Designing and Monitoring Remediation in Fractured Rock Aquifers: Challenges and Progress

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Even with the complexities of fractured rock aquifers, remediation technologies are being implemented.

Drilling bedrock boreholes (mudstone)
Naval Air Warfare Center, West Trenton, NJ

Steam injection apparatus (limestone)
Loring Air Force Base, Aroostook County, ME
Geologic complexity of fractured rock aquifers

- Hierarchy of void space
- Complex fracture connectivity
- Large range of hydraulic properties

Matrix porosity

Fractures

Fault zones

Granite and schist, Mirror Lake, NH

<table>
<thead>
<tr>
<th>Depth below top of casing (meters)</th>
<th>Acoustic televiewer log</th>
<th>Transmissivity (m²/s)</th>
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<tbody>
<tr>
<td>30</td>
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<td>10⁻¹⁰ 10⁻⁸ 10⁻⁶ 10⁻⁴</td>
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<td>50</td>
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<td>Detection limit</td>
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Borehole FSE6
Even relatively “simple” fractured rock environments are subject to significant complexity in the characterization of contaminant transport.

- **Hierarchy of void space**
- **Complex fracture connectivity**
- **Large range of hydraulic properties**

Matrix porosity

Lockatong Mudstone, West Trenton, NJ

Naval Air Warfare Center Borehole 68BR

Transmissivity (m²/s)

Detection limit

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Graph showing transmissivity with depth.
In fractured rock, where is the DNAPL?

Small “pool” heights of DNAPL force DNAPL into small aperture fractures.
Small “pool” heights of DNAPL force DNAPL into small aperture fractures

- 9 micron ($9 \times 10^{-6}$ meters) fracture aperture needed to stop 1 meter “pool” height of TCE

- Diameter of human hair ~50 microns

\[
H = \frac{2 \sigma \cos \theta}{(P_n - P_w)gb}
\]

- $H =$ DNAPL head
- $b =$ fracture aperture
- $g =$ gravitational acceleration
- $\theta =$ contact angle (DNAPL – water)
- $\sigma =$ interfacial tension (DNAPL – water)
In fractured rock, where is the DNAPL, and where is the dissolved phase DNAPL?

Complex topology of fracture surfaces

High permeability flow path

Fracture surface

DNAPL forced into small aperture sections of fractures

Chemical diffusion into matrix porosity
Most remediation technologies are inconsistent with the geologic complexities of fractured rock aquifers.

Influent flushing solution (e.g., steam, alcohol, surfactants, chemical oxidizers, microbial agents, etc.)

Contaminated fluids pumped to on-site or off-site treatment

Chemical and/or microbial reactions with DNAPL and its dissolved phase, or increase mobility and/or solubility of the DNAPL
Most remediation technologies require contact with the DNAPL or its dissolved phase.

High-permeability flow paths bypass small aperture fractures.

Dissolved phase contaminants in rock matrix.

Remediation technologies will be effective in the most permeable fractures.
Even with all the complexities associated with fractured rock, . . . reducing contaminant mass in permeable fractures may be a part of addressing project objectives.

TCE and DCE are electron acceptors which compete with all other electron acceptors.

Reactive transport models will be critical in evaluating the cost/benefit of applying remediation technology in fractured rock.
Designing and monitoring remediation at the Naval Air Warfare Center, West Trenton, NJ

Bioaugmentation (US Navy, USGS, Geosyntec, 2008)

Bioaugmentation (US Navy, Geosyntec, USGS 2005)

Thermal conductive heating (US Navy, TerraTherm, Queens Univ., USGS, 2009)

Legend
- Bedrock borehole
- NAWC Boundary
- Fault
- Building
- Pump-and-treat well
In situ bioaugmentation

- Water pumped from 36BR-A into 2 bladders (bladders pre-flushed with argon to keep formation water anaerobic)
- One bladder dosed with EOS and Vitamin B12
- Injection of ~50 gallons EOS solution
- Injection of 20 L microbial consortium KB-1
- Injection of ~100 gallons EOS solution
- Injection of ~100 gallons formation water (anaerobic)

October 15, 2008
Bioaugmentation pilot study (2005) using EOS and KB-1

Red lines indicate injection and withdrawal well pairs to introduce amendments

Amendments added

Concentration (micrograms per Liter)

41BR


TCE  DCE  VC

Red lines indicate injection and withdrawal well pairs to introduce amendments

220 ft

25 ft
Red lines indicate injection and withdrawal well pairs to introduce amendments.

Bioaugmentation pilot study (2005) using EOS and KB-1

Amendments added

TCE 10 ppb
DCE 96 ppb
VC 54 ppb

Borehole drilled in 2007 showed no significant signs of remediation.

TCE 10 ppb
DCE 96 ppb
VC 54 ppb
Interpreting the contaminant concentrations at points of ground water discharge

Aquifer test conducted at the NAWC by manipulating the discharge of pump-and-treat wells

Responses to pumping indicate potential contaminant pathways, but do not indicate the residence time and chemical mixing
Ground water flow and transport models have been developed that represent the results of *in situ* hydraulic and tracer experiments.

Ground water drawn into 15BR comes predominantly along the strike of bedding.

Diagram of bedding used in the ground-water flow model of the mudstone at the NAWC.

15BR draws significantly less water from the down dip direction of bedding.
Interpreting the contaminant concentrations at points of ground water discharge

- Remedial design is improved through direct evidence of ground water residence times and chemical mixing
- Designing the monitoring of remediation is improved through the understanding of the geologic framework, flow regime, and direct evidence of chemical transport
- Multilevel monitoring boreholes (70BR, 71BR, and 73BR) were installed prior to the bioaugmentation experiment
From complexities of fractured rock, we should anticipate...

• Complex distribution of DNAPL (free and dissolved phase), with contaminant mass in small aperture fractures and the primary porosity of the rock

• Remediation technology will be most effective in most permeable fractures

• Designing containment and remediation requires understanding of geologic framework, ground water flow regime, and chemical residence time and mixing

• Monitoring at manipulated boreholes, pumped boreholes, and intermediate locations
A few final thoughts. . .

• We have had great success in developing tools for characterizing ground water flow and chemical transport in fractured rock. . .our success makes it possible to design and implement containment and remediation strategies. . .

• Expectations of remediation success must be tempered by the reality of the complexities of fractured rock. . .