Mobility Control in Surfactant Floods:

Improving NAPL recovery by in-situ control of viscosity

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EPA NAPL Seminar, Chicago
December 11, 2002

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Mobility Control

The term refers to controlling the viscosity, and subsequently, the direction of flow of injected fluids in heterogeneous oil reservoirs

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Mobility Control

Mobility ratio:

mobility of NAPL ÷ mobility of injectate

Where mobility $= \mu_j \div k_{eff,\, j}$

If $\mu_{INJ} > \mu_{NAPL}$, there is better sweep in-situ and higher NAPL recovery

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Choice of Approaches

There are two ways of changing in-situ viscosities and thereby overcoming the effects of heterogeneities

1. Surfactant-Foam flooding
2. Surfactant-Polymer flooding

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1: Foam Flooding

- Surfactant solutions foam when air is injected into them
- In-situ this forms a high viscosity and therefore stationary environment in the high perm zones,
- Foam is temporary & reversible

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1: Foam Flooding

Sequential injection of slugs of first surfactant solution then air cause temporary blocking of high-perm units, i.e., low mobility, thus

Foam causes redirection of surfactant into low-perm zones

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Applications of Foam Flooding

Pilot Scale Test at Hill AFB in 1997 by INTERA and Rice University

Two large-scale Foam floods at Hill in 2001 and 2002 to remove TCE DNAPL

Advisor: George Hirasaki, Rice University

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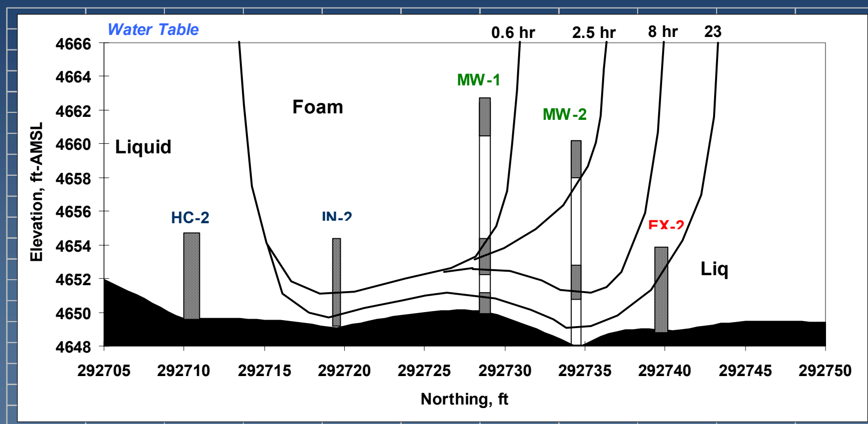
1997 AATDF Surfactant-Foam Flood Demonstration, OU2, Hill AFB



Cross Section Showing Growth of Foam Front, see Meinardus et al., 2002, JCH 54:173-193

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Foam is produced from upper ports, DNAPL from the base

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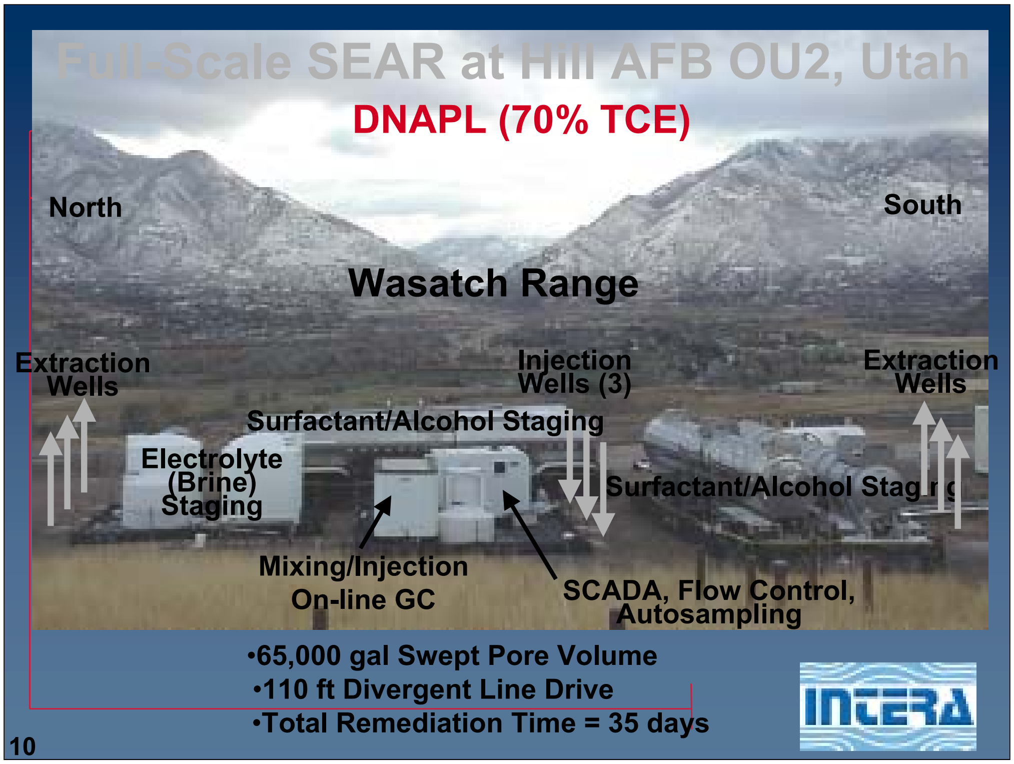

FULL-SCALE Surfactant-Enhanced Aquifer Remediation (SEAR) conducted at Hill Air Force Base, Operable Unit 2 (OU 2), Utah to remediate the area most contaminated with dense nonaqueous phase liquid (DNAPL), primarily TCE.

- **Objectives.**
  - *Remove all of the DNAPL* in the target zone, while
  - *Maintaining hydraulic control* over all remedial fluids in the well field, and
  - *Achieving efficient surfactant use*, all
  - *Verified* with a defensible performance assessment (PA).
- **Dimensions.** The pore volume treated ~ 65,000 gals using a 110 ft long divergent line drive well field with 6 extraction wells and 3 injection wells.
- **Field operations.** Schedule: (1) an initial 4-day water flood, (2) surfactant injection for ~ 12 days, (3) final water flood for ~ 17 days. No surfactant recovery and recycling, and SEAR effluent treated in a steam stripper to remove VOCs followed by polishing in the base's industrial WWTP.
- **Quantitative performance assessment.** Partitioning interwell tracer test (PA PITT), supplemented by post-flood sediment samples from confirmation borings.
- **Photograph.** SEAR system, looking east toward the N-S trending Watsach Mountain Range. Four tankers were used to stage the surfactant and alcohol prior to automatic in-line mixing and injection. Poly tanks on the right are electrolyte (brine) tanks for the injection system. Utility trailers in the center house the Supervisory Control and Data Acquisition System (SCADA), the automatic flow control system, the automatic sampling system (including online GC) and the injection system. The three injection wells can be seen just to right of the central secondary containment liner. The northern extraction wells are located to the left of the containment system containing the brine tanks, and the southern extraction wells are to the right of the surfactant tankers on the right side of the photo.

2: Polymer Flooding

- Hundreds of polymer floods conducted since 1960s by the oil industry
- The purpose is to maintain local hydraulic gradients and thus cause the injected polymer solution to enter low perm units

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2: Polymer Flooding

- Polymer solutions have high viscosity, e.g., 5 – 20 cP, relative to the NAPL they are to displace
- Polymer flooding will displace only free-phase NAPL not residual
- Surfactant-polymer flooding displaces both free- and residual-phases
  - Advisor: Gary Pope, UT-Austin

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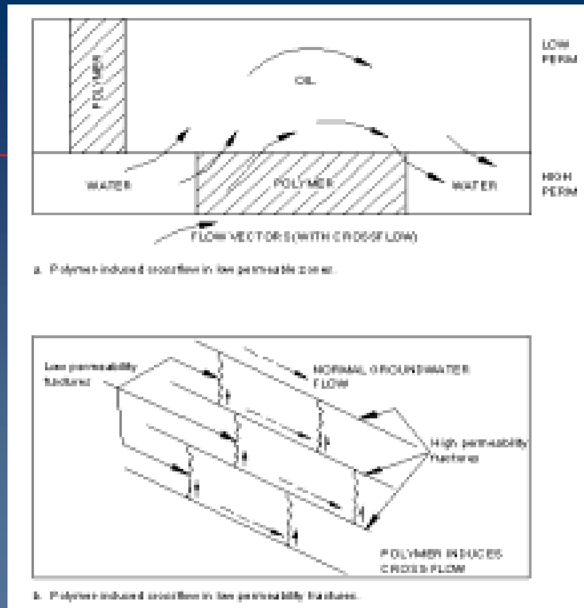
Mobility Control with Polymers:- allows surfactants or biostimulants to be pushed into low-k zones



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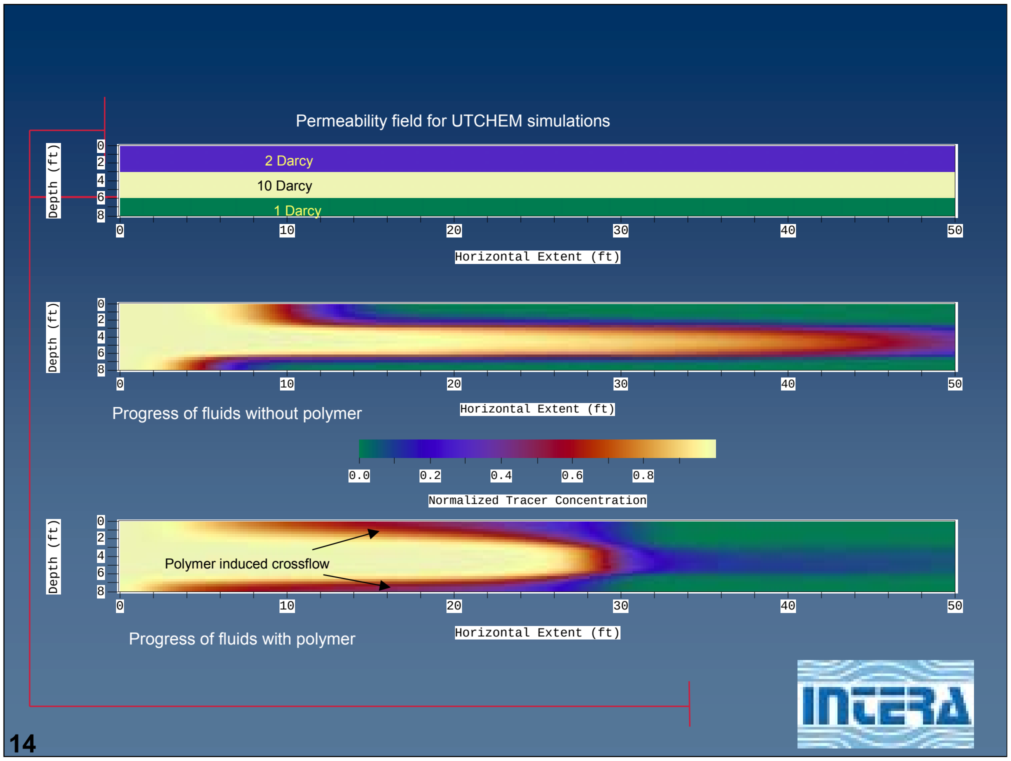

Permeability field for UTCHEM simulations
2 Darcy
10 Darcy
1 Darcy
Depth (ft)
Horizontal Extent (ft)
Progress of fluids without polymer
Normalized Tracer Concentration
Polymer induced crossflow
Progress of fluids with polymer
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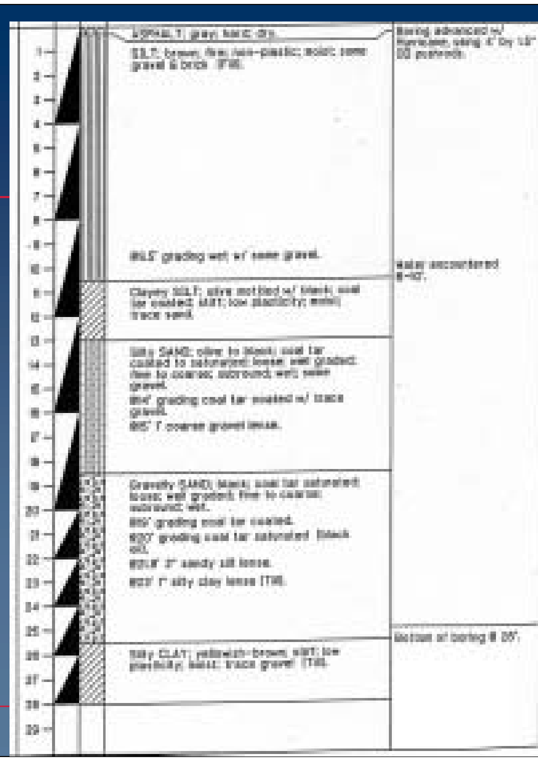
Soil Boring Log



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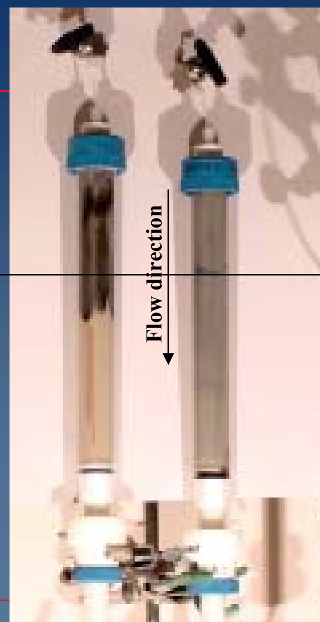
Column Study Results: The Effect of Polymers

Surfactant flood

Polymer/ surfactant flood



50-60% coal tar recovery

85-90% coal tar recovery

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Surfactant System

4% Alfoterra 123-8 PO-Sulfate
8% Secondary Butyl Alcohol
0.13% Xanthan gum biopolymer
0.08% Calcium Chloride

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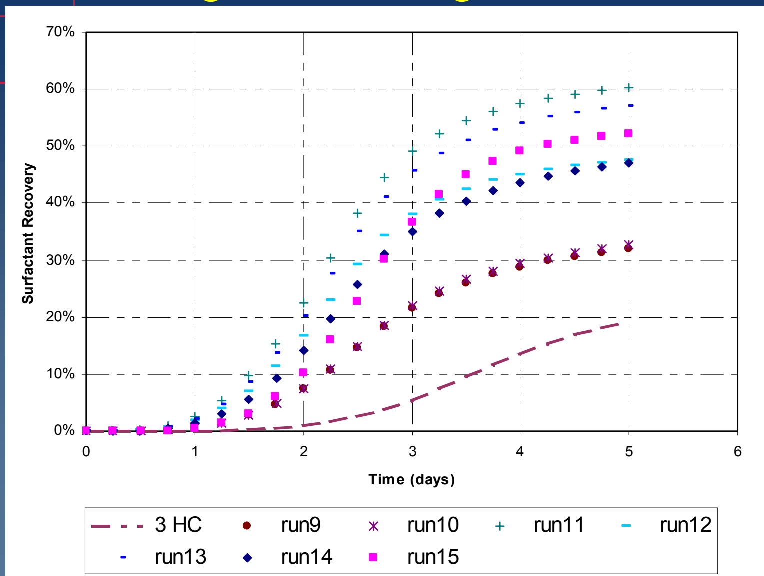
Design simulations for different well configurations using UTCHEM



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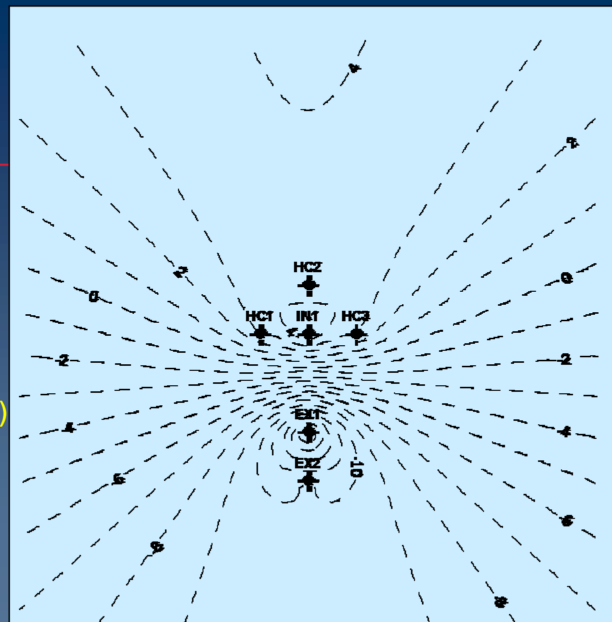
Piezometric Surface during Flood

natural grad = 0.001
imposed grad = 1.7 (60°)



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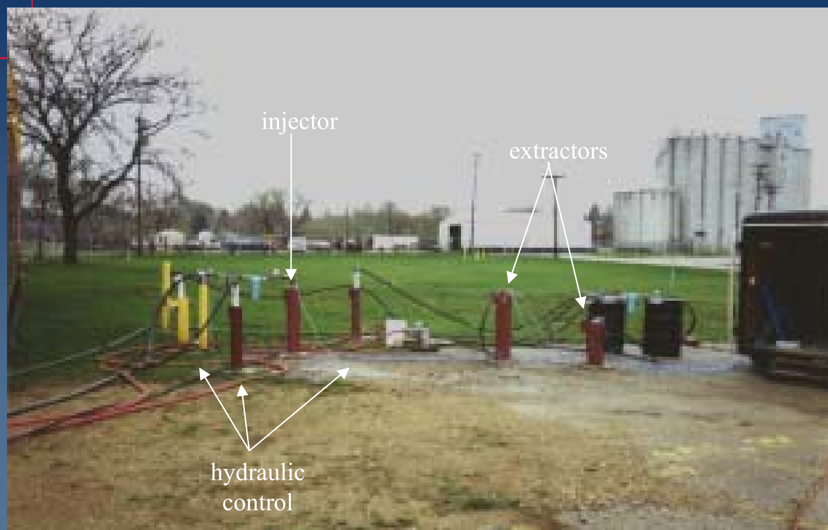
Wellfield



Pore volume = 7,000 L

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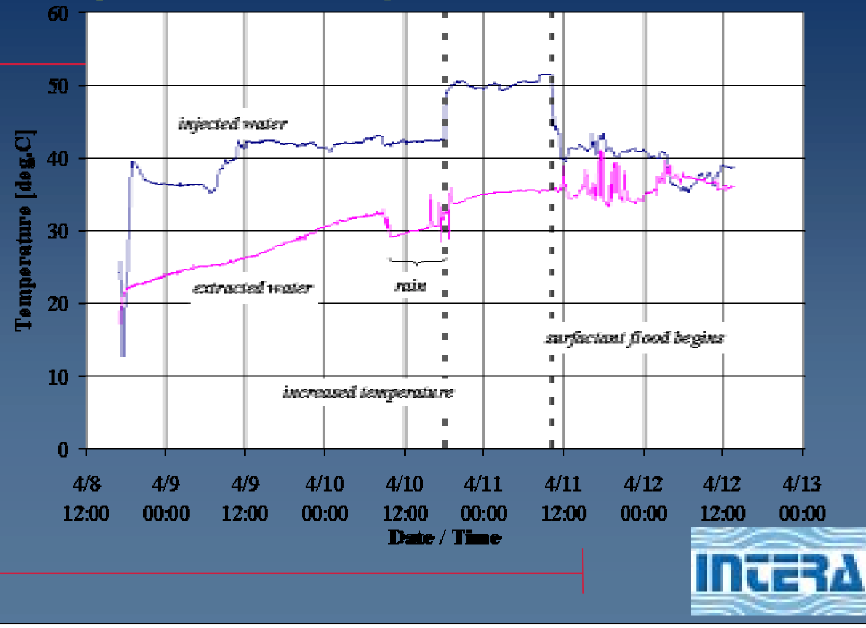
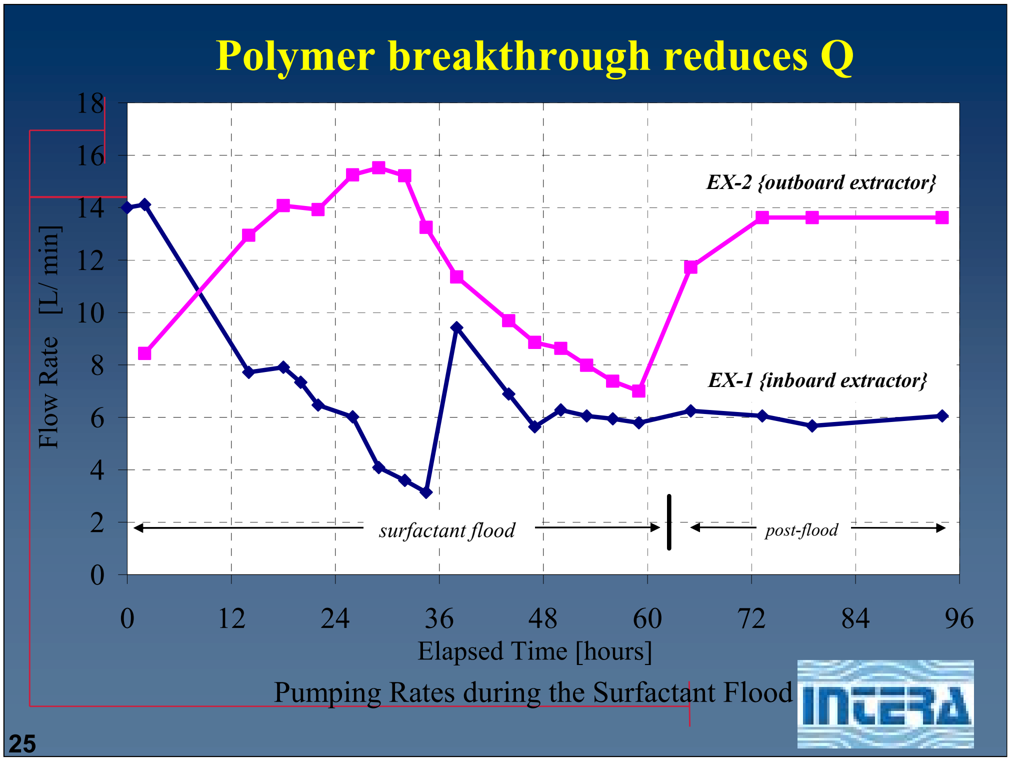
Temperature History




Polymer breakthrough reduces Q
Flow Rate [L/ min]
Elapsed Time [hours]
EX-2 {outboard extractor}
EX-1 {inboard extractor}
surfactant flood
post-flood
0
2
4
6
8
10
12
14
16
18
0
12
24
36
48
60
72
84
96
Pumping Rates during the Surfactant Flood
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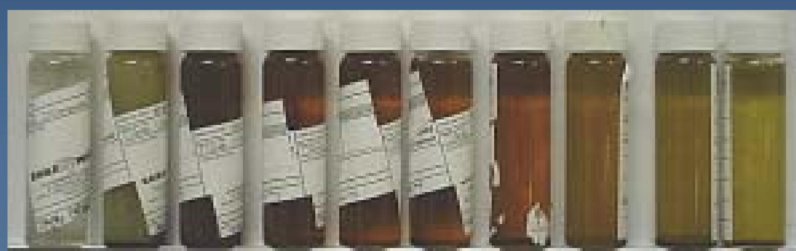
Samples from EX-1

Flood begins 04/11 1000

Post-Flood begins 04/14 0300

4/11 0800
4/11 1200
4/12 0800
4/12 1500
4/12 1800
4/13 0800
4/13 1800
4/14 1115
4/14 1700
4/15 0800



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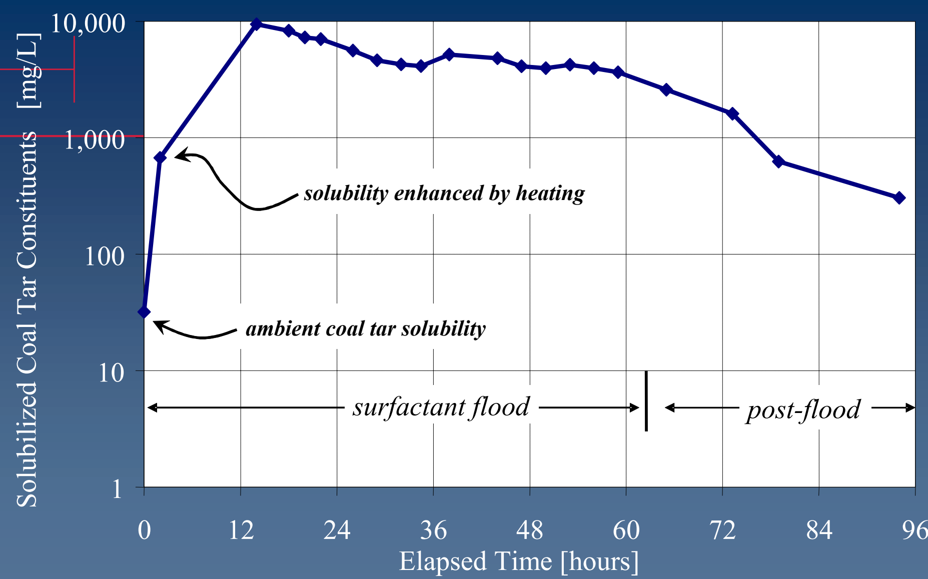

Coal Tar Solubilization at Well EX-1

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Samples from EX-2

Flood begins 04/11 1000

Post-Flood begins 04/14 0300

4/11 0800 | 4/12 0000 | 4/12 0800 | 4/12 1200 | 4/12 1500 | 4/12 1800 | 4/12 2028 | 4/13 1200 | 4/14 0300 | 4/14 1700 | 4/15 0800

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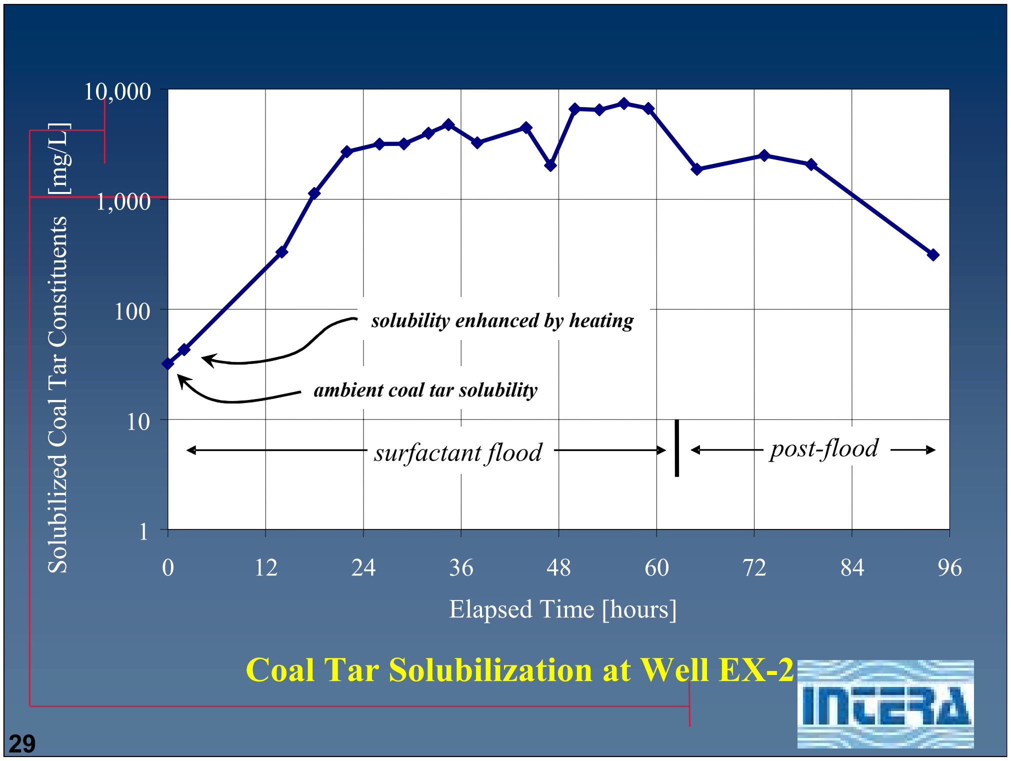
10,000
1,000
100
10
1
Solubilized Coal Tar Constituents [mg/L]
solubility enhanced by heating
ambient coal tar solubility
surfactant flood
post-flood
0
12
24
36
48
60
72
84
96
Elapsed Time [hours]
Coal Tar Solubilization at Well EX-2
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Coal-Tar Recovery

- 2,621 L free-phase by mobilization
- 305 L of residual by solubilization
- Total recovery=2,926 L
  - i.e., 42% of the 7,000 L test pore volume

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Performance Assessment

- Conducted by on-site contractors
  - [Burns & McDonnell, Oak Brook IL]
- Before and after soil sampling indicated removal of
  - 92% of benzene and
  - 86% of PAHs

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SEAR is Cost Competitive

Estimate for SEAR at Bloomington:

~ $95 / yd^3 of aquifer volume

Typical excavation/disposal costs:

~ $100 - $150 / yd^3

(both estimates are based on excavated yardage)

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Summary

Heterogeneities in alluvium and fractured rock can be overcome by controlling the injectate viscosity

1. Surfactant-foam flooding
2. Polymer flooding
3. Surfactant-polymer flooding

Path Forward

- Coupling Pressure Pulse Testing with surfactant-polymer flooding for creosote removal at Cape Fear NC
- Use of polymer to push biostimulants or oxidants into low-perm units following surfactant flooding

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