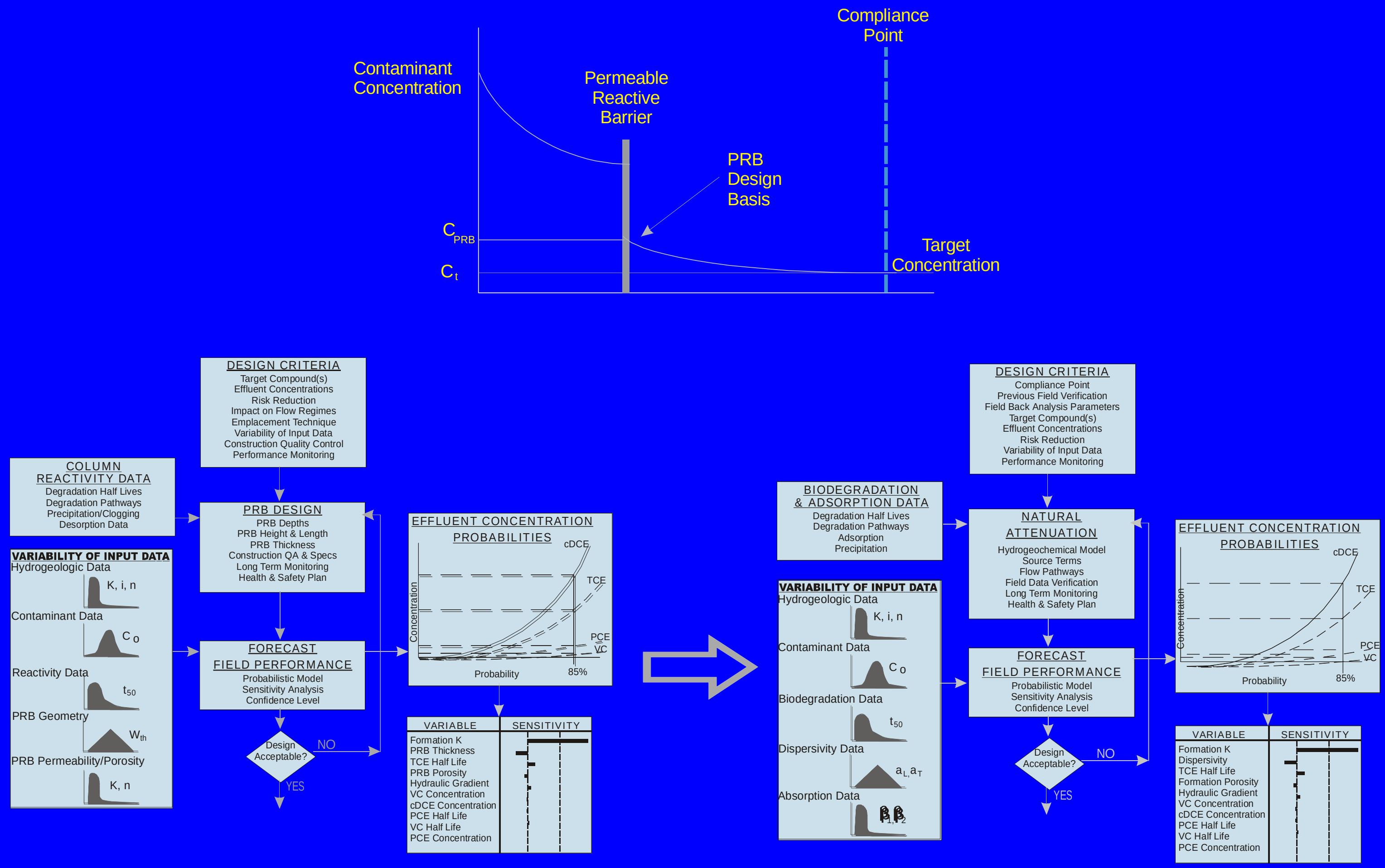
Deep Installation of PRBs

- PRBs are no longer limited to Shallow Depths
  - Azimuth Controlled Vertical Hydrofracturing
    - » Casing Systems installed by conventional drilling
    - » Initiation Tooling remains inside casing system
    - » Robust strong casing string enables multiple re-entry and multiple re-fracturing of same horizon
    - » Real time imagery of PRB geometry during construction
    - » Technology ensures continuous vertical barrier
    - » Technology applicable to both shallow and deep PRB installations
    - » Eight (8) PRBs installed in a variety of geological environments from shallow to significant depth
- Applicable to Complex Geologies
  - Clay till, silts and sands
  - Flowing Sands
  - Gravel and Cobbles

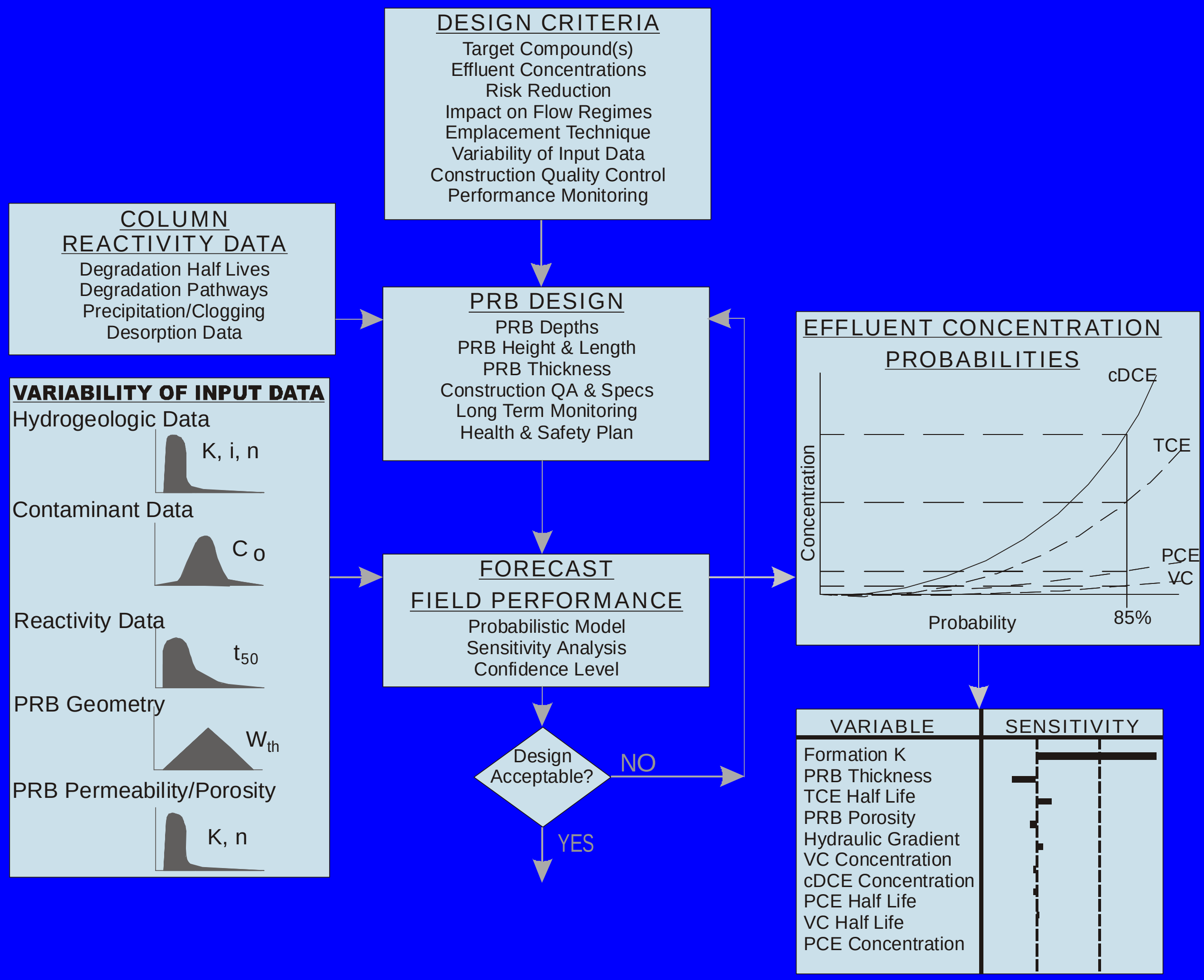
PRB and Natural Attenuation Design Basis



PRB and Natural Attenuation Probabilistic Design Methodology



PRB Design Forecast



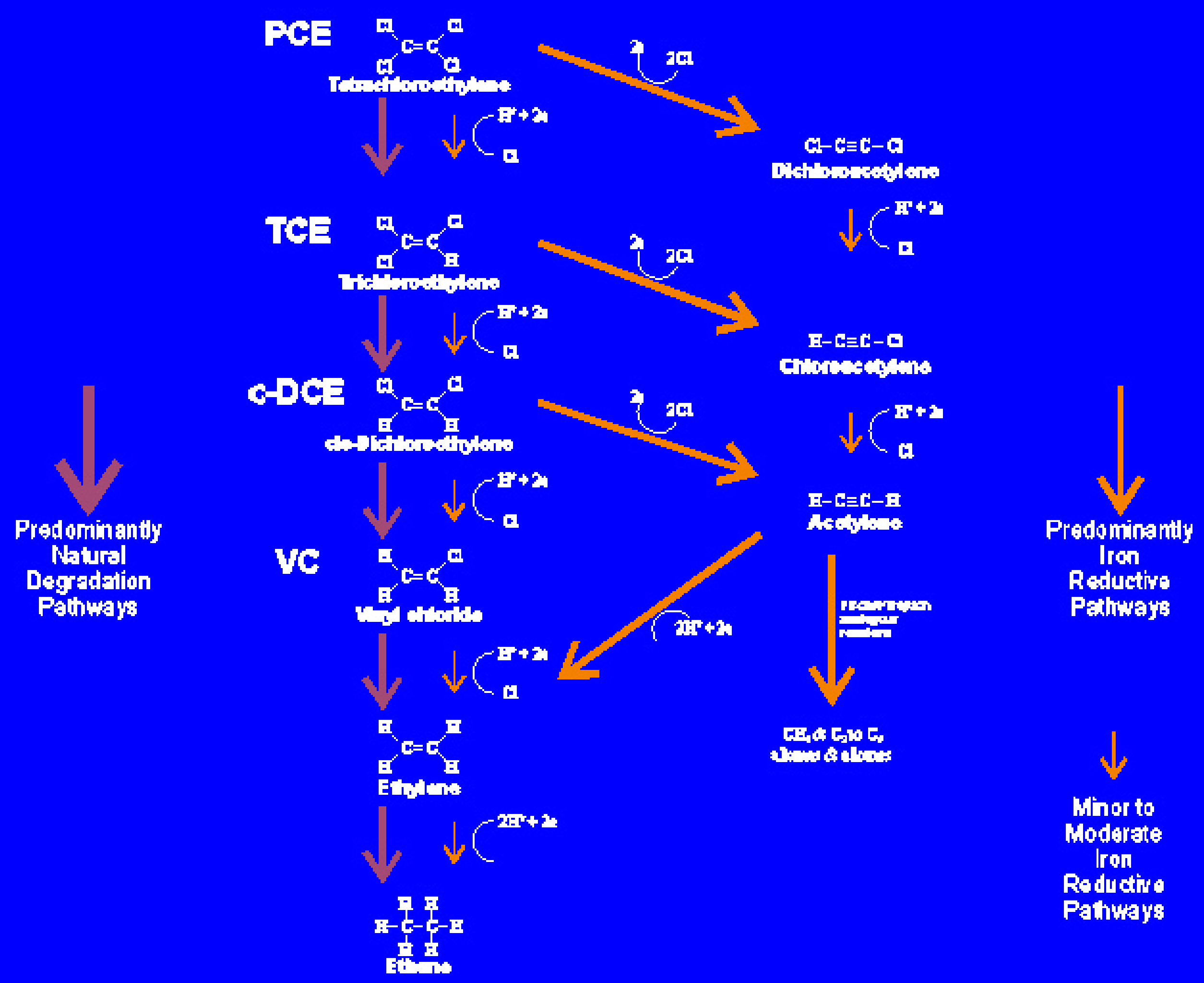
Reductive Dechlorination of Chlorinated Solvents by Iron

- PCE, TCE, cis-DCE and VC Reduced to Ethene and Ethane by Zero Valent Iron
- Iron Filings Placed In Situ Below Groundwater Table
- Corrosion of Iron Is Low Due to Reducing Environment
- In Situ Iron Systems Have Performed as Good or Better than Expectations from Laboratory Tests

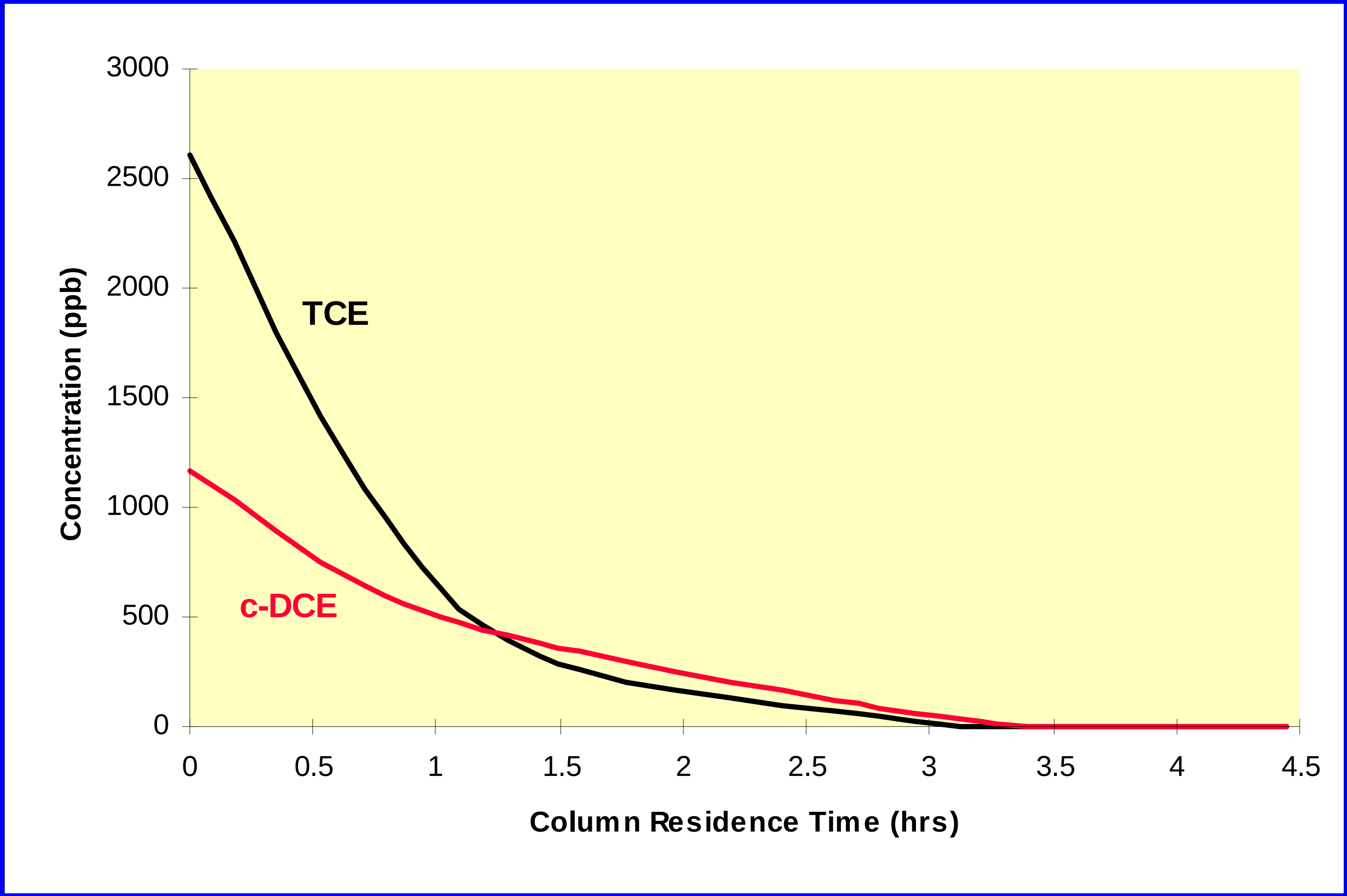
Chlorinated Compounds Destroyed in the Presence of Zero Valent Iron

Common Name	*Common Abbreviation*	*Other Pseudonyms*	*CAS Number*
Methanes			
Tetrachloromethane	CT, PCM	Carbon Tetrachloride	56-23-5
Trichloromethane	TCM	Chloroform	67-66-3
Tribromomethane	TBM	Bromoform	75-25-2
Ethanes			
Hexachloroethane	HCA	Carbon Hexachloride	67-72-1
1,1,1,2-Tetrachloroethane	1,1,1,2-TeCA		630-20-6
1,1,2,2-Tetrachloroethane	1,1,2,2-TeCA	Acetylene Tetrachloride	79-34-5
1,1,1-Trichloroethane	1,1,1-TCA	Methyl Chloroform	71-55-6
1,1,2-Trichloroethane	1,1,2-TCA	Vinyl Trichloride	79-00-5
1,1-Dichloroethane	1,1-DCA		75-34-3
Ethenes			
Tetrachloroethene	PCE	Perchloroethylene	127-18-4
Trichloroethene	TCE	Ethylene Trichloride	79-01-6
cis 1,2-Dichloroethene	cis 1,2-DCE	cis 1,2-Dichloroethylene	540-59-0
trans-1,2-Dichloroethene	trans 1,2-DCE		540-59-0
1,1-Dichloroethene	1,1-DCE	Vinylidene Chloride	75-35-4
Vinyl Chloride	VC	Chloroethene	75-01-4
Propanes			
1,2,3-Trichloropropane	1,2,3-TCP	Allyl Trichloride	96-18-4
1,2-Dichloropropane	1,2-DCP	Propylene Dichloride	78-87-5
Other Chlorinated			
N-Nitrosodimethylamine	NDMA	Dimethylnitrosamine	62-75-9
Dibromochloropropane	DBCP		96-12-8
Lindane		Benzene Hexachloride	58-89-9
1,1,2-Trichlorotrifluoroethane		Freon 113	76-13-1
Trichlorofluoromethane		Freon 11	75-69-4
1,2-Dibromoethane	1,2-EDB	Ethylene Dibromide	106-93-4

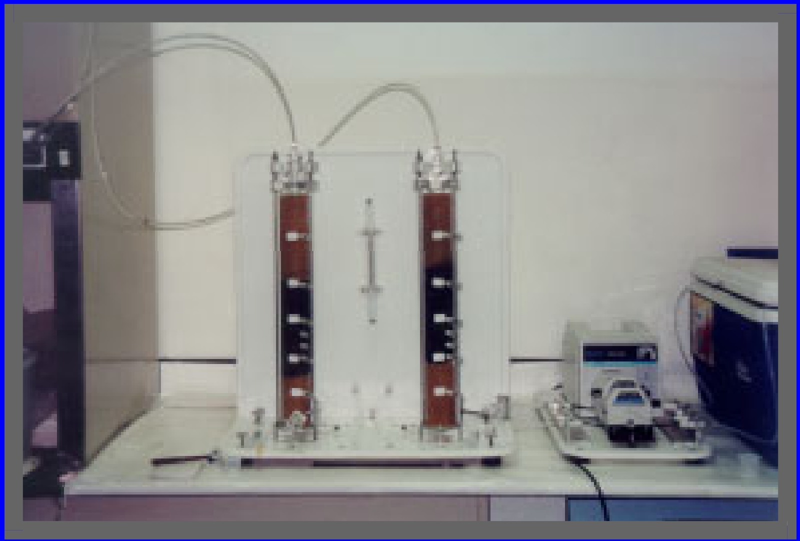
Reductive Degradation of Chloroethene Compounds

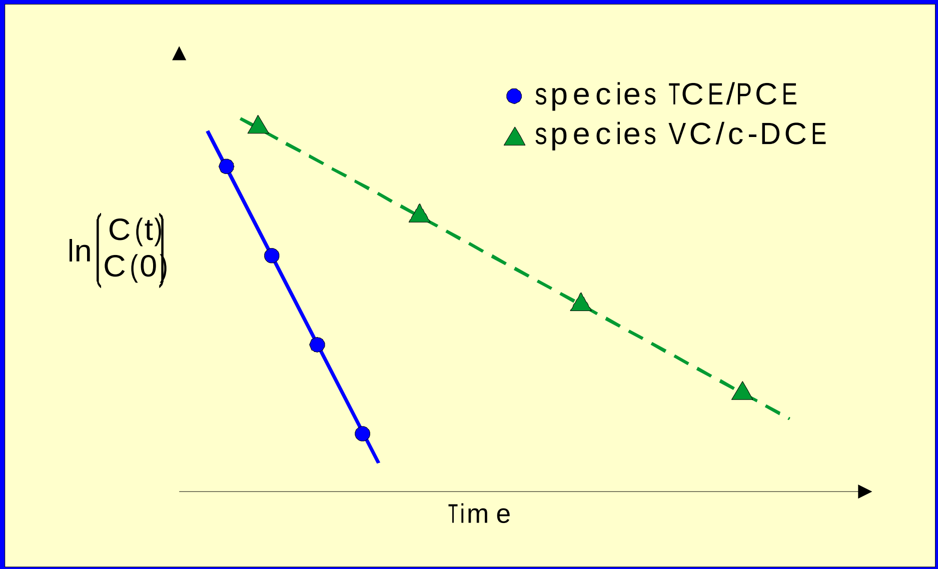


Degradation of TCE/c-DCE



Column Reactivity Test and First Order Reduction by Zero Valent Iron





Results of Column Reactivity Test with Iron

First Order Rate Degradation Model and Constants

- First Order Kinetic Degradation Model Equation

$$dC/dt = -\lambda_i C$$

$$C = C_0 e^{-\lambda_i t}$$

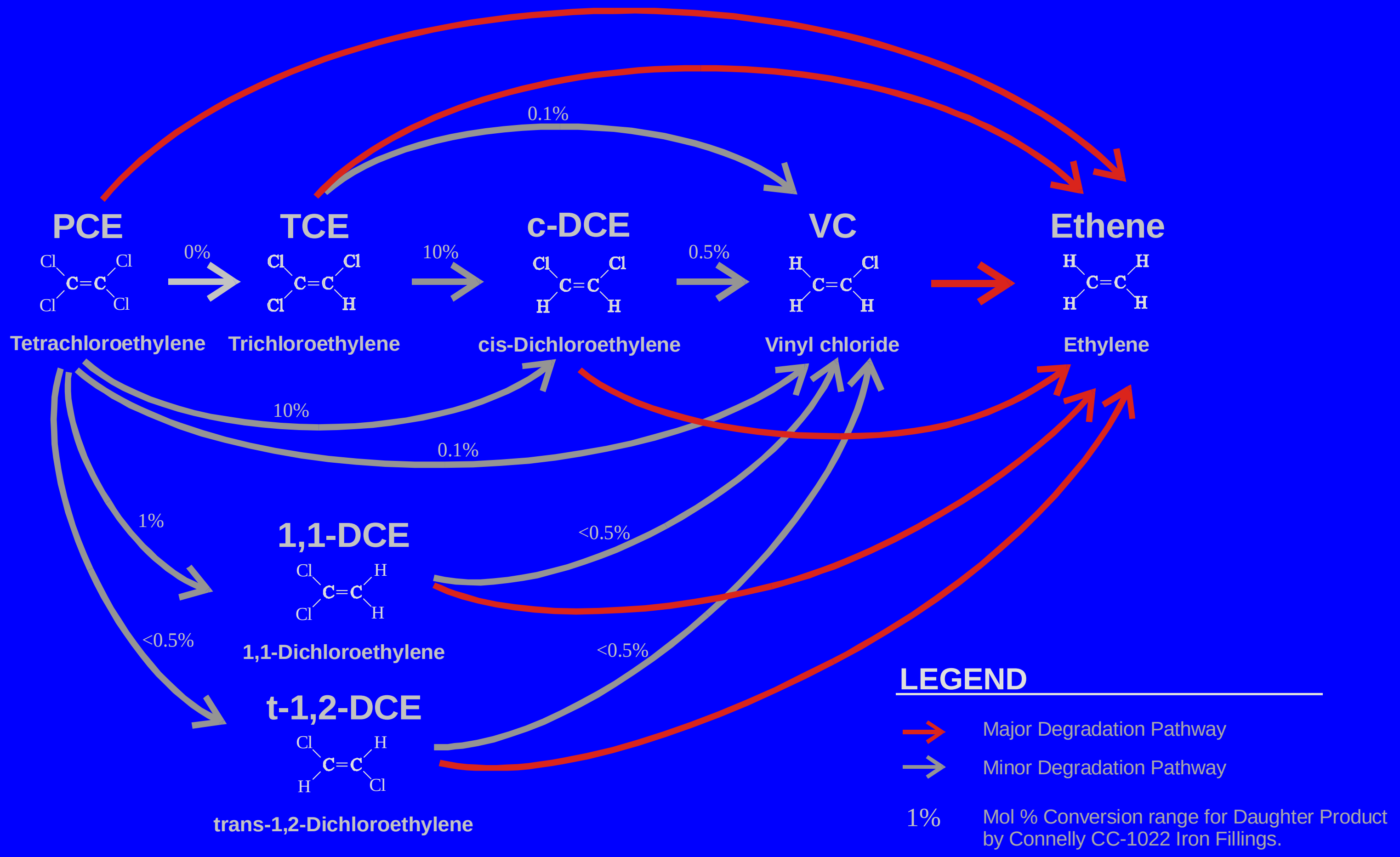
- The First Order Rate Constant

$$\lambda_i = -\frac{\ln\left(\frac{C}{C_0}\right)}{t}$$

- Half Life

$$t_{0.5} = {}^{0.693}\!/_{\lambda_i}$$

Iron Reductive Pathways for Chloroethenes Compounds



Simultaneous Differential Equations due to Degradation Pathways

- **First Order Differential Equations for Degradation of Chloroethene Compounds**

Iron Reductive First Order Model with Daughter Products

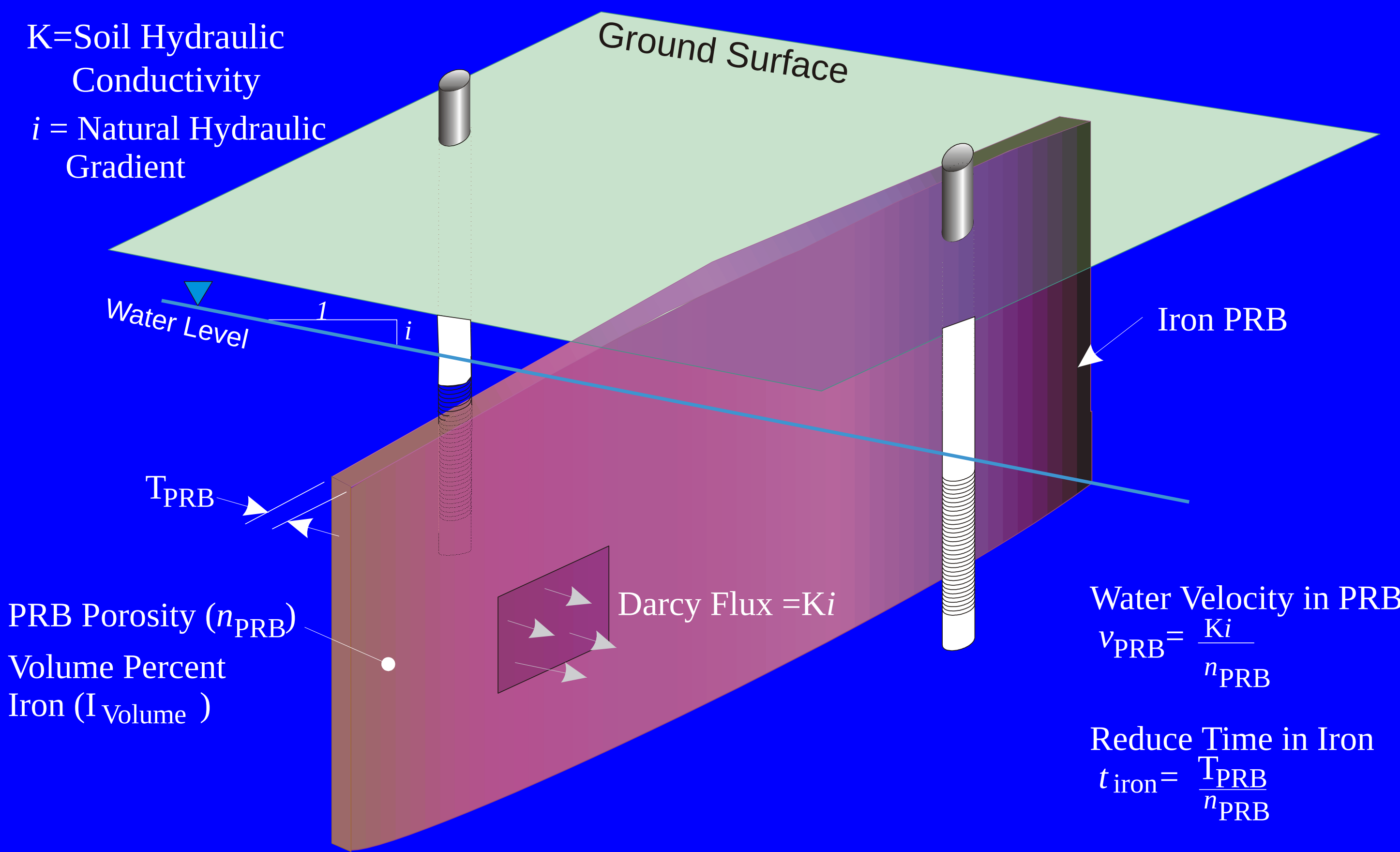
PCE----TCE----cDCE----VC----Ethene
------------tDCE---------------
----------11DCE------------

Solves: y'=- λ.y+(frac).λp.Cp etc

- **Multiple Differentials for Degradation Pathways**

$$D(t,Y) := \begin{bmatrix} -\lambda p \cdot Y_0 \\ fpt \cdot \lambda p \cdot Y_0 - \lambda t \cdot Y_1 \\ fpd \cdot \lambda p \cdot Y_0 + ftd \cdot \lambda t \cdot Y_1 - \lambda d \cdot Y_2 \\ fptd \cdot \lambda p \cdot Y_0 - \lambda td \cdot Y_3 \\ fpdce \cdot \lambda p \cdot Y_0 - \lambda dce \cdot Y_4 \\ fpv \cdot \lambda p \cdot Y_0 + ftv \cdot \lambda t \cdot Y_1 + fdv \cdot \lambda d \cdot Y_2 + ftdv \cdot \lambda td \cdot Y_3 + fdcev \cdot \lambda dce \cdot Y_4 - \lambda v \cdot Y_5 \end{bmatrix}$$

Contaminant Resident Time in Iron PRB



Functional Design Requirements of the PRB

- Minimal Impact on Natural Groundwater Flow Regimes
- High Groundwater Residence Time in PRB
- Degradation of VOCs and Daughter Products
- Use of Commercially Available Iron Filings
- Use of Proven Emplacement Method
- PRB Design to Accommodate Variability of Data and Site Uncertainty
- Construction QA/QC Procedures Implementable during Construction
- Monitored Performance
- Minimal O&M

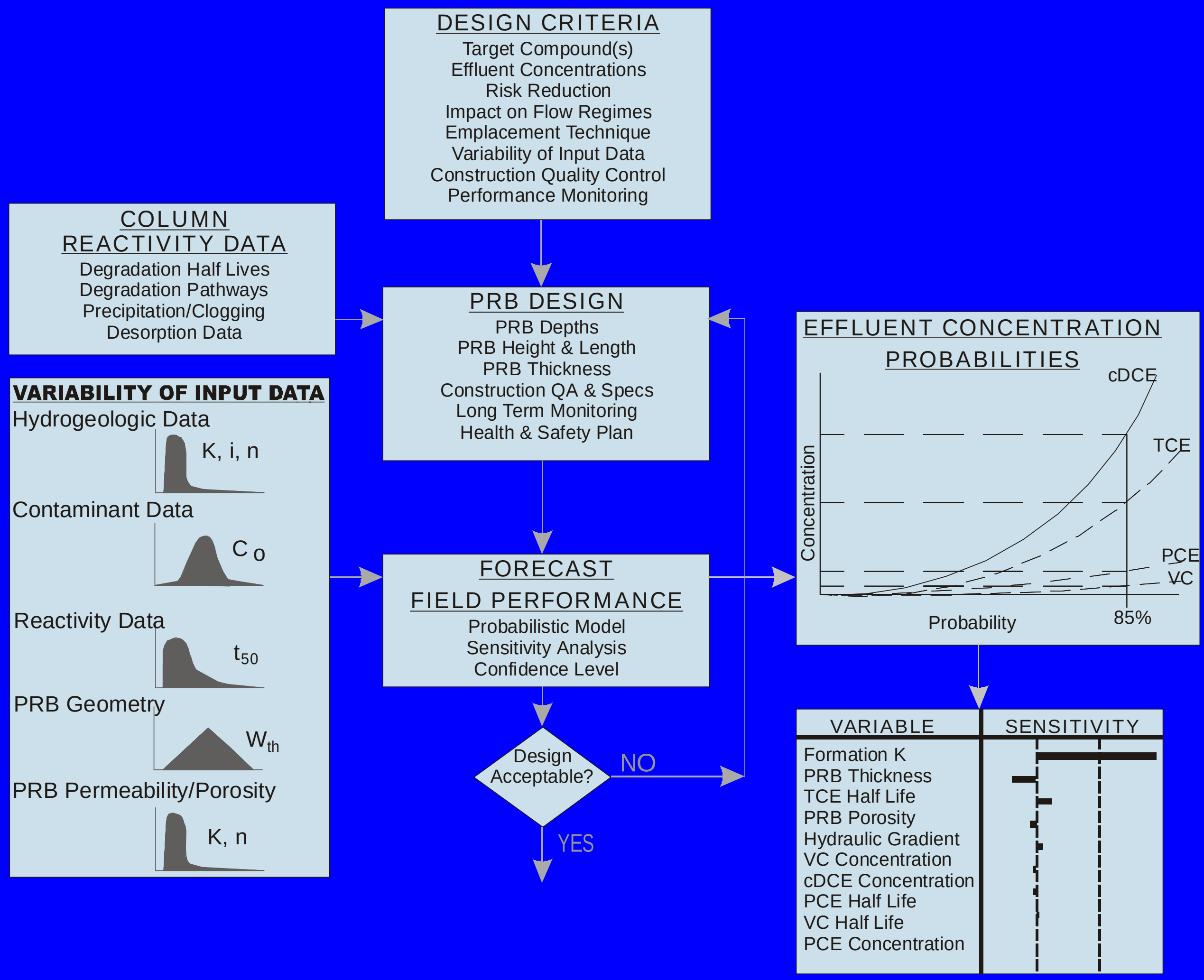
PRB Design Criteria

- Minimal Impact on Groundwater Flow Regimes
  - PRB Permeability > Soil Permeability
  - Filter Pack Design Criteria to Avoid Commingling of Soil and Iron Filings
  - Minimal Clogging/Precipitation Impact on PRB Permeability
- High Residence Time of Groundwater in the PRB
  - Maintain High PRB Porosity
- VOC Degradation
  - All VOCs Degraded
- Longevity
  - Expected PRB Functioning for >>10 years
- Passive System
  - Minimal O&M

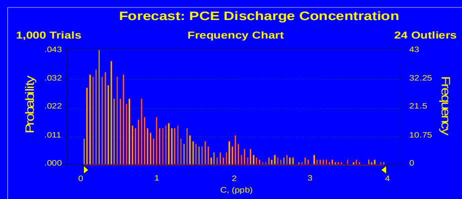
Iron Column Treatability Test using Site Groundwater

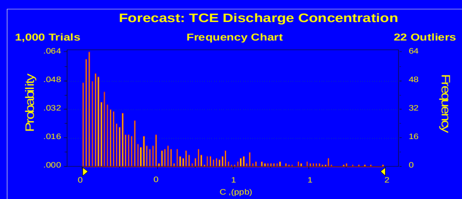
- Bench Scale Treatability Column Test
  - Site Groundwater used
  - Connelly CC-1022 Iron Filings
  - Test run to steady state conditions
- Test Results and Findings
  - Parent & Daughter Product Degradation Quantified
  - Half Lives Quantified for PCE, TCE, cis-1,2-DCE & VC
  - Site Groundwater Suitable for Iron PRB (No Precipitation or Clogging Issues)
  - All Contaminants Degraded

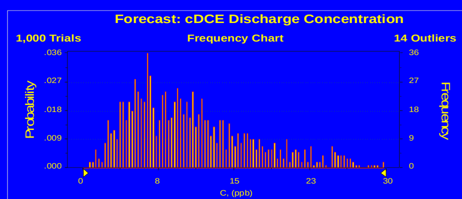
PRB Design Forecast

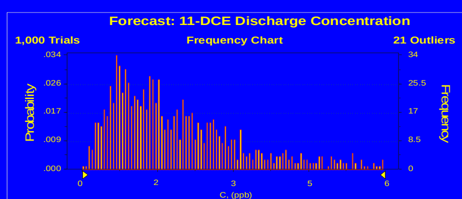


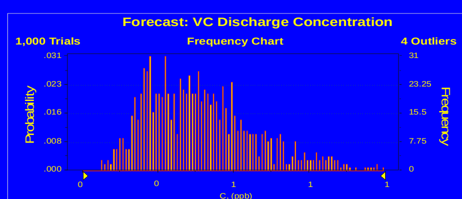
PRB Probabilistic Design Analysis Output Data

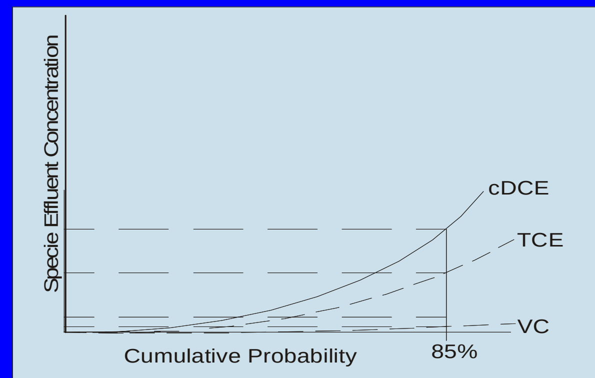


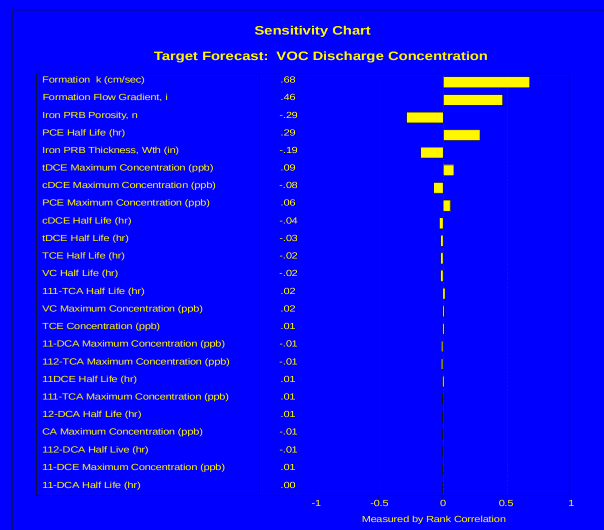












Installed Iron Permeable Reactive Barriers

Iron Reactive Barriers	Location	Date
Full Scale Remediation Projects		
Industrial Facility	California	Dec-94
Industrial Facility	California	Sep-95
Industrial Facility	Northern Ireland	Dec-95
Industrial Facility	Kansas	Jan-96
USCG Facility	North Carolina	Jun-96
FHA Facility	Colorado	Oct-96
Industrial Facility	South Carolina	Oct-97
Industrial Facility	Colorado	Nov-97
Research Facility	Tennessee	Nov-97
Industrial Facility	New York	Dec-97
Industrial Facility	Oregon	Feb-98
Superfund Site	New Jersey	Mar-98
DOE Facility	Missouri	Apr-98
Industrial Facility	Denmark	Jun-98
DOE Facility, RFETS	Colorado	Jul-98
Industrial Facility	New Jersey	Aug-98
Industrial Facility	Vermont	Aug-98
Industrial Facility	Germany	Oct-98
DOD Facility	New York	Oct-98
Shaw AFB	South Carolina	Nov-98
Industrial Facility	Denmark	Nov-98
Industrial Facility	Louisiana	Nov-98
DOD Facility	New York	Dec-98
Industrial Facility	North Carolina	Aug-99
DOD Facility	Colorado	Aug-99
DOD Facility	New Hampshire	Aug-99
Industrial Facility	Massachusetts	Aug-99
Industrial Facility	Denmark	Aug-99
DOE Facility (2nd system RFETS)	Colorado	Sep-99
Industrial Facility	Kansas	Oct-99
Industrial Facility	Washington	Oct-99
Industrial Facility	Ohio	Oct-99
Industrial Facility	Iowa	Oct-99
Industrial Facility	California	Nov-99
DOD Facility	New Hampshire	Jun-00
DOD Facility	Missouri	Aug-00
Somersworth Landfill	New Hampshire	Aug-00
Industrial Facility	Ohio	Sept-00
Dry Cleaning Site	New York	Sept-00

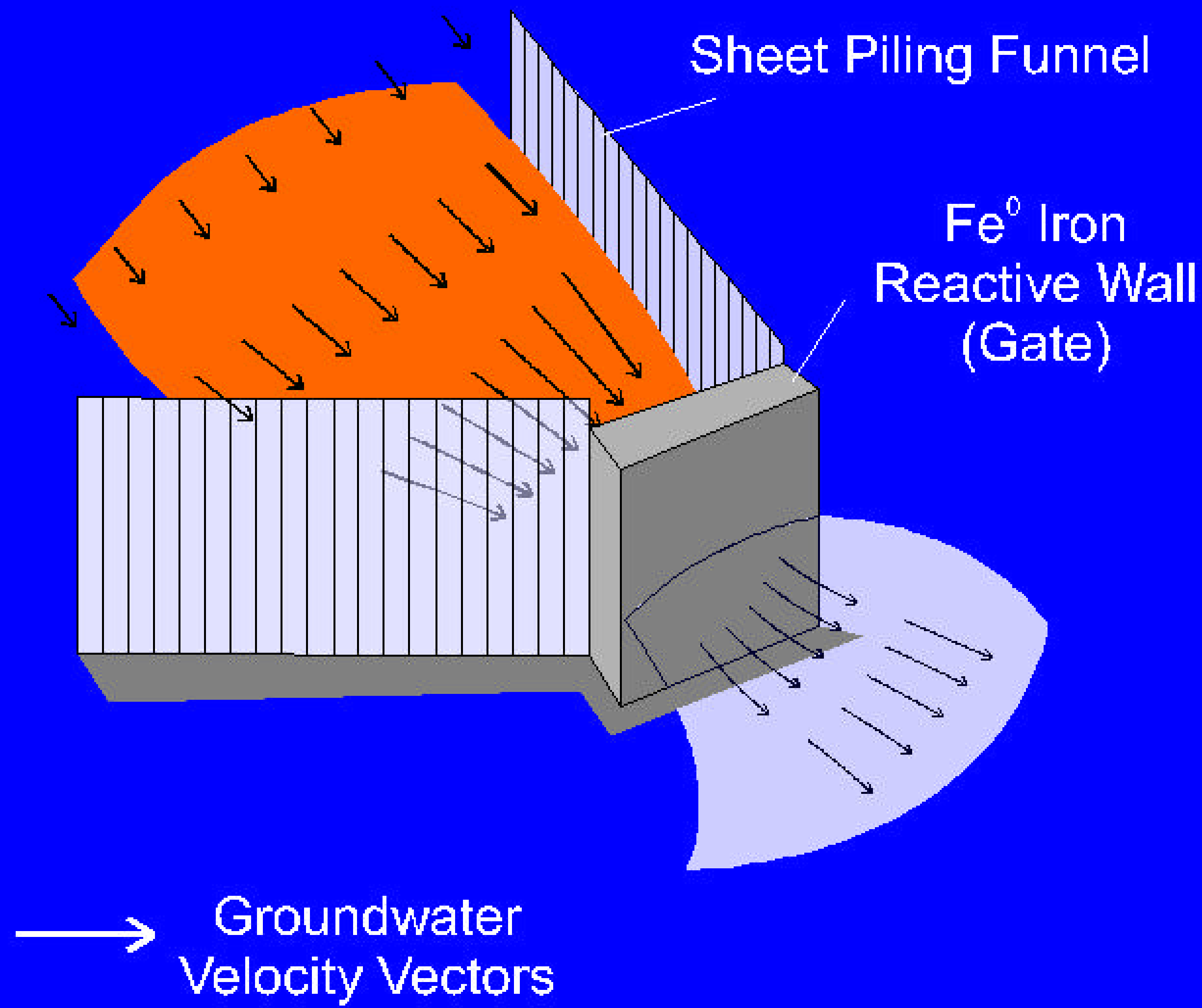
Iron Reactive Barriers	Location	Date
Full Scale Remediation Projects (Continued)		
Industrial Facility	Germany	Dec-00
Industrial Facility	California	Dec-00
DuPont Facility	California	Jan-01
Industrial Facility	Massachusetts	Jul-01
Industrial Facility	Vermont	Sept-01
Industrial Facility	Northern England	Oct-01
Industrial Facility	Missouri	Oct-01
Industrial Facility	Florida	Mar-02
DOD Facility	Texas	Apr-02
NASA Facility	Mississippi	May-02
Industrial Facility	Virginia	May-02
Industrial Facility	Japan	Jun-02
Industrial Facility	Germany	Jul-02
DOD Facility	Texas	Jul-02
Industrial Facility	Michigan	Jul-02
Industrial Facility	Netherlands	Sept-02

Iron Reactive Barriers	Location	Date
In-Situ Pilot Demonstrations		
Research Facility	Borden	Jun-91
Industrial Facility	New York	May-95
Lowry AFB	Colorado	Dec-95
Moffet Field Air Station	California	Apr-96
Industrial Facility	Georgia	Apr-96
Superfund Site	New Hampshire	Nov-96
Alameda air Station	California	Dec-96
Savannah River Site	South Carolina	Jul-97
Cape Canaveral	Florida	Nov-97
Argonne national Laboratory	Illinois	Nov-97
Dover AFB	Delaware	Nov-97
NASA Demonstration	Florida	Feb-98
Otis ANGB	Massachusetts	Jul-98
Maxwell AFB	Alabama	Jul-98
Industrial Facility	Germany	Jul-98
Industrial Facility	Germany	Jul-98
Industrial Facility	Australia	Feb-99

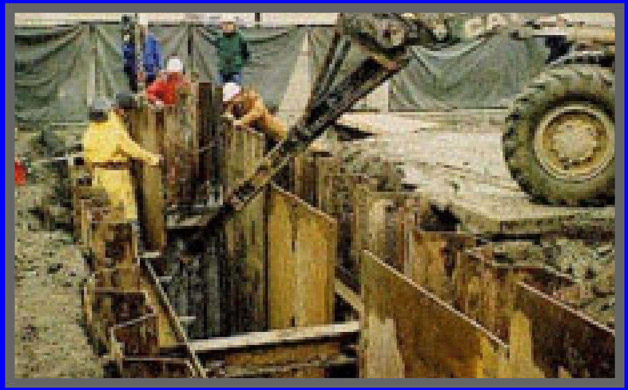
Permeable Reactive Barrier Installation Methods

- Funnel and Gate Systems
  - Braced Excavation & Sheet Piling
  - Trenching & Slurry Wall
- Continuous Permeable Barriers
  - Trenching
  - Slurry Wall
  - Azimuth Controlled Vertical Hydrofracturing
- Experimental Installation Methods
  - Vibrating Beam
  - Jetting

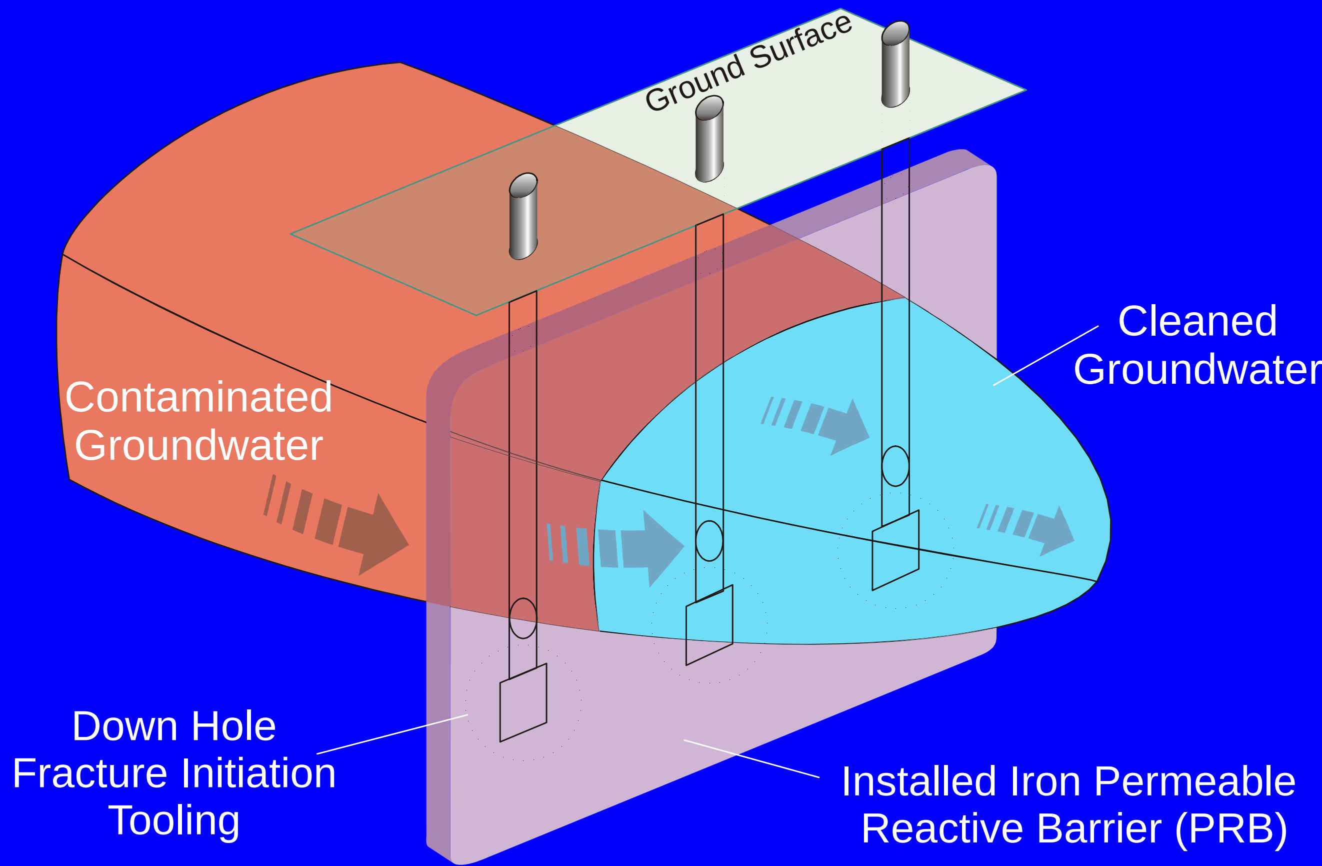
Funnel and Gate Passive Treatment System



Various Reactive Barrier Construction Techniques



Azimuth Controlled Vertical Hydrofracturing Installed Iron Permeable Reactive Barrier



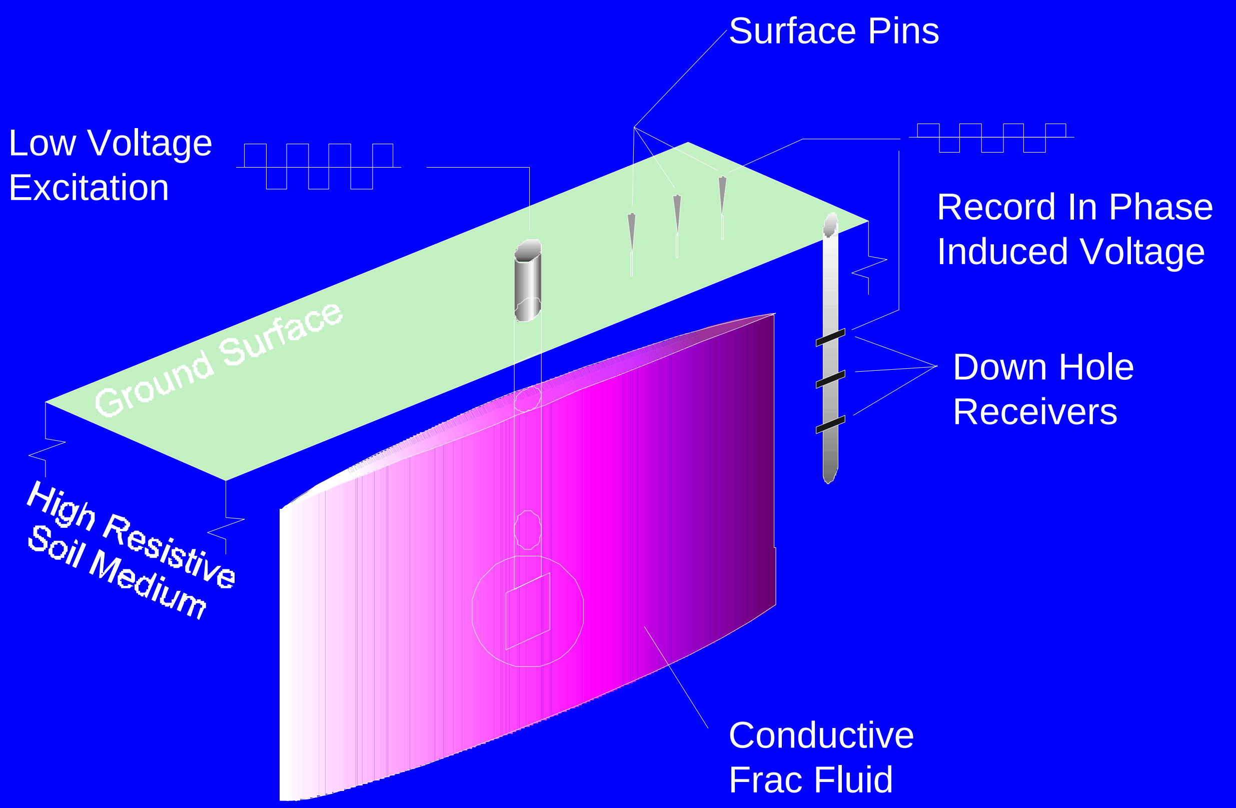
Azimuth Controlled Vertical Hydraulic Fracturing Technology

- Initial Artificial Fracture at Required Azimuth
  - Pre-aligned frac initiation casing system
  - Dilation of the casing, grout and surrounding soil
- Pore Pressure Relief Ensures Coalescence
  - Casing delimiters enable use of pore pressure relief to ensure fracture coalescence even with slight drilling offsets and casing orientation mis-alignment
- Multiple Re-Fracturing at Same Horizon
  - Achieve Barrier Thicknesses up to 9” thick

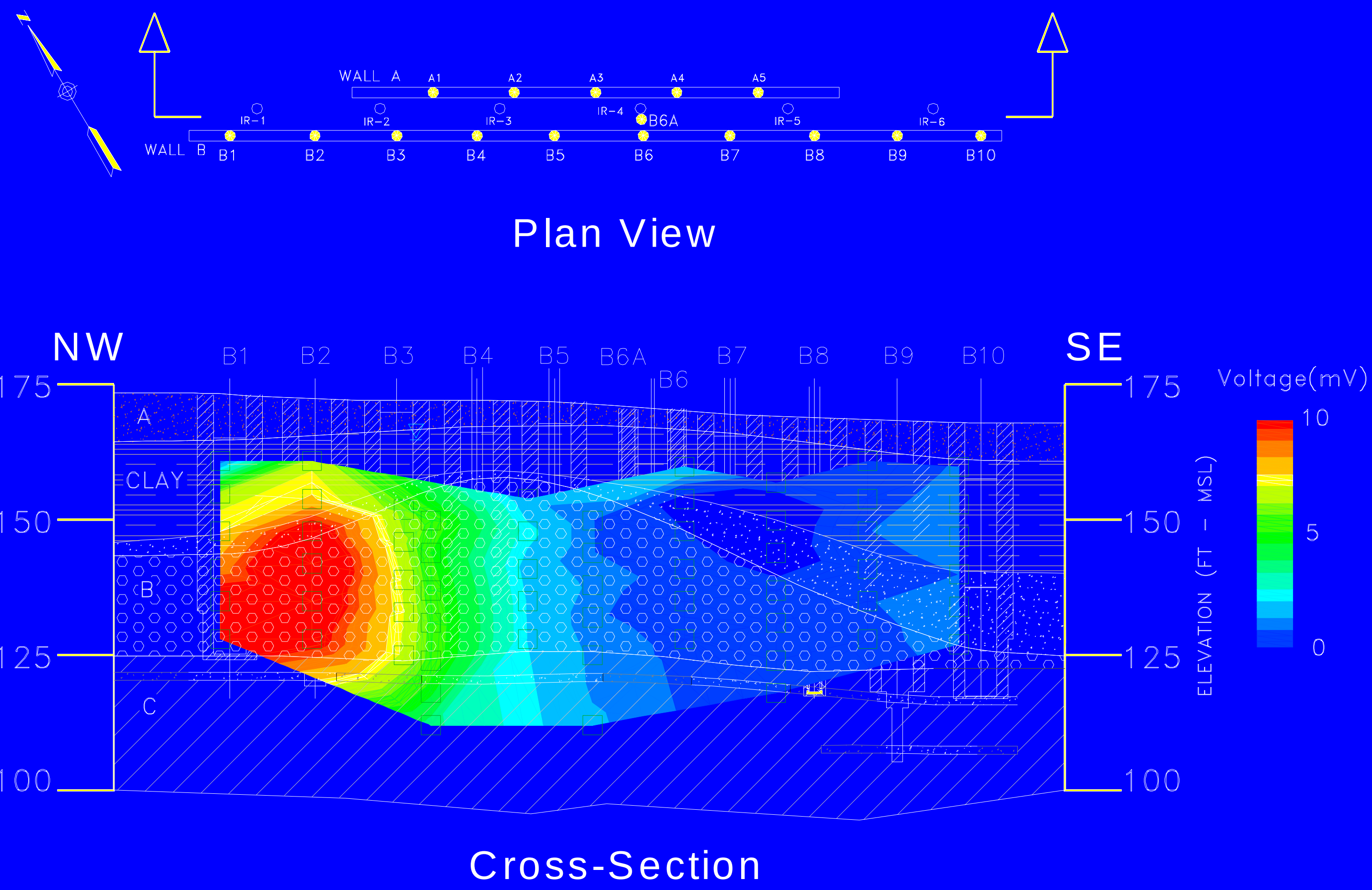
Construction QA/QC Procedures

- Real Time PRB Geometry Imaging During Construction
  - Electrical Excitation of Frac Fluid
  - Frac Fluid Highly Viscous with Minimal to Zero Leak-Off to the Formation
  - Monitored Injected Quantities
  - Frac Geometry Images During Installation
  - Frac Coalescence Observed between Frac Wells
- Inclined PRB Thickness Profiling
- Field Verification of Minimal Impact on Groundwater Flow Regimes
  - Pre and Post PRB Pulse Tests across PRB Alignment

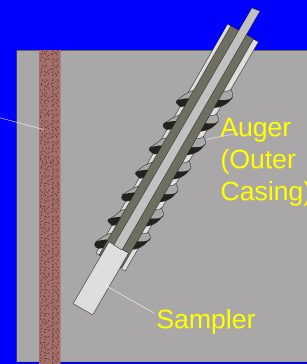
Real Time Active Resistivity Imaging Technology



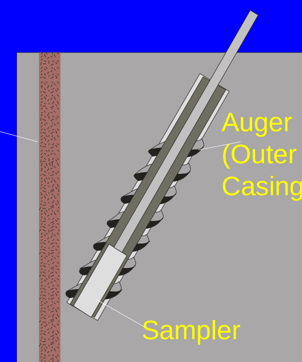
Real Time Resistivity Imagery
HydroFrac Injection in B1 & B2



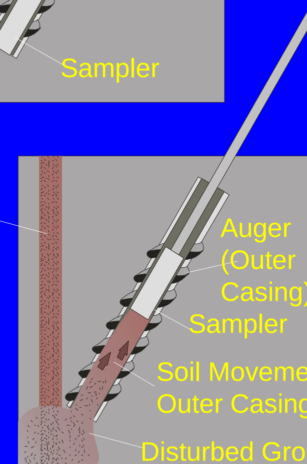
Disturbed Sampling of a PRB at Depth and/or in Flowing Ground



SAMPLER DRIVEN OR CORED TO DEPTH

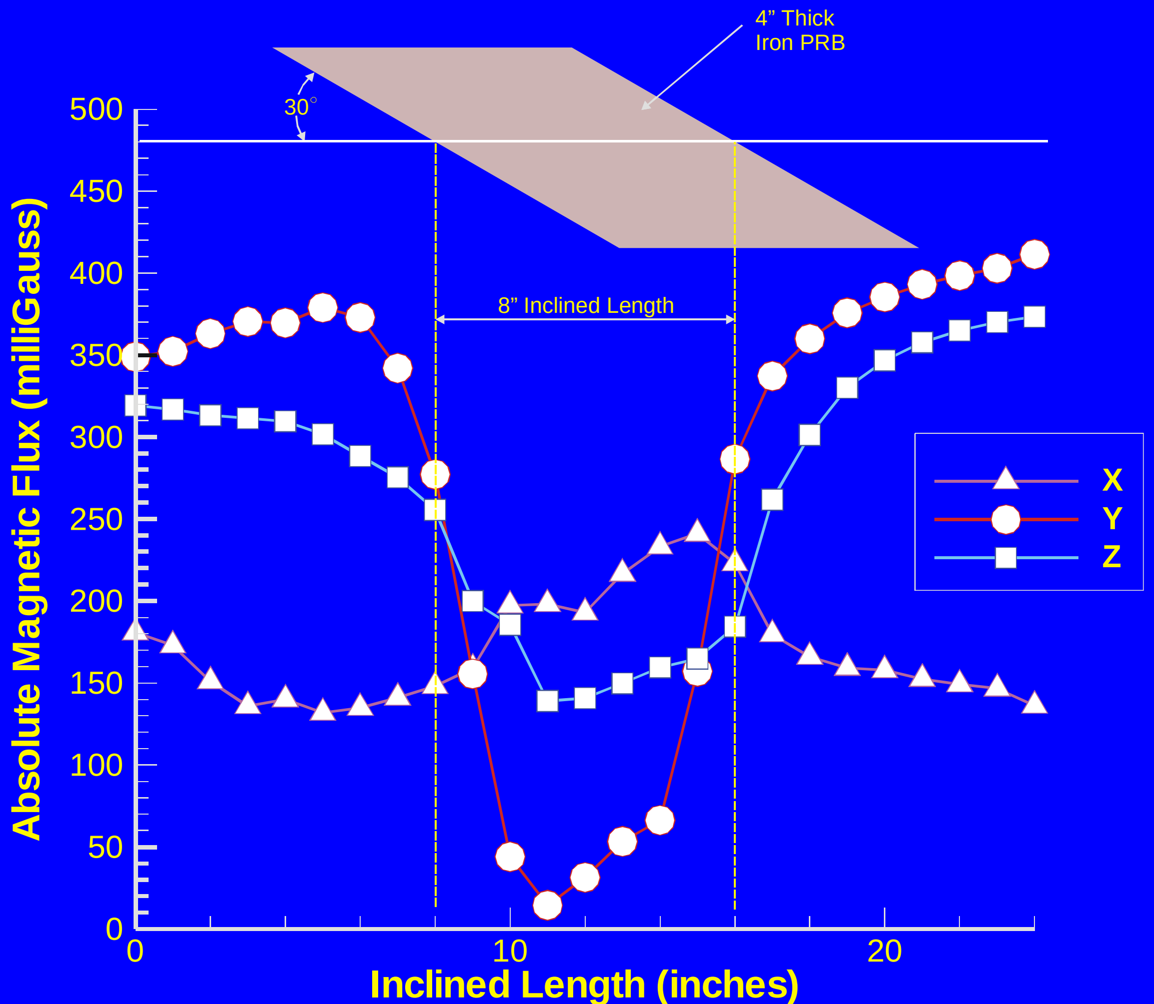


OUTER CASING OR AUGERS DRIVEN OVER SAMPLER

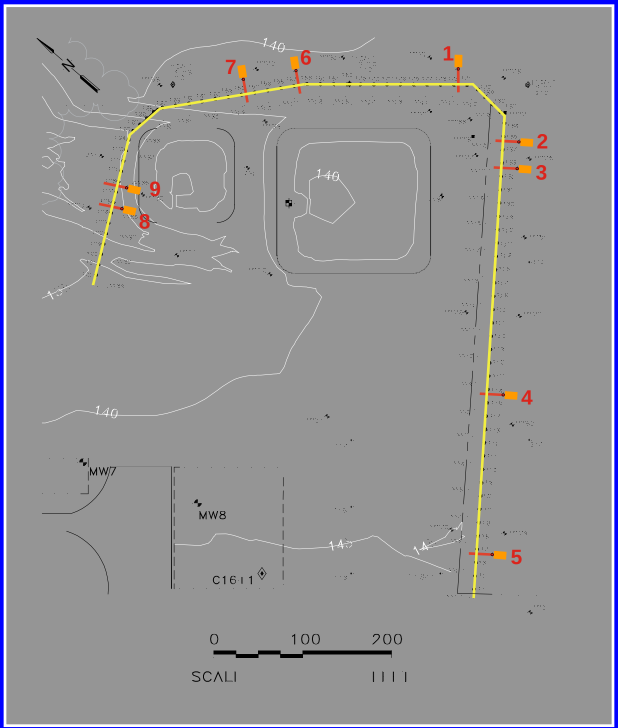


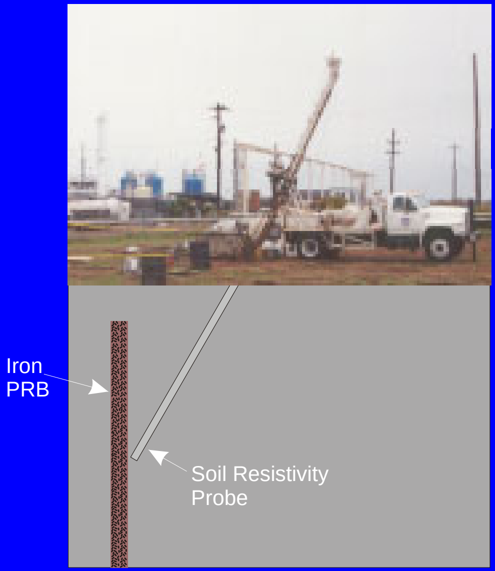
SAMPLER EXTRACTED GIVING RISE TO DISTURBED SAMPLING INTERVAL

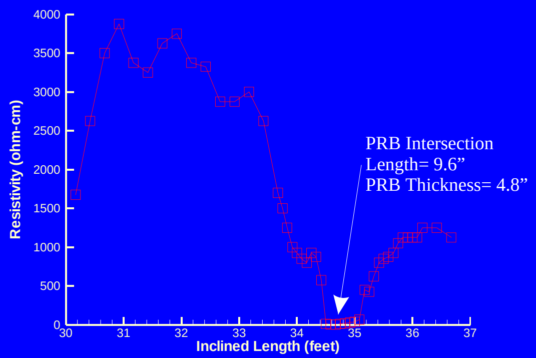
Inclined Magnetometer Probe Profile of 4” Iron PRB



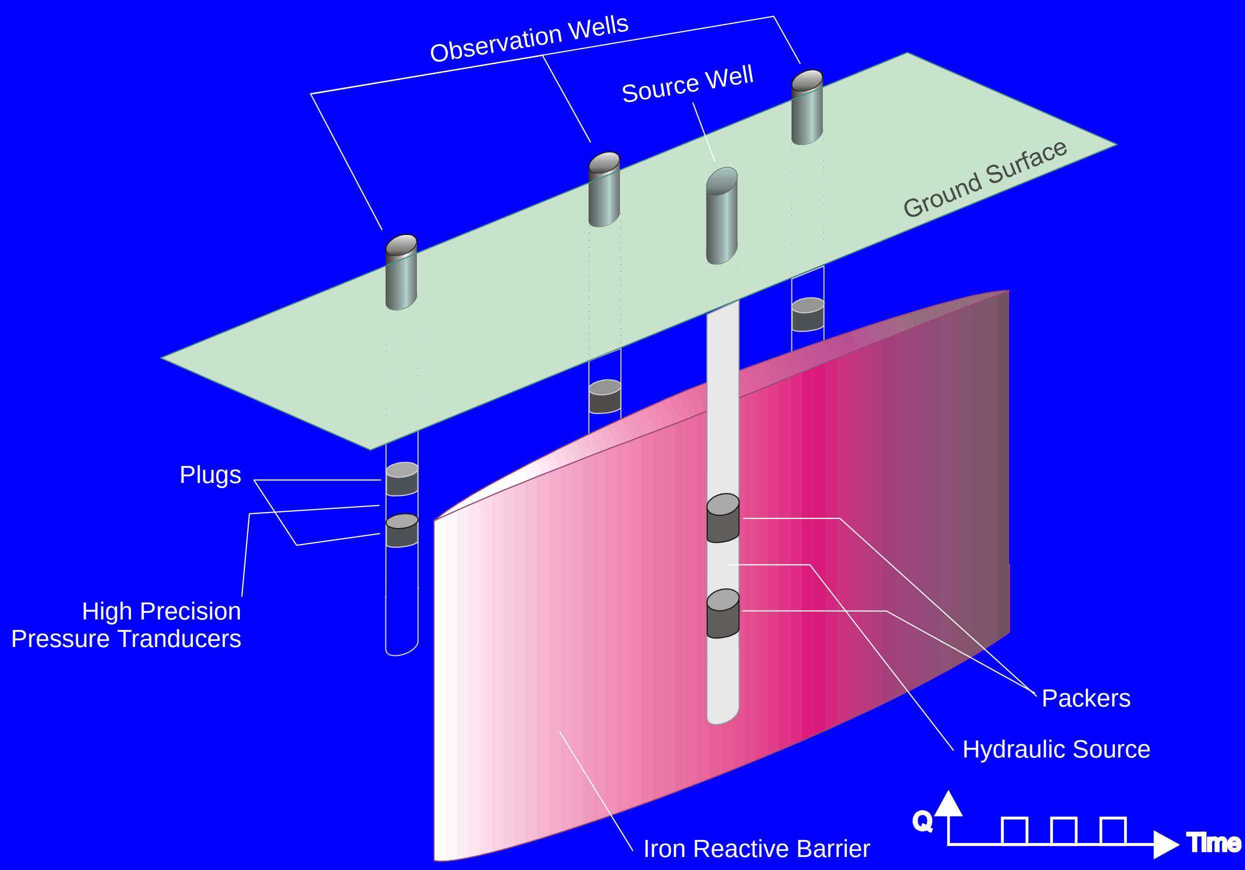
Inclined PRB Thickness Profiling





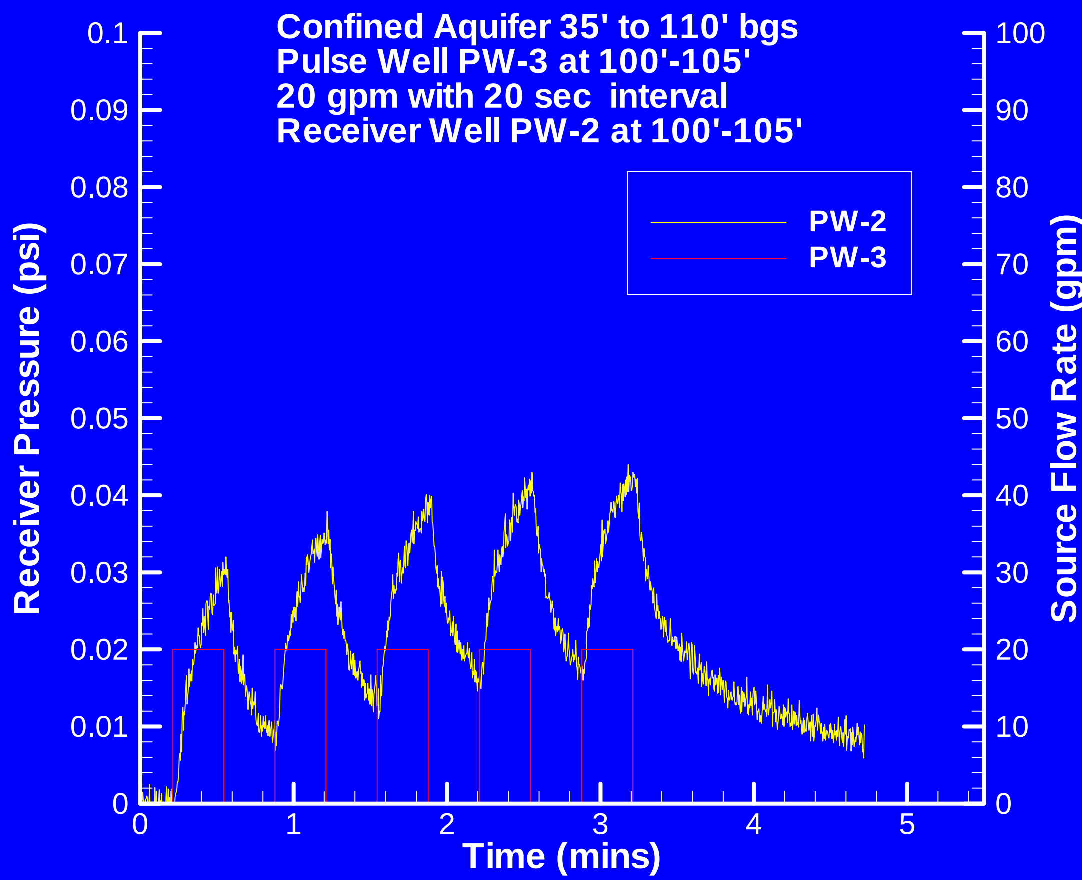


Hydraulic Pulse Interference Test

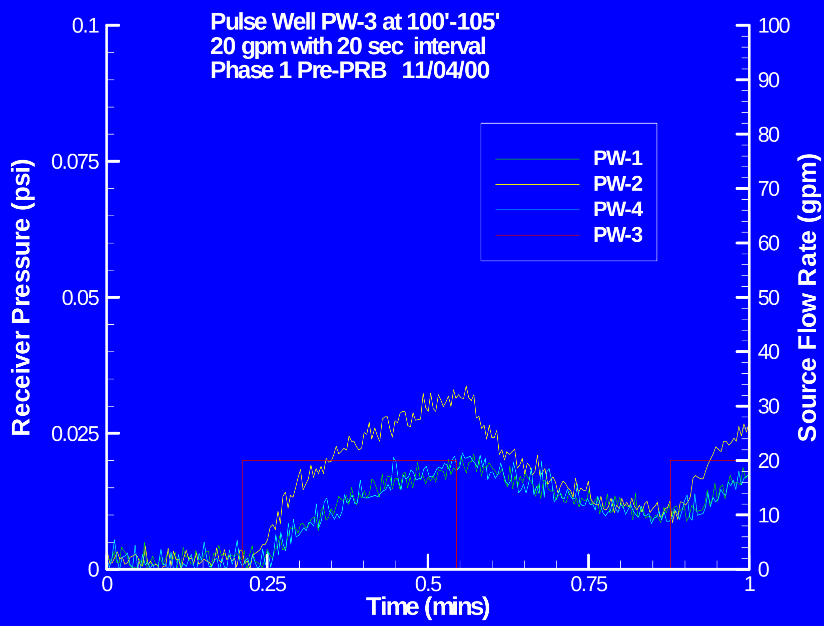


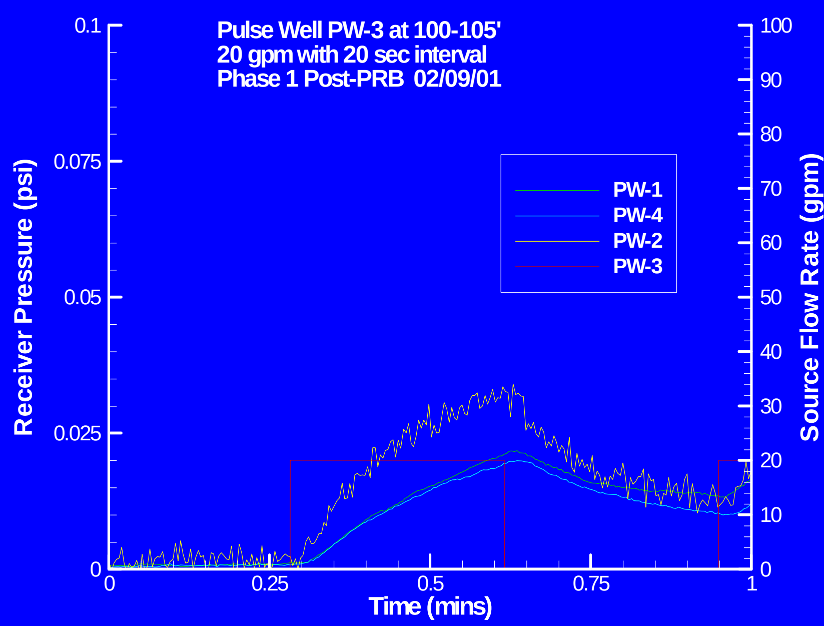
Typical Hydraulic Pulse Interference Test Setup

Typical Hydraulic Pulse Interference Response Data



Pre and Post PRB Construction Pulse Interference Tests





Azimuth Controlled Vertical Hydrofracturing Technology

- Azimuth Control
  - Special Purpose Frac Casing System Installed by Conventional Drilling
  - Downhole Tooling & Packers Installed
  - Frac Initiated by Casing System
  - Frac Continuity Assured by Dilating Frac and Pore Pressure Gradient Coalescence
- Iron Gel Mixture
  - Iron Filings Transported in Highly Viscous Degradable Food Grade Gel
  - High Specific Gravity Fluid
- Monitored Injected Geometry
  - Real Time Monitoring by Active Resistivity Imaging
  - Monitored Injected Iron Loading
- QA Tests on PRB Thickness and Hydraulic Characteristics

Advantages of Azimuth Controlled Vertical Hydrofracturing Technology

- Proven Technology
  - Construction of Full Scale Iron PRBs Shallow and at Depth in a variety of Geological Environments
  - Capable of Installing PRBs of High Permeability and Porosity
  - Minimal Impact on Natural Groundwater Flow Regimes
- Construction QA/QC and Verification Tests
  - Real Time Monitored PRB Constructed Geometry and Continuity
  - Monitored Injected Iron Loading
  - Thickness Verification by Inclined Profiling
  - In Situ PRB Hydraulic Characteristics Quantified
- Minimal Excavation and Site Disturbance
- Low Personnel and Property Risk Exposure
- Excellent Health and Safety Record