In-Situ Flushing Technologies: Combined Remedies

Kurt D. Pennell, Ph.D., P.E.
School of Civil and Environmental Engineering
Georgia Institute of Technology
and
Department of Neurology
Emory University School of Medicine

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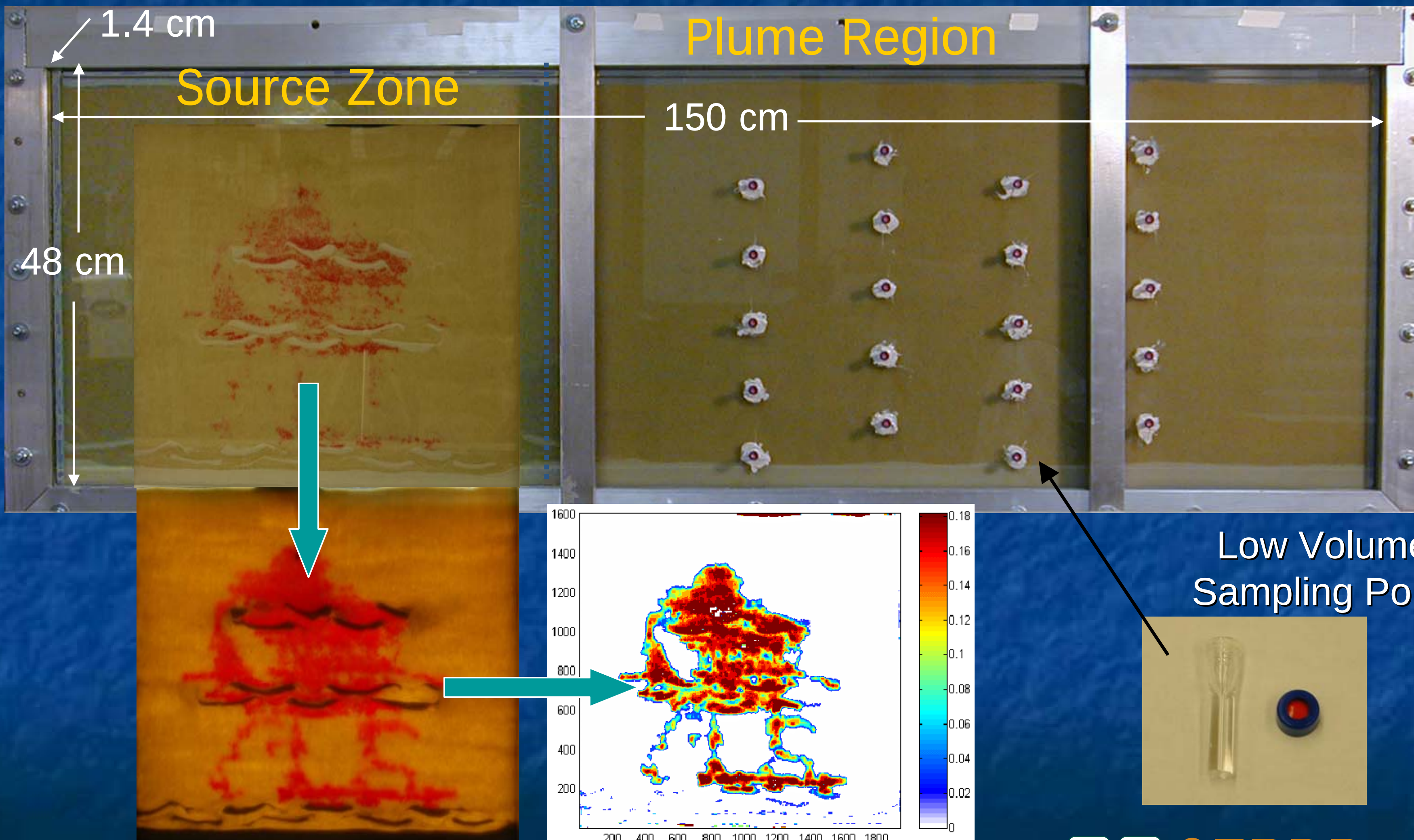
One of the Primary Challenges Facing In Situ Flushing Technologies is Cost

- Steps to Reduce Actual and Perceived Costs
  - Focus on relatively high permeability sites (k_i > 1 X 10^{-9} cm^2) with identifiable, localized and highly-contaminated source zones.
  - Select low-cost (<$1.50/lb or <$1.00/gal) surfactants/cosolvents, rather than "custom/designer" formulations; limit use of additives (e.g., polymers, cosolvents, salts).
  - Minimize the swept volume and corresponding injected volume.
  - Don't recycle unless you absolutely have to, instead focus on low-cost methods to treat/reduce volume of effluent waste stream.
  - When comparing costs, consider both mass/volume of DNAPL removed and the volume of soil/aquifer ($/$yd^3$) treated. Avoid "Apples (DNAPL recovered from a localized source) vs. Oranges (dissolved phase plume)".

In Situ Flushing: Technical Issues and Opportunities

- Post-Treatment/Incomplete Mass Removal
  - For coupled treatments to be applied effectively, we need to understand the distribution, configuration and amount of residual DNAPL mass.
- Surfactant Compatibility (Bioremediation)
  - Non-toxic, minimal inhibition.
  - Source of reducing equivalents (Tween 80/Ethanol).
- Minimize/Counter Downward Mobilization
  - Select formulations possessing high solubilization capacity w/o ultra-low IFT (Tween 80).
  - In situ density conversion (DNAPL→LNAPL) followed by low-IFT displacement flood (Aerosol/Butanol).

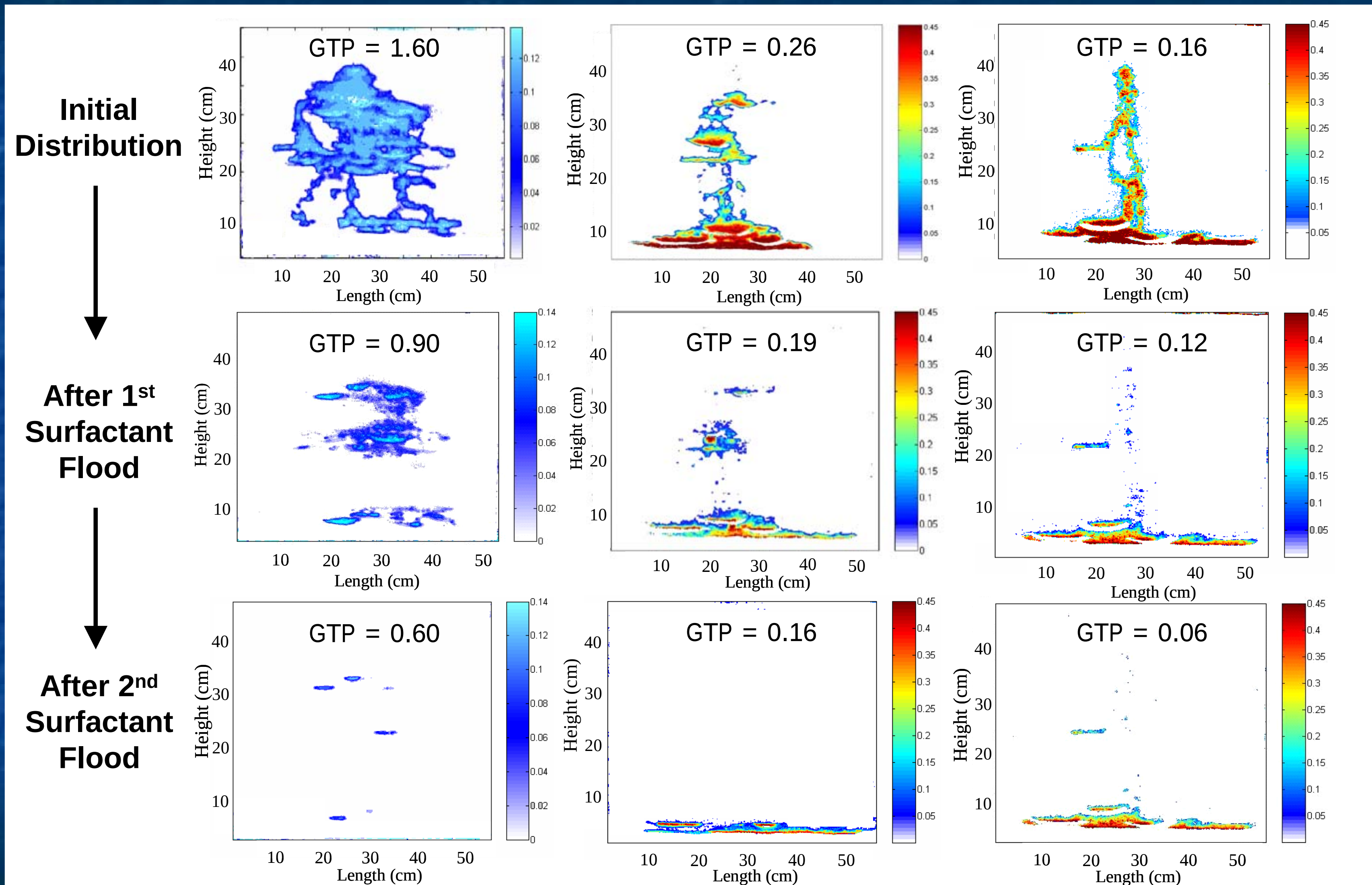
Effect of Mass Removal on PCE Saturation Distribution and Mass Flux/Discharge: Experimental



Light Transmission Imaging (~0.3 mm^2/pixel resolution)

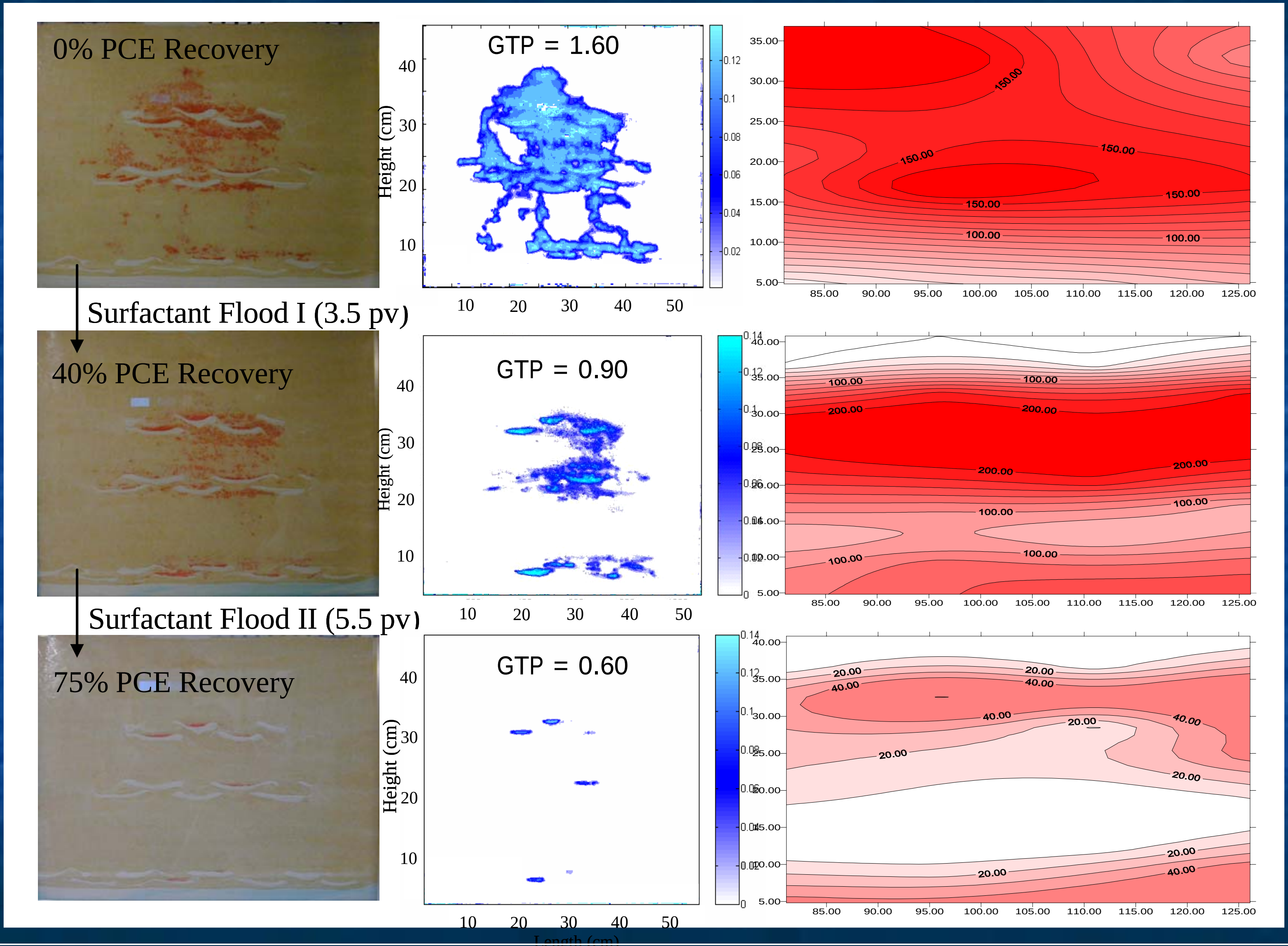
DoD EPA DOE SERDP
Strategic Environmental Research and Development Program

Changes in Source Zone Architecture as a Function of Mass Removal



Suchomel, E.J. and K.D. Pennell. 2006. Reductions in contaminant mass flux following partial mass removal from DNAPL source zones. *Environmental Science and Technology* (revised).

PCE Saturation Distribution and Plume Concentration Profiles ("High" GTP Case)



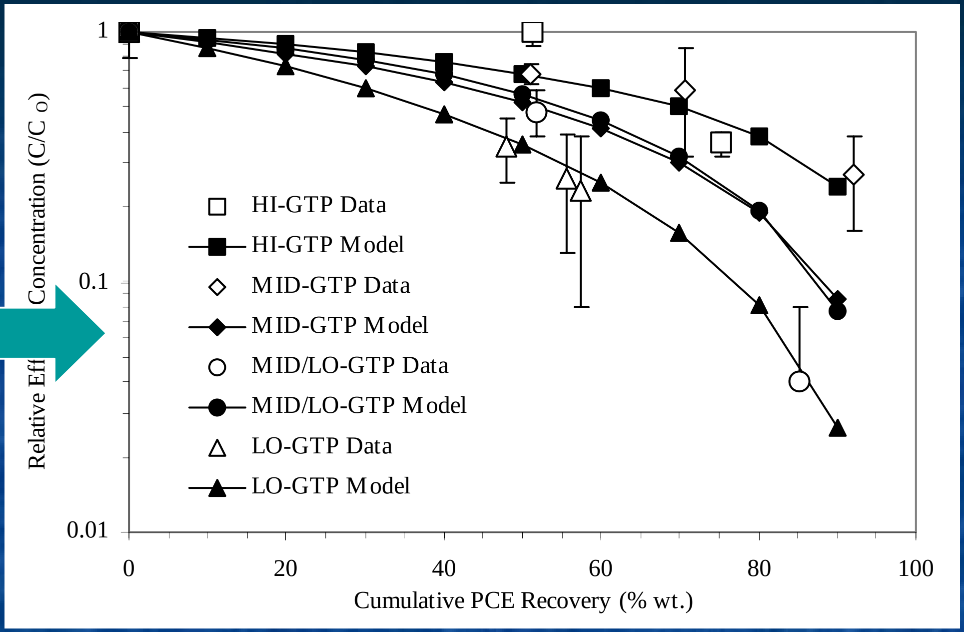
Suchomel, E.J. and K.D. Pennell. 2006. Reductions in contaminant mass flux following partial mass removal from DNAPL source zones. *Environmental Science and Technology* (revised).

Mass Flux/Mass Removal Correlations

Input: Initial GTP ratio and flux-averaged conc.

$$C^{a} / C^{a^{eq}} = 1 - \left(1 - C^{a^{t=0}} / C^{a^{eq}}\right)^{\left(\frac{M}{M^{0}}\right)^{A \times GTP^{B}}}$$

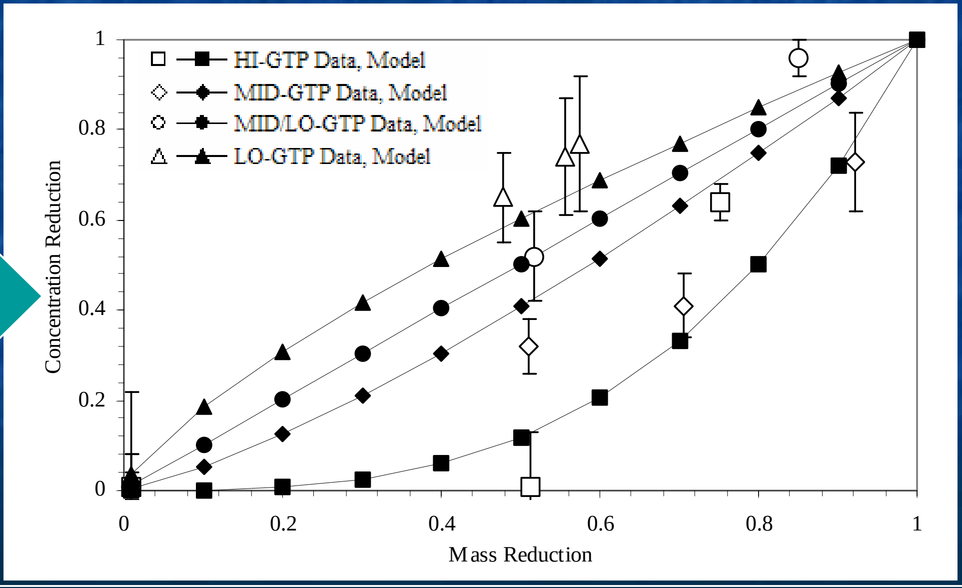
Christ et al., 2006 (revised)



Input: GTP included in gamma exponent

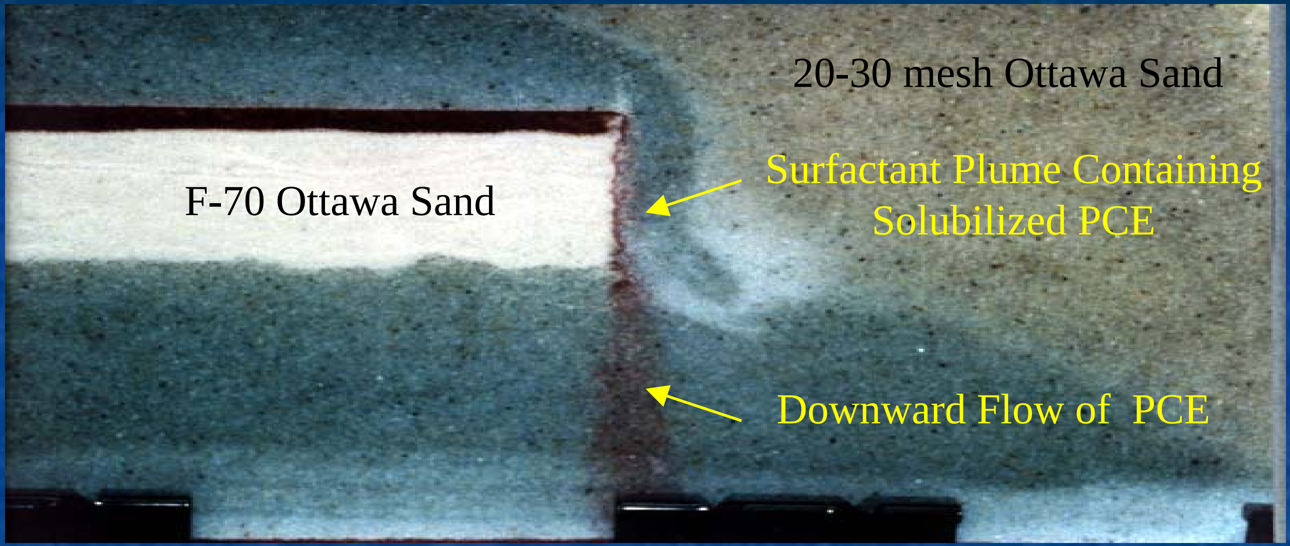
$$C^{a} / C^{a^{eq}} = \left(M / M^{0}\right)^{\Gamma}$$

Falta et al., 2005



Suchomel, E.J. and K.D. Pennell. 2006. Reductions in contaminant mass flux following partial mass removal from DNAPL source zones. *Environmental Science and Technology* (revised).

Uncontrolled DNAPL Mobilization



Capillary Number: $N_{Ca} = \dfrac{q\mu}{\sigma_{ow}\cos\theta}$

Bond Number: $N_B = \dfrac{\Delta\rho g k k_{rw}}{\sigma_{ow}\cos\theta}$

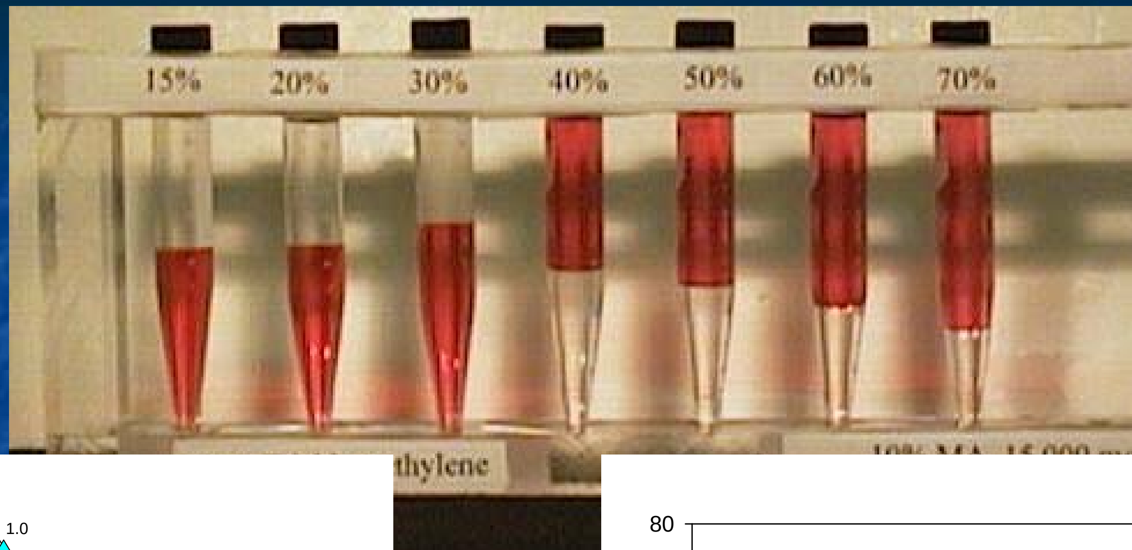
Total Trapping Number: $N_T = \sqrt{N_{Ca}^2 + 2N_{Ca}N_B\sin\alpha + N_B^2}$

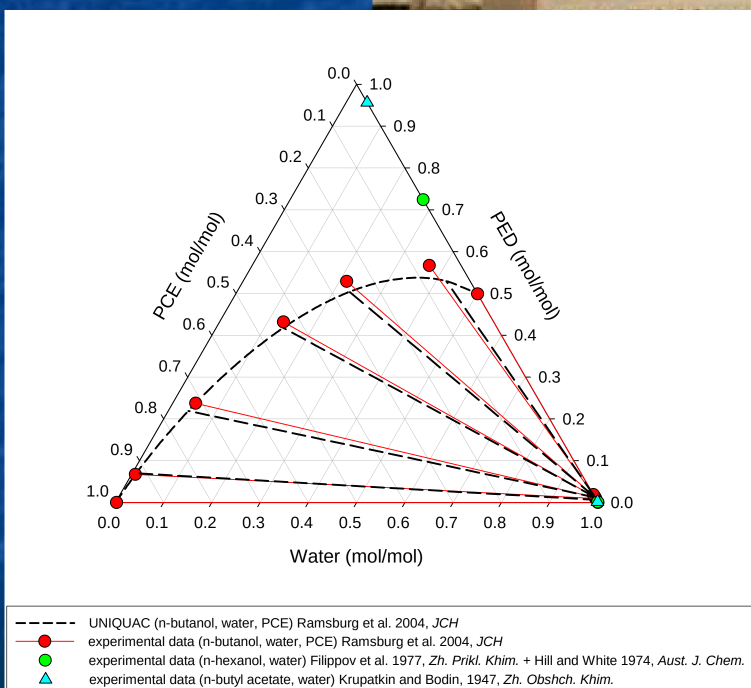
> $1X10^{-4}$ Complete Mobilization of Residual

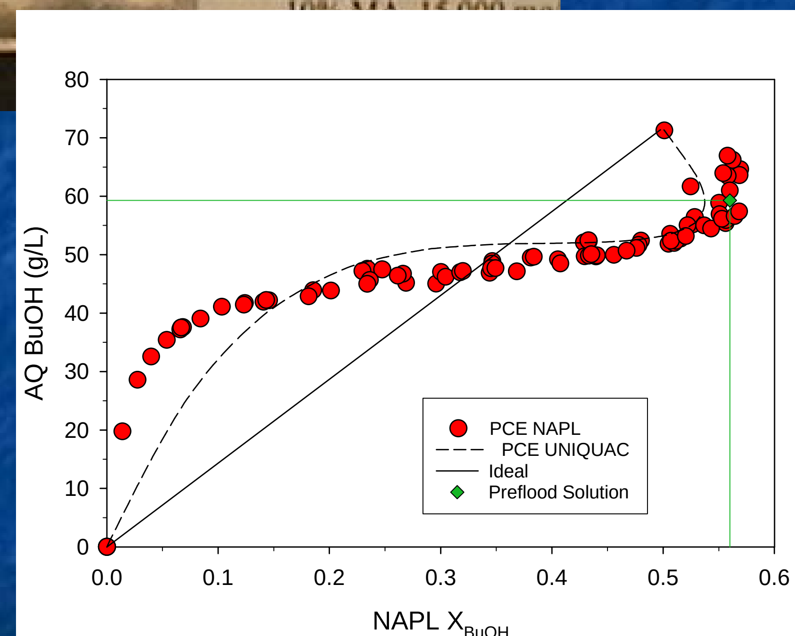
Vertical: $N_T = \left|N_{Ca} + N_B\right|$ *Horizontal:* $N_T = \sqrt{N_{Ca} + N_B}$

Pennell, K.D., L.M. Abriola, and G.A. Pope. 1996. Influence of viscous and buoyancy forces on the mobilization of residual tetrachloroethylene during surfactant flushing. *Environmental Science and Technology*, 30:1328-1335.

In Situ DNAPL Density Modification (TCE or PCE)



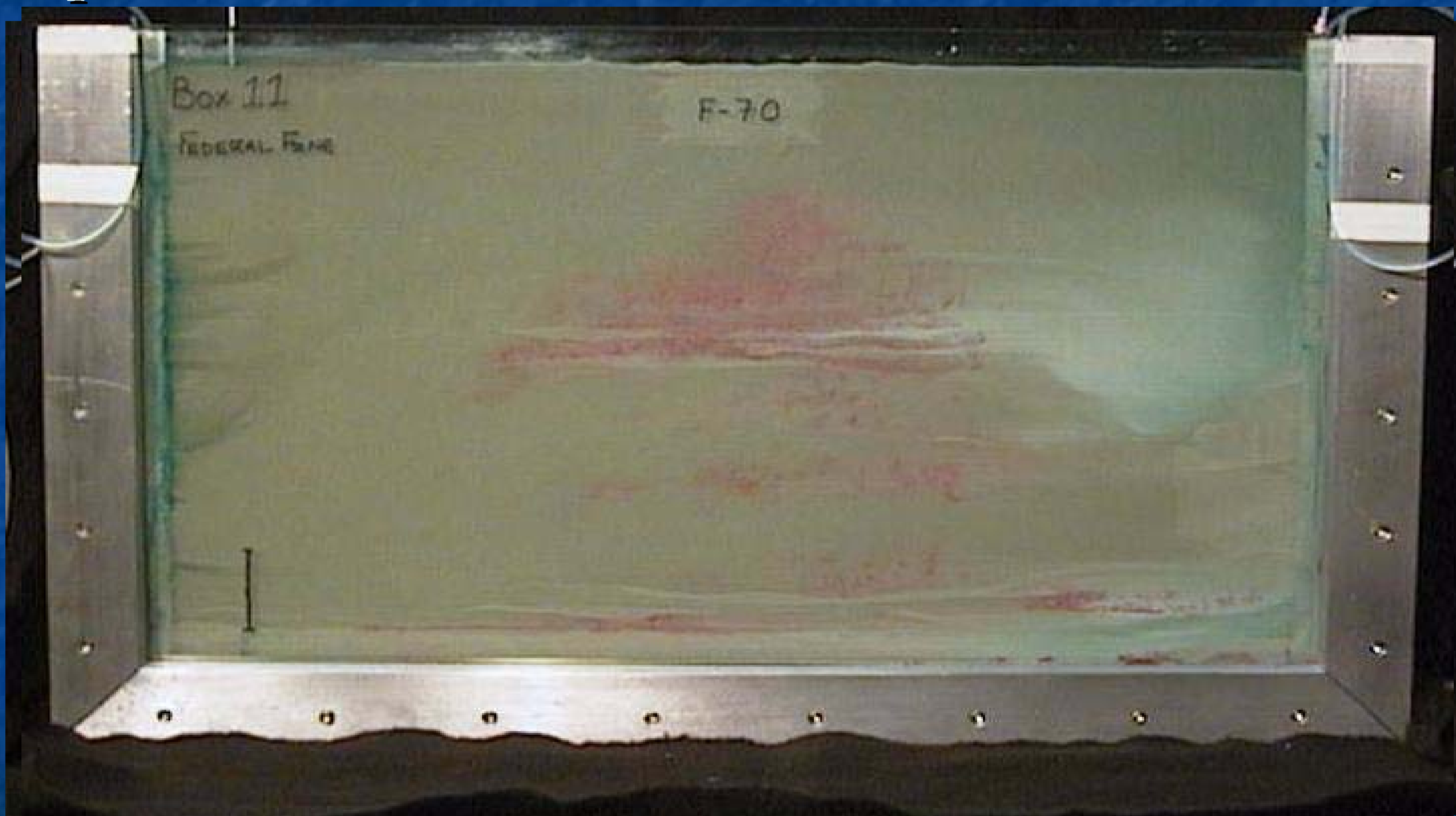




Ramsburg, C.A. and K.D. Pennell. 2002. Density-modified displacement for DNAPL source zone remediation: Density conversion and recovery in heterogeneous aquifer cells. *Environmental Science and Technology*, 36:3176-3187.

Macroemulsion Preflood-TCE (15% butanol)

Elapsed Time: [illegible] min   Volume: [illegible] mL



Ramsburg, C.A., K.D. Pennell, T.C.G. Kibbey and K.F. Hayes. 2003. Use of a surfactant-stabilized macroemulsion to deliver n-butanol for density-modified displacement trichloroethene-NAPL. *Environmental Science and Technology*, 37:4246-4253.

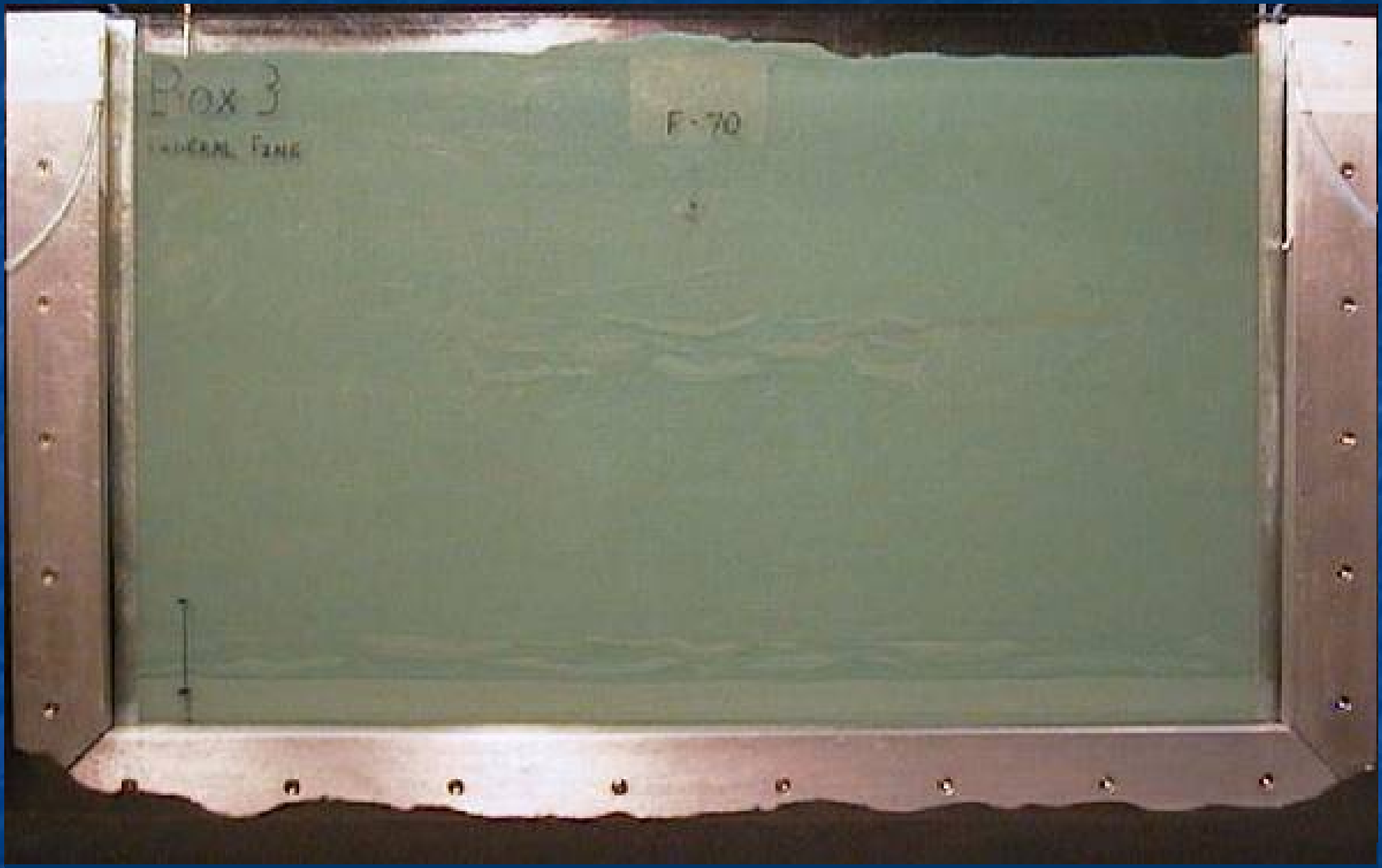
Low-IFT Displacement Flood-TCE (Butanol+Aerosol MA)

Elapsed Time: [illegible] min Volume: [illegible] mL

Ramsburg, C.A., K.D. Pennell, T.C.G. Kibbey and K.F. Hayes. 2003. Use of a surfactant-stabilized macroemulsion to deliver n-butanol for density-modified displacement trichloroethene-NAPL. *Environmental Science and Technology*, 37:4246-4253.

4% Tween 80 Flushing of TCE-DNAPL

(Solubility=63,000 mg/L; WSR=1.9; IFT=5.0 dyne/cm; N_T=2.0X10^{-5})



Time: 1200 min **Volume: 5160 mL**

Suchomel, E.J., Ramsburg, C.A. and K.D. Pennell. 2006. Efficient recovery of trichloroethene using a biodegradable nonionic surfactant. *Environmental Science and Technology* (in prep).

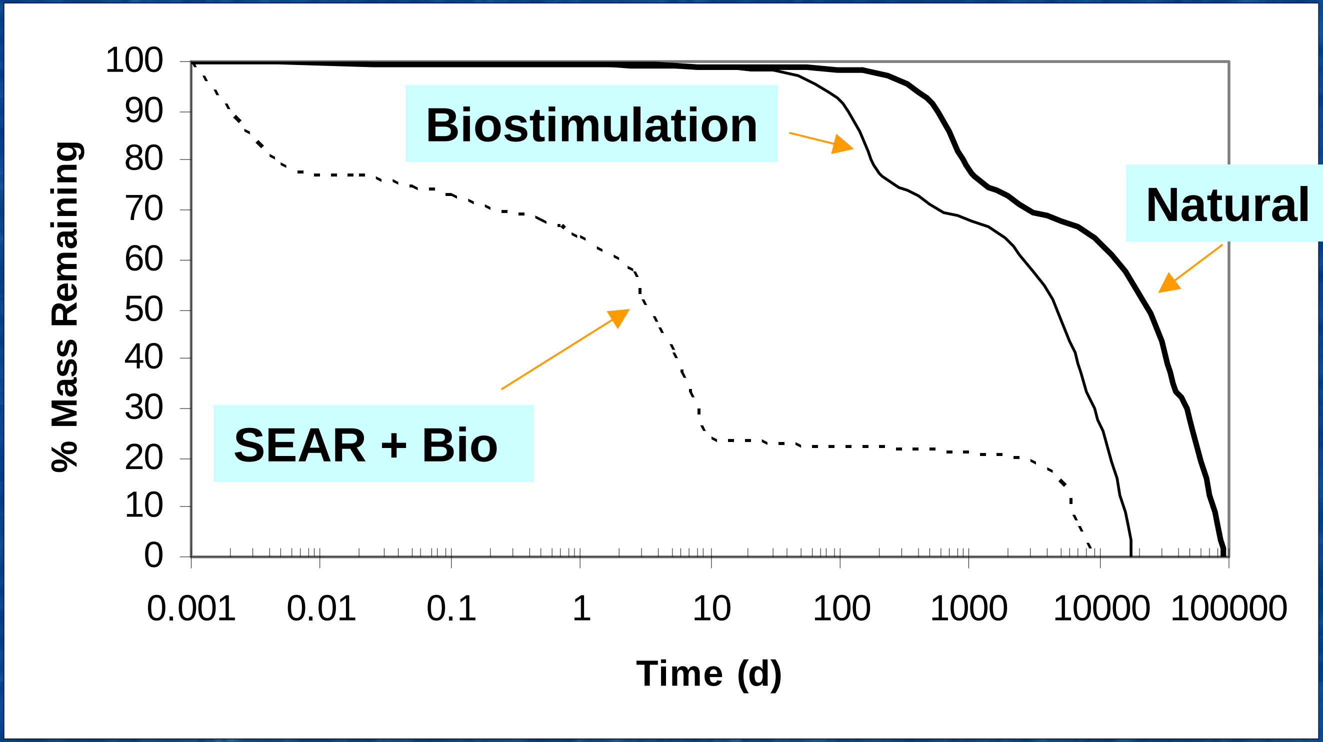
Bachman Road Down Gradient Monitoring Well Data: 450 days after treatment

Conc. (mg/L)	ML1-B 4.9m	ML1-E 6.8m	ML3-E 6.8m	ML5-A 2.9m	ML5-B 4.1m
PCE	5.20	0.13	2.60	0.02	0.17
TCE	0.56	NQ<0.001	4.00	0.12	0.05
cis-DCE	0.27	25.0	100	0.47	0.57
trans-DCE	NQ<0.001	0.084	0.540	NQ<0.001	NQ<0.001
VC	NQ<0.001	0.079	0.410	NQ<0.001	NQ<0.001
Tween 80	NQ<50.0	52.1	2750	NQ<50.0	NQ<50.0
Acetate (mM)	NQ<0.10	1.82	4.60	NQ<0.10	0.49

- PCE concentrations reduced by approximately 2 orders-of-magnitude in source zone.
- No concentration rebound observed 1 yr after test; attributed to post-treatment microbial activity.

Ramsburg, C.A., L.M. Abriola, K.D. Pennell, F.E. Löffler, M. Gamache, and B.K. Amos. 2004. Stimulated microbial reductive dechlorination following surfactant treatment at the Bachman road site. *Environmental Science and Technology*, 38:5902-5914.

Mathematical Modeling of Source Longevity: Potential Benefits of Combined Remedies



Christ, J.A., C.A. Ramsburg, L.M. Abriola, K.D. Pennell, and F.E. Löffler (2005). Coupling aggressive mass removal with microbial reductive dechlorination for remediation of DNAPL source zones: A review and assessment. *Environ. Health Perspectives,* 113:465-477.