# Analysis of Bacterial Random Motility and Chemotaxis in Porous Media using MRI

Mira Stone Olson, James A. Smith,
Roseanne M. Ford, Erik J. Fernandez

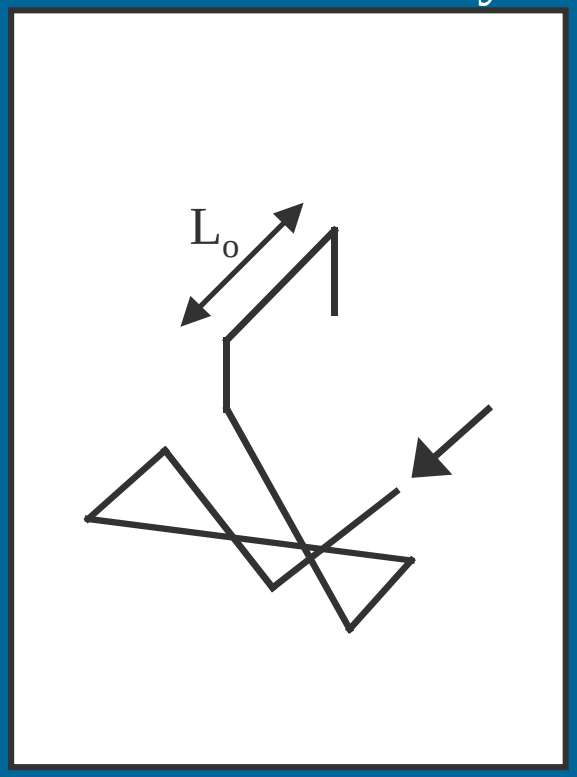
# Introduction

- Conventional pump-and-treat remediation systems often leave contamination in regions of low permeability (aquitards, clay lenses)
- Aquitards can act as long-term reservoirs for contaminants
- Contaminants diffuse into more permeable regions, creating a chemical gradient surrounding the layer of contamination
- *In situ* bioremediation is a common remediation technique, but is limited by bacterial transport

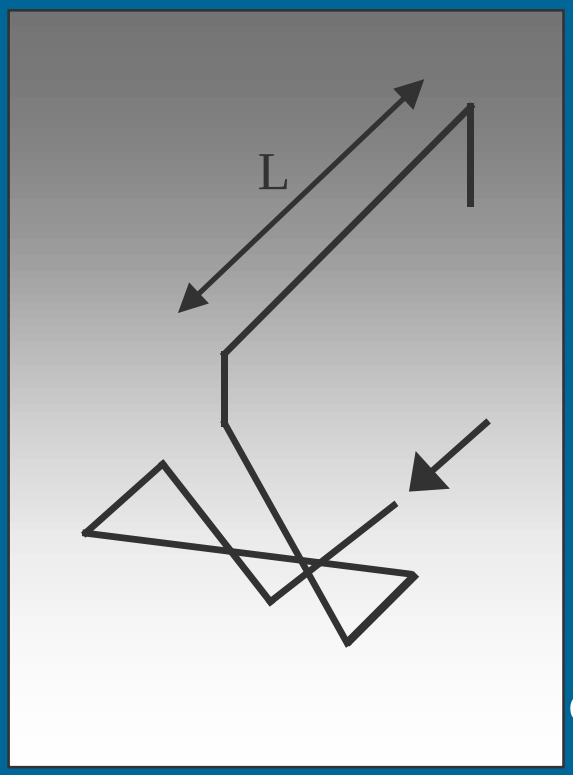
# Bacterial Chemotaxis

Chemotaxis is defined as the ability of bacteria to bias their motion towards regions of high contaminant concentration

Random Motility




Chemotaxis




increasing attractant concentration

Figure adapted from Macnab, R.M. (1980). Biological Regulation and Development. New York, Plenum

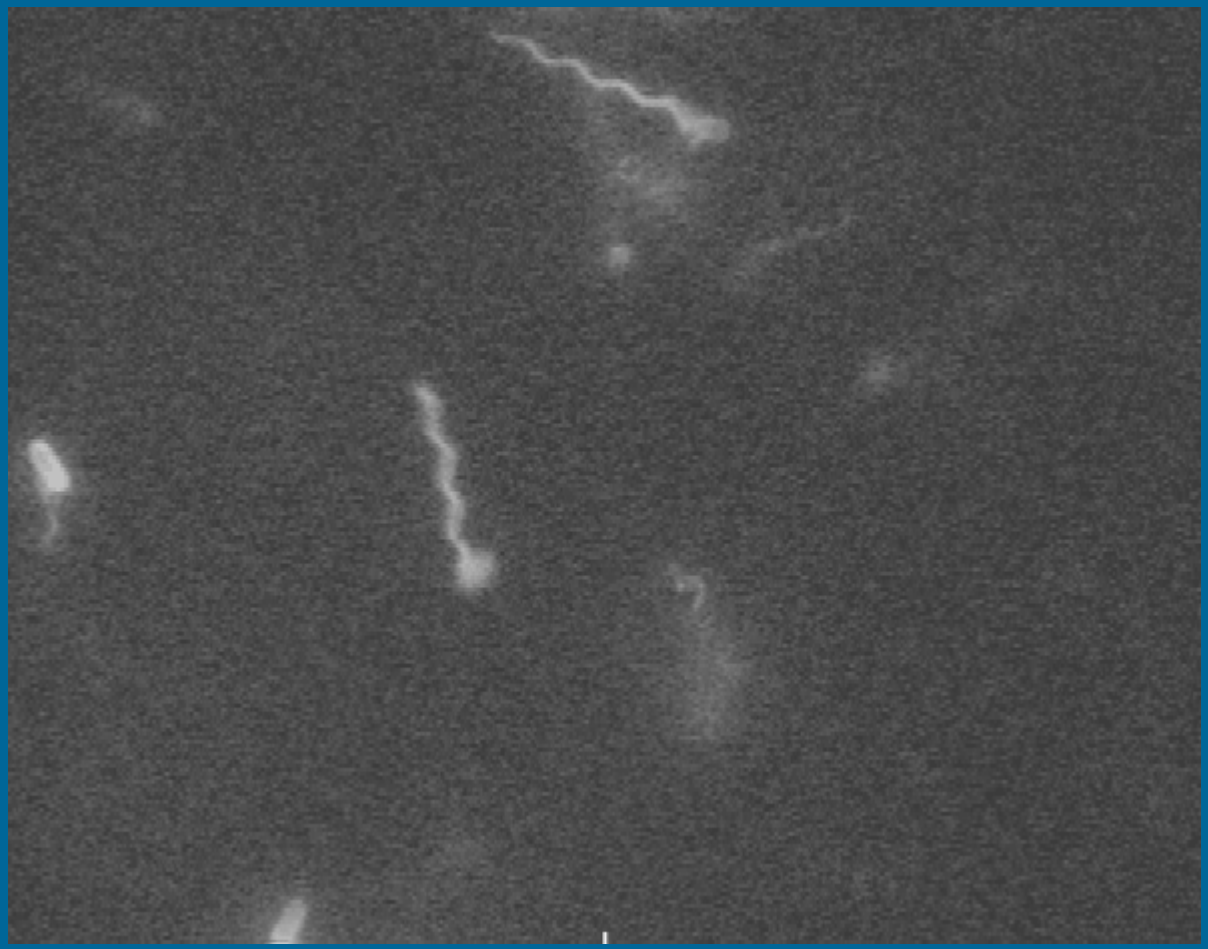
# Objective

- To study how chemotaxis affects the transport of motile bacteria through porous media in the presence of a contaminant gradient
  - Quantify the chemotactic response of *Pseudomonas putida* F1 to TCE
  - Use MRI to image the behavior of magnetically-labeled bacteria in a packed column

# Experimental System

- *Pseudomonas putida* F1 are a native soil-inhabiting bacterial strain
- Trichloroethylene (TCE) is a common and persistent ground-water contaminant
- *P. putida* exhibit chemotaxis towards TCE, but cannot use it as a growth substrate
- Porous medium is 250-300-µm-diameter glass-coated polystyrene beads

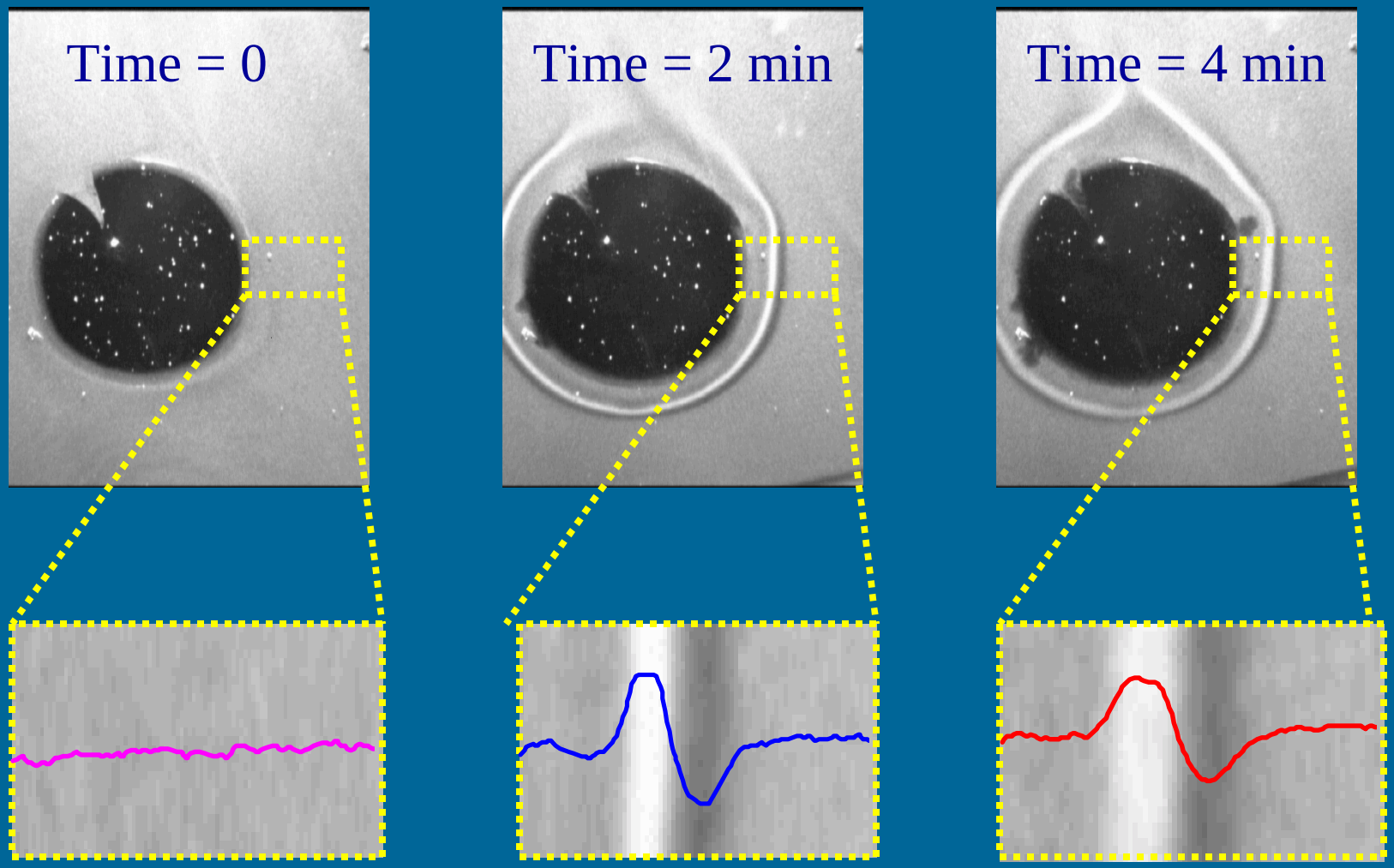
# Bacterial Swimming Properties



From Howard Berg, Rowland Institute of Science, ftp://ftp.rowland.org/pub/download/

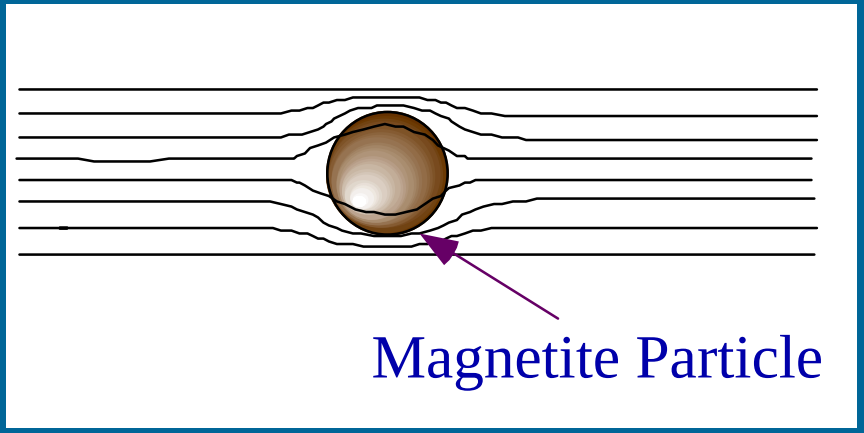
# Chemotaxis - Bulk Response

Chemotaxis of *P. putida* to TCE

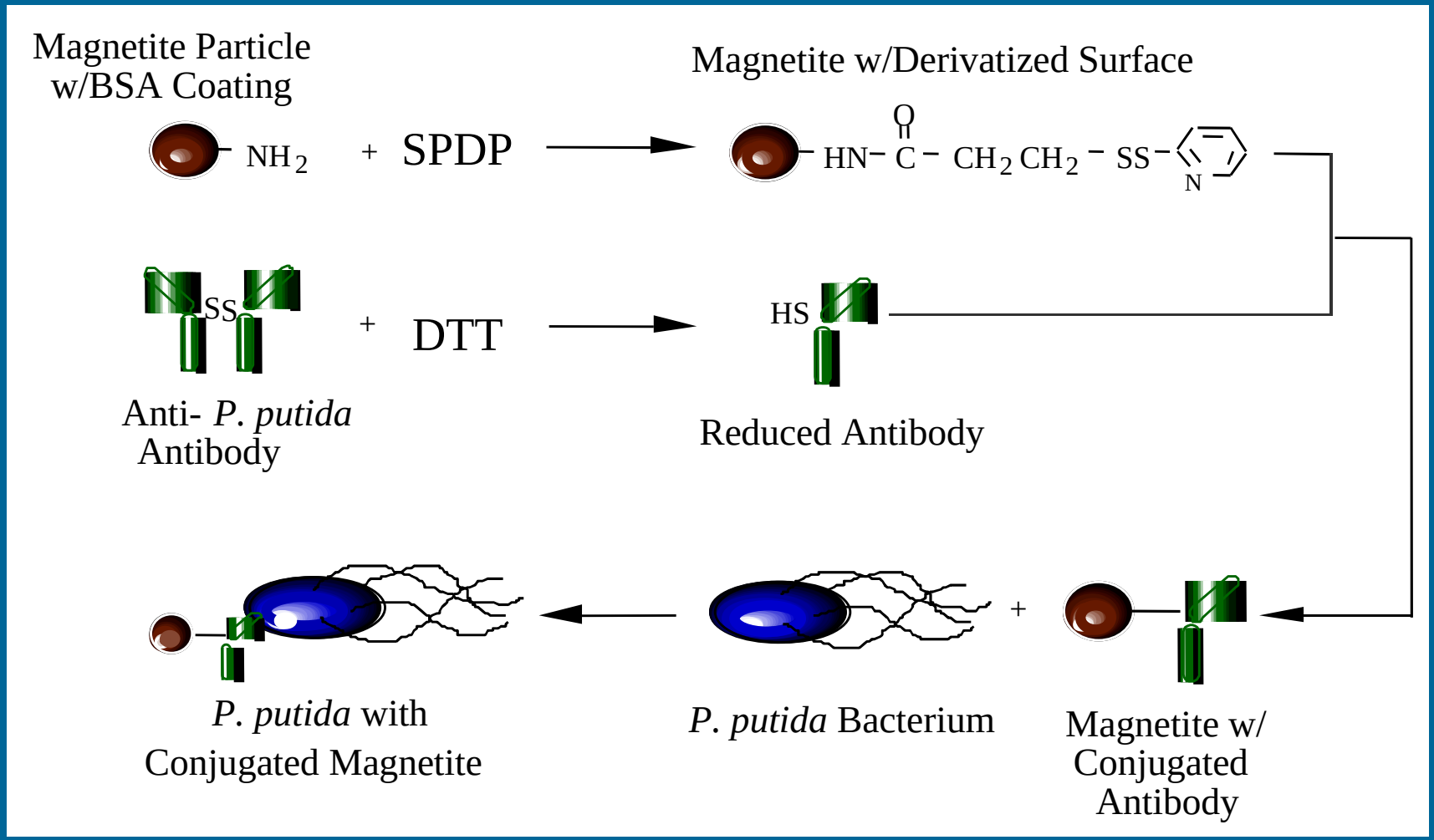


# Overview of Magnetic Resonance Imaging

- Non-invasive technique for taking measurements in an opaque medium
- Signal is based on H nuclei (protons) in water
- Bacteria can be labeled with contrast medium to make them stand out
- Magnetite causes local magnetic field gradients which cause signal attenuation



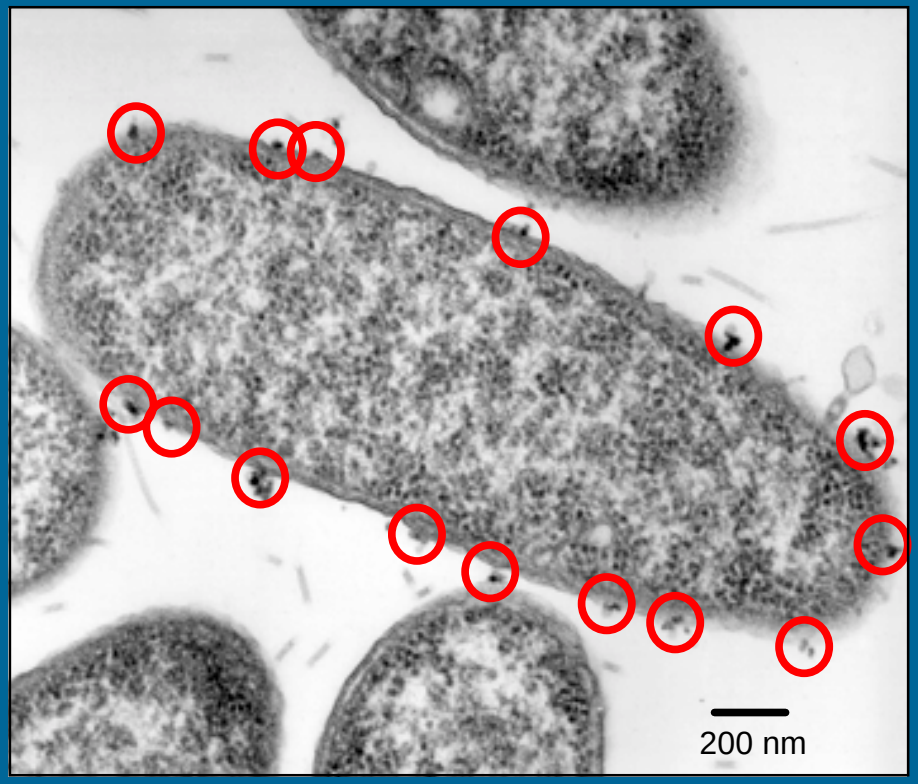
# Bacterial Labeling Procedure




Labeling technique adapted from Nakamura et al., 1993

Antibody to *P. putida* supplied by M.I. Ramos-Gonzalez (CSIC)

# Attached Magnetite




*E. Coli* Bacterium with attached magnetite

# Outline of Experiments

- One-dimensional bacterial transport with no flow:

$$\frac{\partial b}{\partial t} = \frac{1}{\tau}\mu_{bulk}\frac{\partial^2 b}{\partial x^2} - \frac{\partial (v_c b)}{\partial x}$$

$$v_c = \frac{2}{3\tau} v \cdot \tanh\left(\frac{\chi_o}{2v}\frac{K_d}{(K_d + a)^2}\frac{\partial a}{\partial x}\right)$$

$b$ = bacterial concentration
$\tau$ = tortuosity
$\mu_{bulk}$ = motility coefficient
$v_c$ = chemotactic velocity

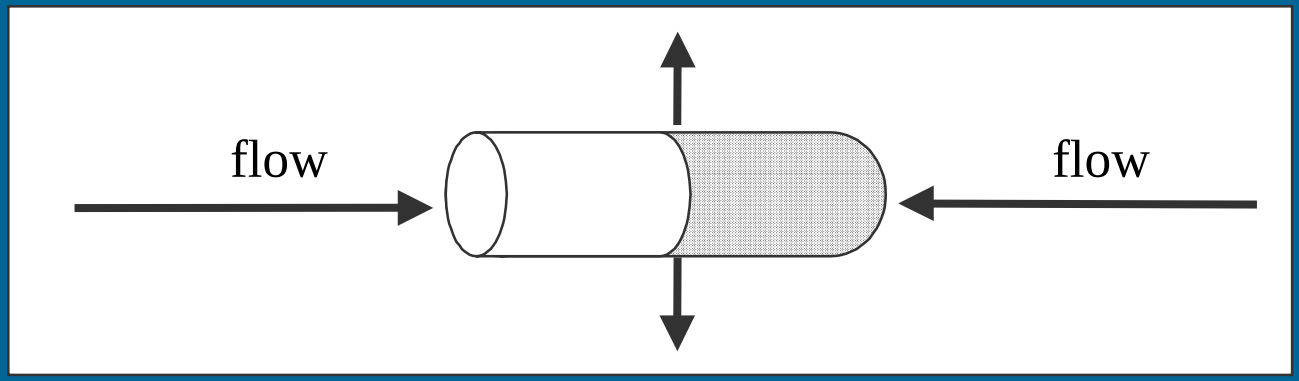
$v$ = bacterial swimming speed
$\chi_o$ = chemotactic sensitivity
$K_d$ = effective dissociation constant
$a$ = TCE concentration

» 1. $MnCl_2$ Experiments to Determine Tortuosity, $\tau$

» 2. Bacterial Motility Experiments to Determine Random Motility Coefficient, $\mu_{bulk}$

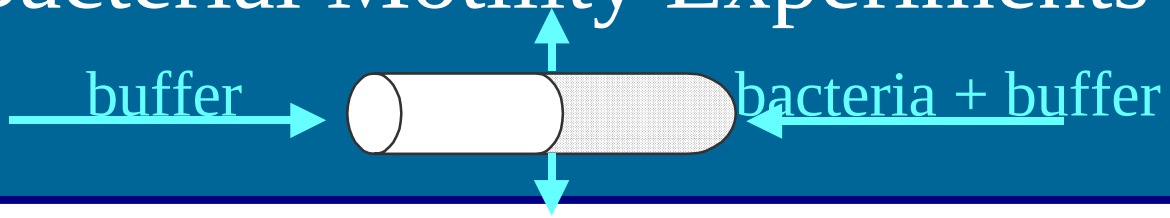
» 3. Bacterial Chemotaxis Experiments to Determine Chemotactic Sensitivity Coefficient, $\chi_o$

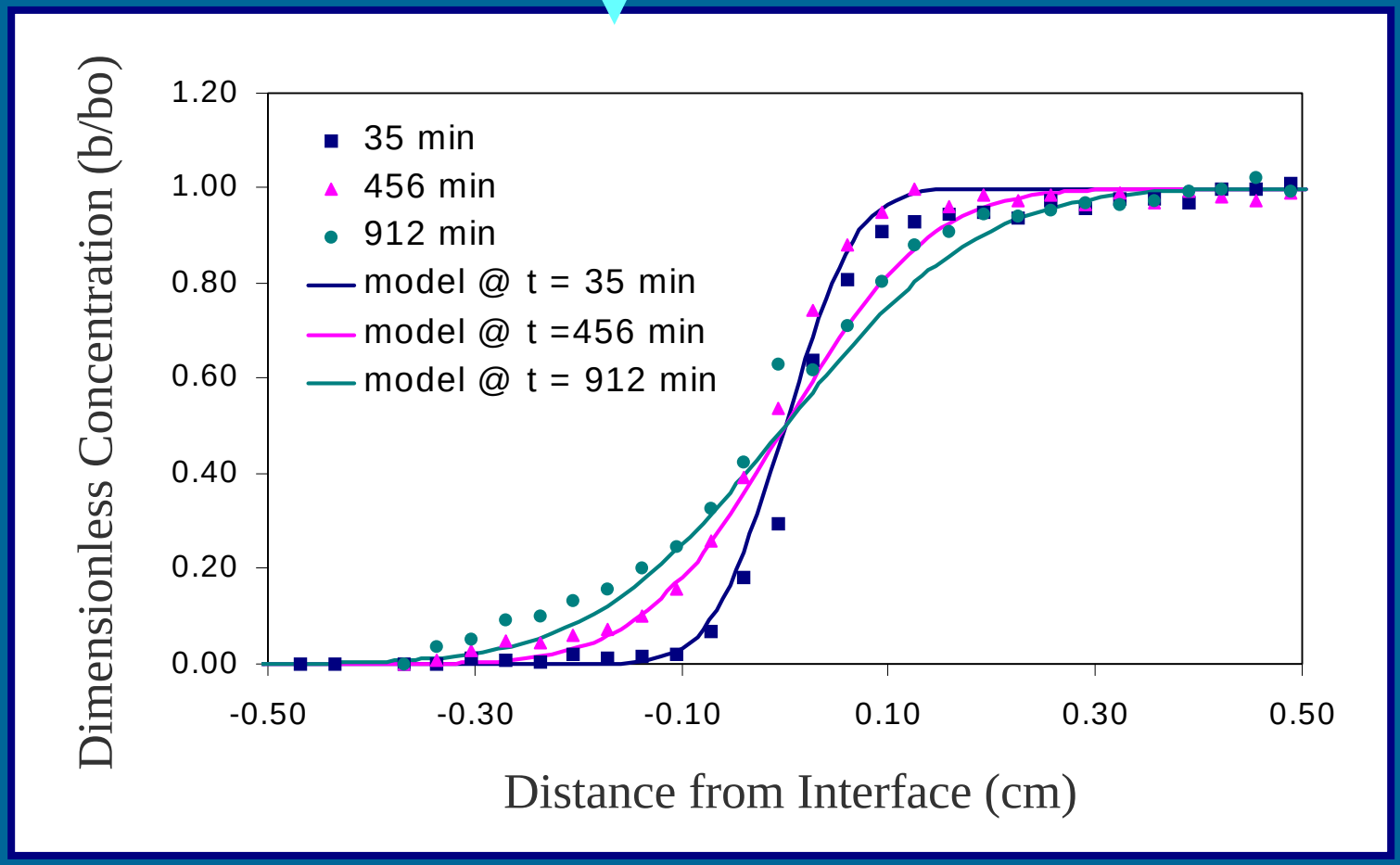
# Experimental Design




- Pre-treat column with unlabeled bacteria
- Set up column with initial step change of bacteria (for random motility experiments) and TCE (for chemotaxis experiments)
- Image column for 17 hours to obtain spatial bacterial concentration profiles over time
- Bacterial concentrations are correlated to reduction in signal caused by contrasting agent (magnetite)

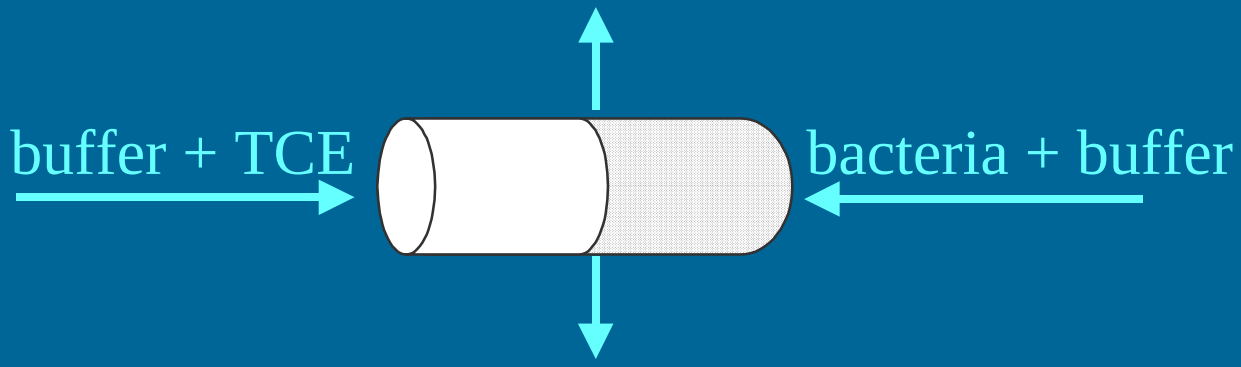
# Bacterial Motility Experiments




Random Motility of *P. putida* F1, $\mu = 1.14 \times 10^{-6}$ cm$^2$/sec, assuming a tortuosity of $\tau = 6.71$

# Chemotaxis Experiments

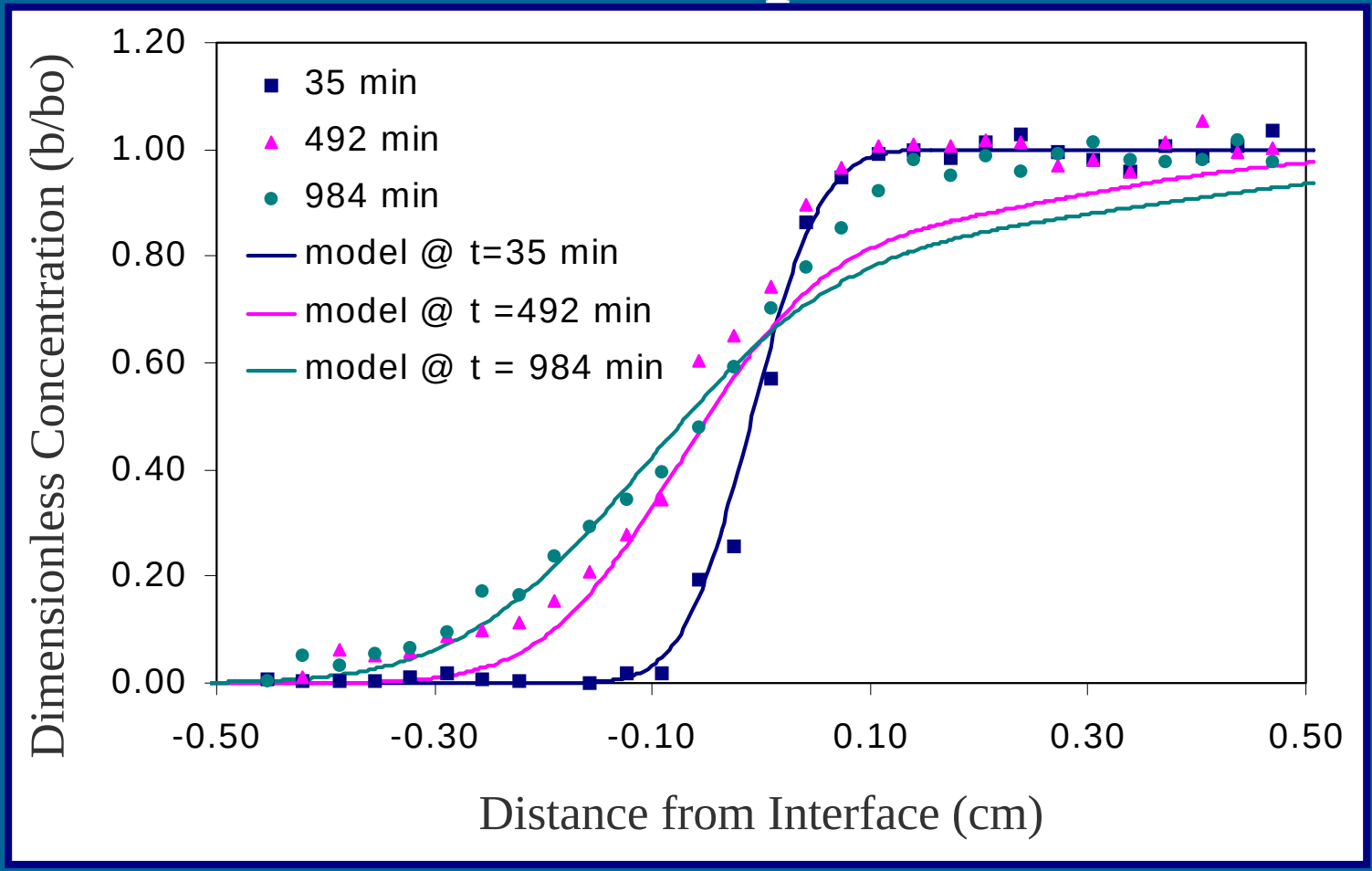



$$\frac{\partial b}{\partial t} = \frac{\mu_{bulk}}{\tau}\frac{\partial^2 b}{\partial x^2} - \frac{\partial (v_c b)}{\partial x} \qquad v_c = \frac{2}{3\tau} v \cdot \tanh\left( \frac{\chi_o}{2v} \frac{K_d}{(K_d + a)^2} \frac{\partial a}{\partial x} \right)$$

$v_c$ = chemotactic velocity $\chi_o$ = chemotactic sensitivity coefficient
$K_d$ = equilibrium dissociation constant $a$ = TCE concentration

- Given the column tortuosity and the bacterial random motility coefficient, we solve the bacterial transport equation for the chemotactic sensitivity coefficient, $\chi_o$

# Chemotaxis Experiments




Chemotactic Sensitivity of *P. putida* F1 to TCE, $\chi_o = 2.9 \times 10^{-4}$ $cm^2/sec$, assuming a random motility coefficient of $\mu = 1.14 \times 10^{-6}$ $cm^2/sec$ and a tortuosity of $\tau = 6.71$

# Conclusions

- A noninvasive imaging technique was used to quantify bacterial transport through porous media
- Preliminary data suggests that the increased accumulation of bacteria in regions of favorable contaminant concentration is due to chemotaxis
- Numerical simulations predict the following parameters:
  - Column tortuosity, $\tau = 6.71 \pm 0.25$
  - Random Motility of *P. putida* F1, $\mu = 1.14 \times 10^{-6}$ $cm^2/sec$
  - Chemotactic Sensitivity of *P. putida* F1 to TCE, $\chi_o = 2.9 \times 10^{-4}$ $cm^2/sec$