Geocentrifuge Studies of Flow and Transport in Porous Media

Carl D. Palmer
Idaho National Laboratory
Earl D. Mattson
Idaho National Laboratory
Robert W. Smith
University of Idaho

Environmental Remediation Sciences Program
PI Meeting
Airlee Conference Center, Warrenton, VA
April 3-5, 2005

Idaho National Laboratory

INL Geocentrifuge

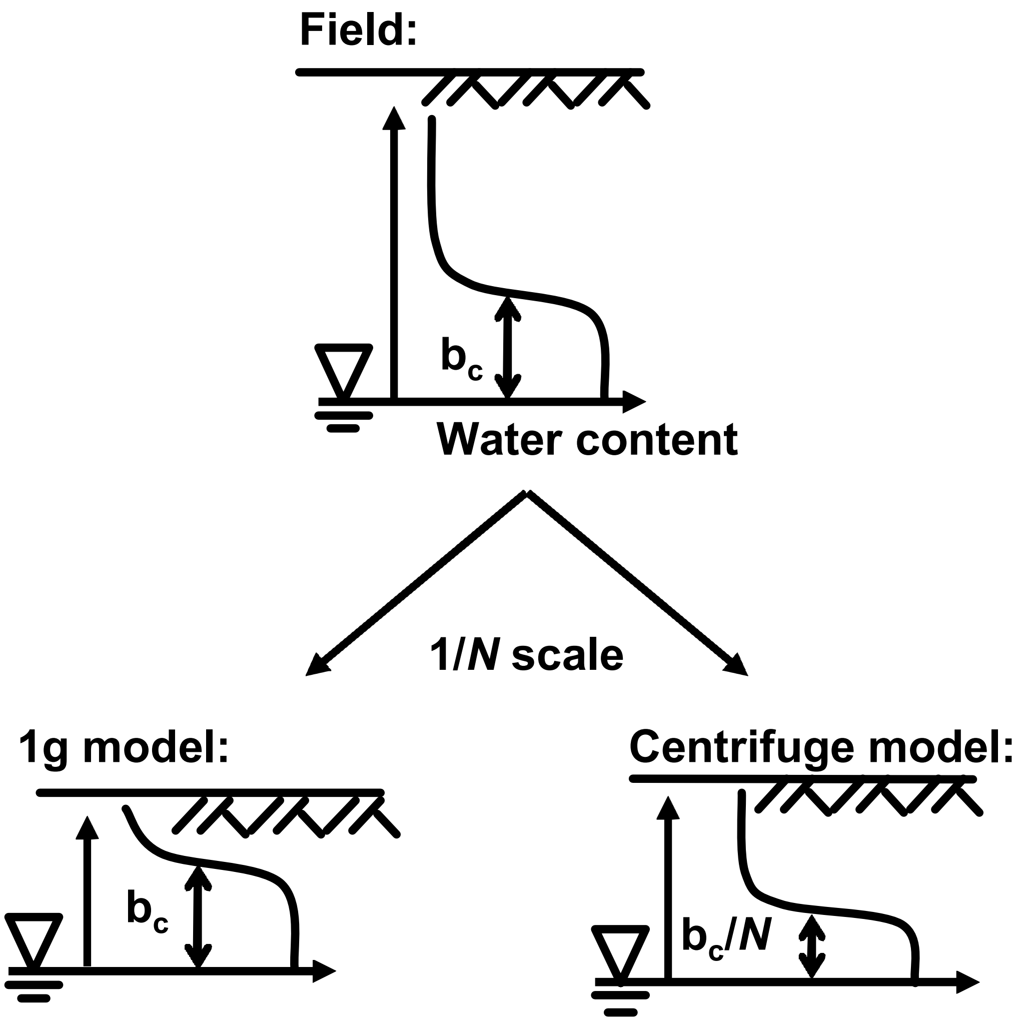
- Actidyn Systemes
- 2-meter radius
- 5-130 g acceleration

Idaho National Laboratory

Motivation for Geocentrifuge

- Decrease the time required to complete an experiment compared to 1g experiments.
- Obtain spatial scaling real-world problems according to the acceleration.
- Study a wider range of conditions than is capable under 1g acceleration.

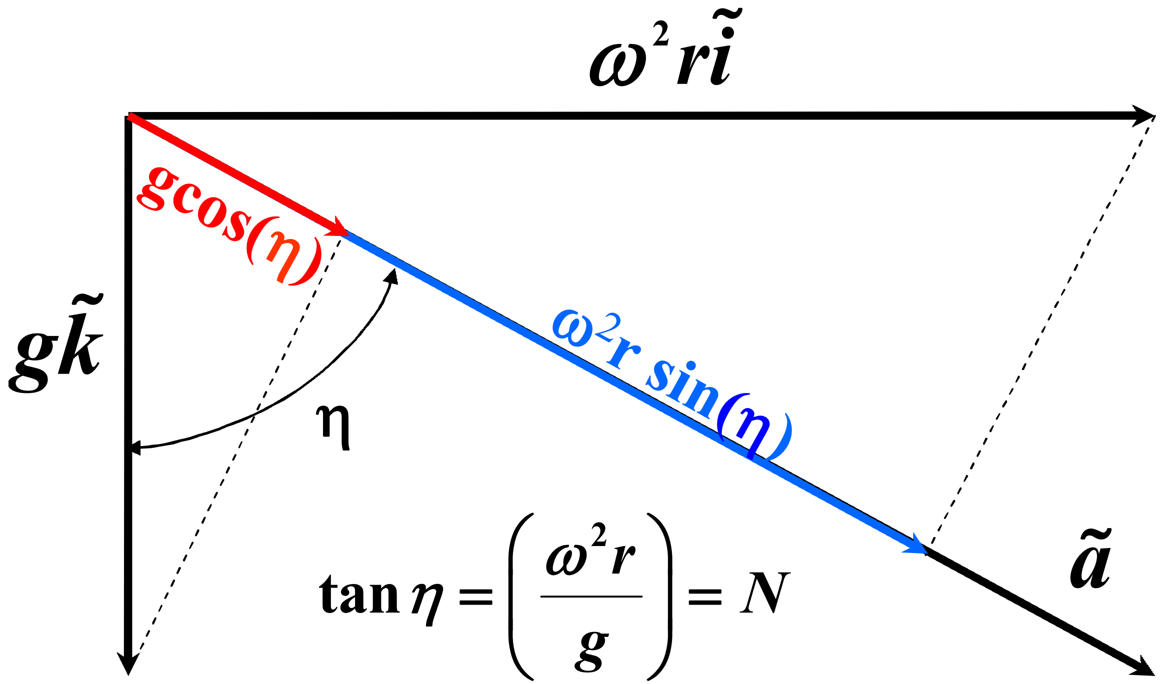
Vadose Zone Transport



Scaling Factors

Gravity	$1/N$
Length	N
Velocity	$1/N$
Time	N^2
Decay Rate	$1/ N^2$
Dispersion	*1*
Porosity	*1*
Temperature	*1*
Pressure	*1*
Density	*1*
Viscosity	*1*
Mass Fractions	*1*

Accelerations



$$\tan\eta = \left(\frac{\omega^2 r}{g}\right) = N$$

Fluid Potential

Velocity Term

$$\phi = -\frac{\omega^2 r^2}{2} + 2\omega u_r(\theta - \omega t) + gz + \frac{\tilde{u} \cdot \tilde{u}}{2} + \frac{p}{\rho_f}$$

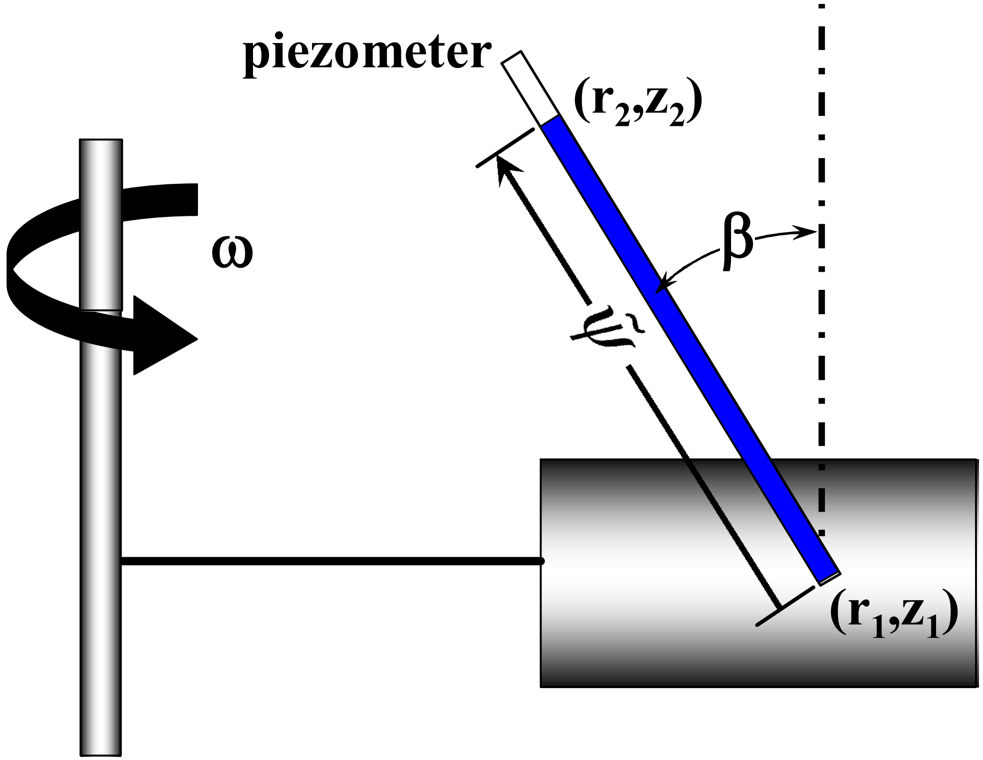
Centripetal Force — Coriolis Term — Gravitational Term — Work-Pressure Term

If Coriolis term is insignificant , velocity is small, and steady-state flow:

$$\boxed{\phi = -\frac{\omega^2 r^2}{2} + gz + \frac{p}{\rho_f}}$$

Pressure and Piezometers

$$p = p_c + p_g = -\rho_f \omega^2 (r_2^2 - r_1^2) + \rho_f g (z_2 - z_1)$$



$$p = -\rho_f \left[\left(\omega^2 \sin^2 \beta \right) \psi^2 - \left(2\omega^2 r_1 \sin\beta + g\cos\beta \right) \psi \right]$$

Pressure and Piezometers

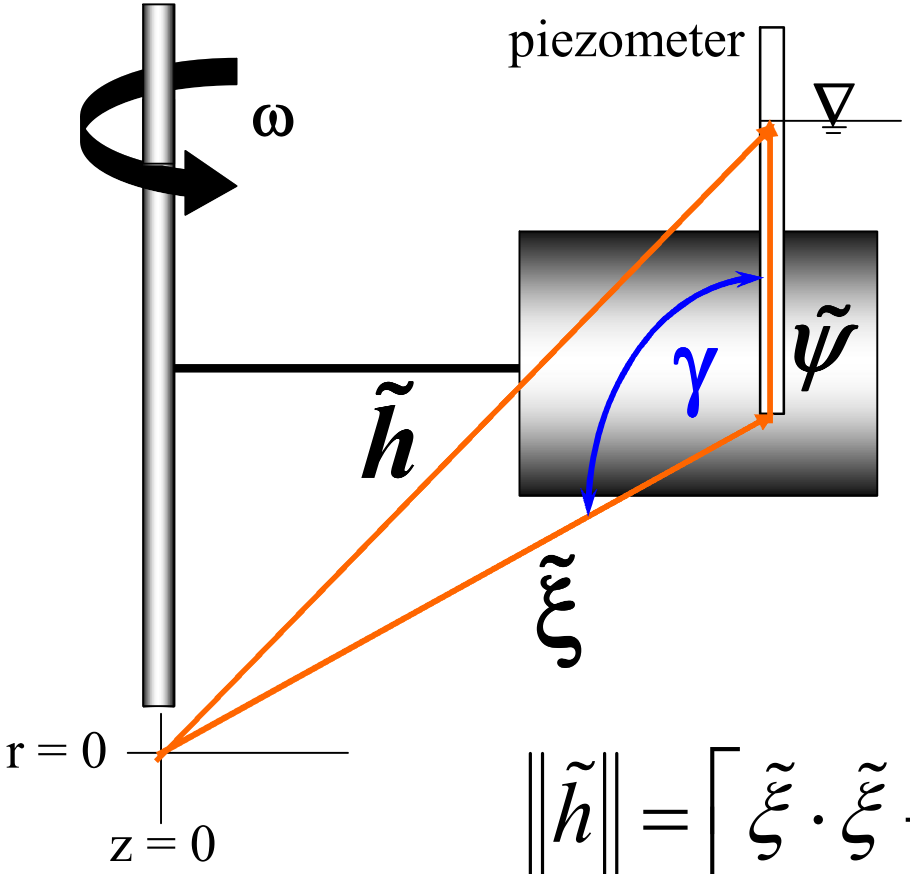
For $\beta = \pi / 2$

$$\psi_{\pi/2} = r\left(1 - \sqrt{1 - \frac{p}{\rho_f \omega^2 r^2}}\right)$$

For $\beta = 0$

$$\psi_0 = \frac{p}{\rho_f g}$$

Elevation Head and Hydraulic Head



$$\tilde{h} = \tilde{\xi} + \tilde{\psi}$$

$$\left\|\tilde{h}\right\| = \left[\tilde{\xi}\cdot\tilde{\xi} + \tilde{\psi}\cdot\tilde{\psi} + 2\left(\tilde{\xi}\cdot\tilde{\psi}\right)\right]^{1/2}$$

$$= \left[\left\|\tilde{\xi}\right\|^2 + \left\|\tilde{\psi}\right\|^2 + 2\left\|\tilde{\xi}\right\|\left\|\tilde{\psi}\right\|\cos\gamma\right]^{1/2}$$

Specific Discharge

$$\tilde{q} = -\frac{\rho_f}{\mu}\overline{\overline{k}}\tilde{\nabla}\phi$$

$$q_r = -\frac{\rho_f}{\mu}\left[k_{rr}\left(-\omega^2 r + \frac{1}{\rho_f}\frac{\partial p}{\partial r}\right) + k_{rz}\left(g + \frac{1}{\rho_f}\frac{\partial p}{\partial z}\right)\right]$$

$$q_z = -\frac{\rho_f}{\mu}\left[k_{zr}\left(-\omega^2 r + \frac{1}{\rho_f}\frac{\partial p}{\partial r}\right) + k_{zz}\left(g + \frac{1}{\rho_f}\frac{\partial p}{\partial z}\right)\right]$$

Specific Discharge

$$q_r = -\frac{k_{rr}\rho_f}{\mu}\left[-\omega^2 r - \left(2\omega^2 \sin^2\beta\right)\psi\frac{\partial\psi}{\partial r} + (2\omega^2 \sin\beta)\psi + \left(2\omega^2 r \sin\beta + g\cos\beta\right)\frac{\partial\psi}{\partial r}\right]$$

$$q_z = -\frac{k_{zz}\rho_f}{\mu}\left[g - \left(2\omega^2 \sin^2\beta\right)\psi\frac{\partial\psi}{\partial z} + \left(2\omega^2 r \sin\beta + g\cos\beta\right)\frac{\partial\psi}{\partial z}\right]$$

Specific Discharge

For $\beta = \pi / 2$

$$q_r = -\frac{k_{rr}\rho_f\omega^2}{\mu}\left[\left(2\psi - r\right) + 2\left(r - \psi\right)\frac{\partial\psi}{\partial r}\right]$$

$$q_z = -\frac{k_{zz}\rho_f}{\mu}\left[g + 2\omega^2\left(r - \psi\right)\frac{\partial\psi}{\partial z}\right]$$

Specific Discharge

For $\beta = 0$

$$q_r = -\frac{k_{rr}\rho_f g}{\mu}\left[-\frac{\omega^2 r}{g} + \frac{\partial \psi}{\partial r}\right] = -K_{rr}\left[-N + \frac{\partial \psi}{\partial r}\right]$$

$$q_z = -\frac{k_{zz}\rho_f g}{\mu}\left(1 + \frac{\partial \psi}{\partial z}\right) = -K_{zz}\left(1 + \frac{\partial \psi}{\partial z}\right)$$

Non-dimensionalization of the Navier-Stokes Equation for Flow in a Centrifugal Field

Or

$$\frac{\partial^2 u^*}{\partial r^{*2}} - \frac{2}{Ek} u^* = \frac{1}{Ek\,Ro} r^* + \frac{\partial p^*}{\partial r^*}$$

where

$$Ek = \nu / \omega r_0^2 = \frac{\text{viscous force}}{\text{Coriolis force}}$$

Ekman Number

$$Ro = V_0 / \omega r_0 = \frac{\text{inertial forces}}{\text{Coriolis force}}$$

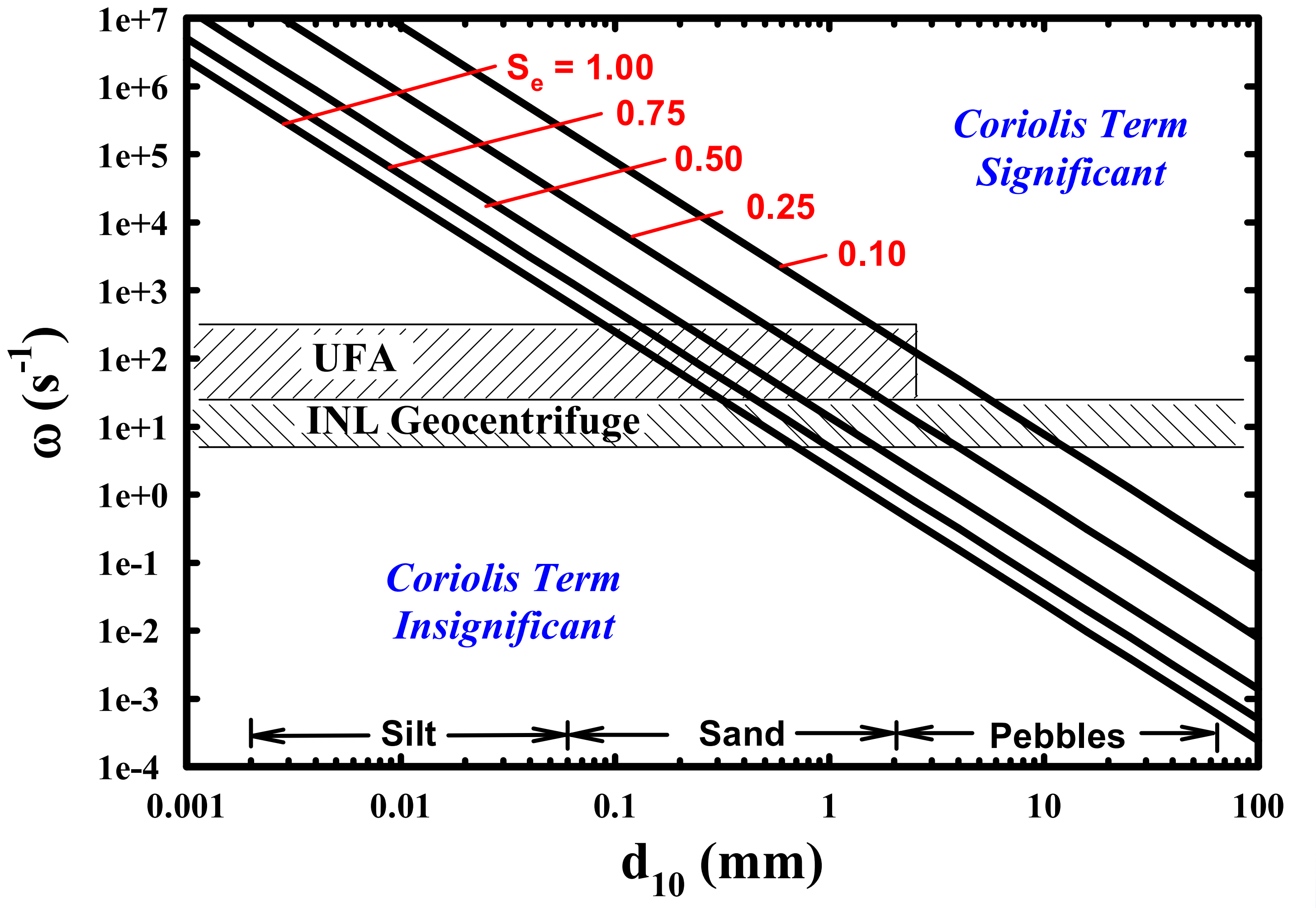
Rossby Number

Coriolis Effects

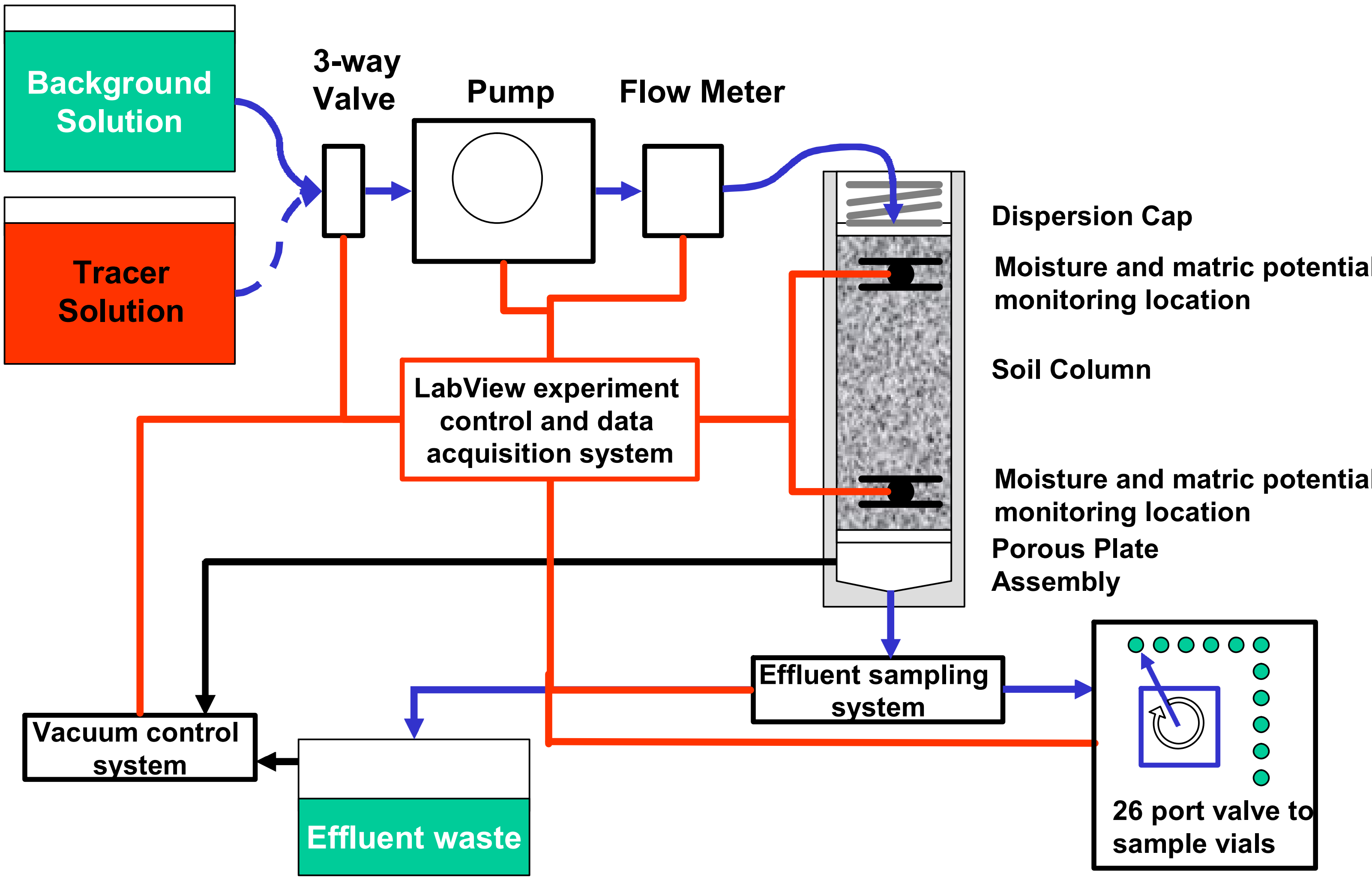
Coriolis effects can be ignored if:

$$\frac{2Ro}{r^*/u^*} = \frac{2u}{\omega r} \gg 1$$

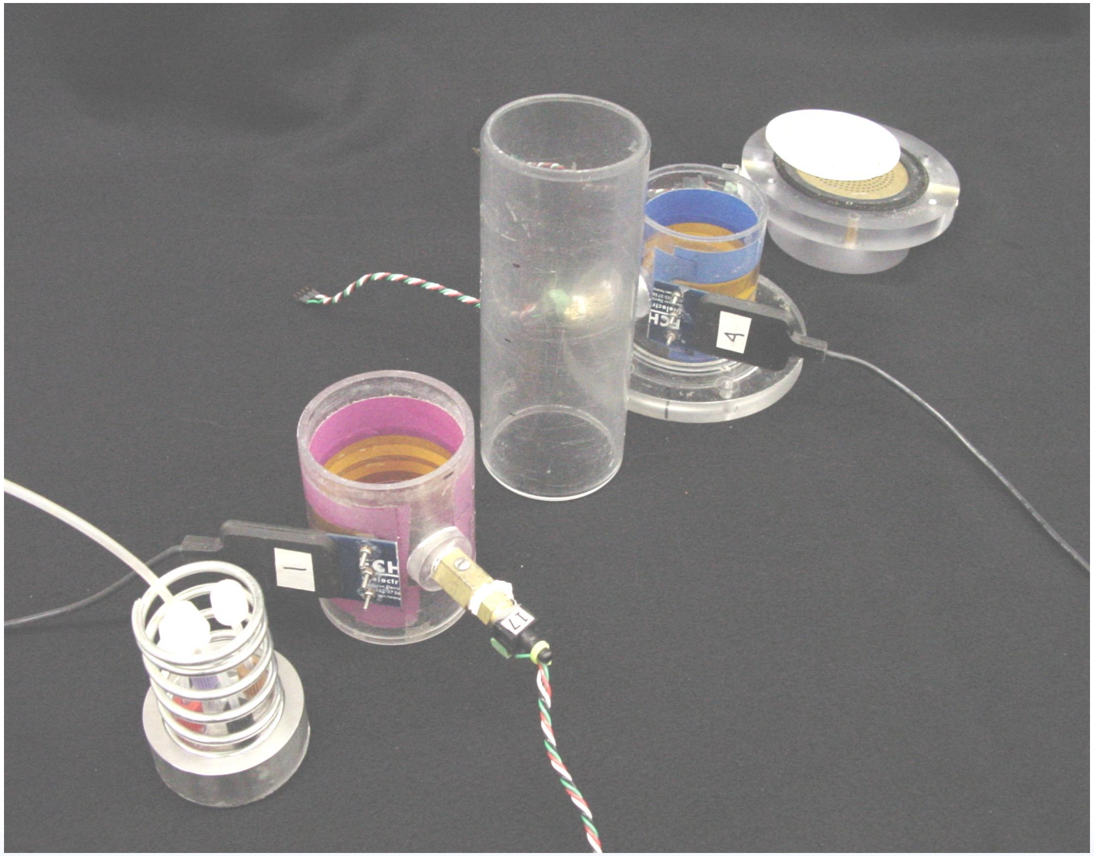
Coriolis Effects



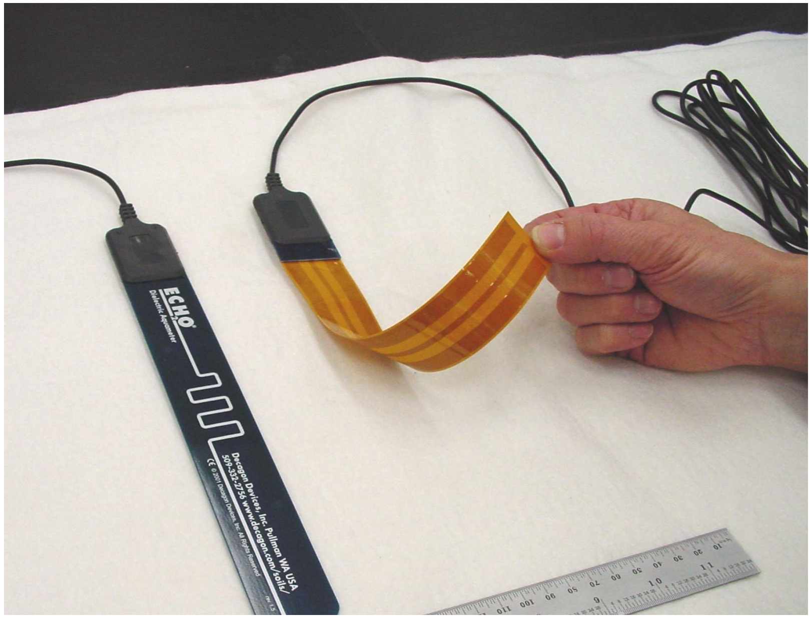
Column Design Schematic



Columns

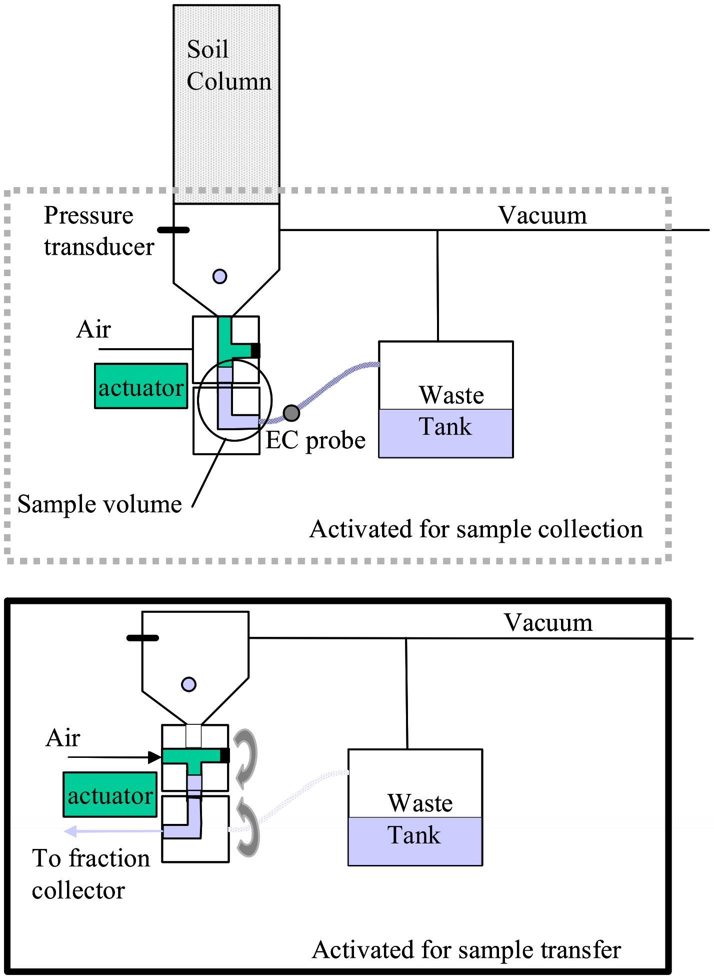


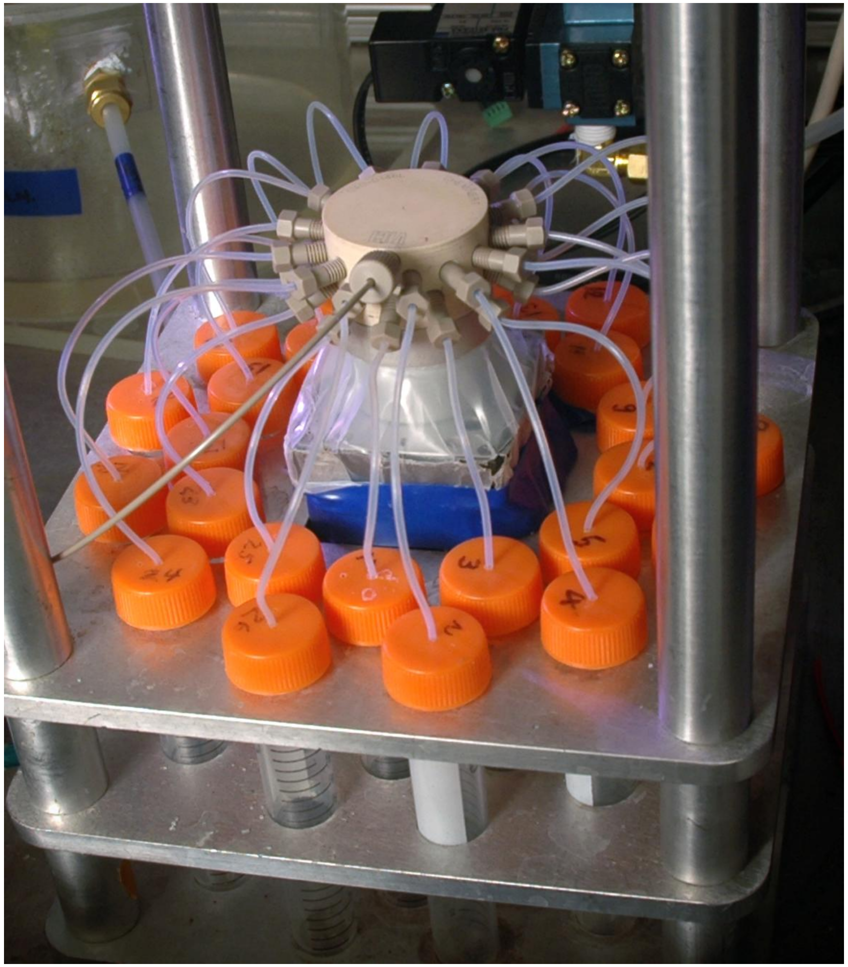
New Flexible Moisture Probe Design



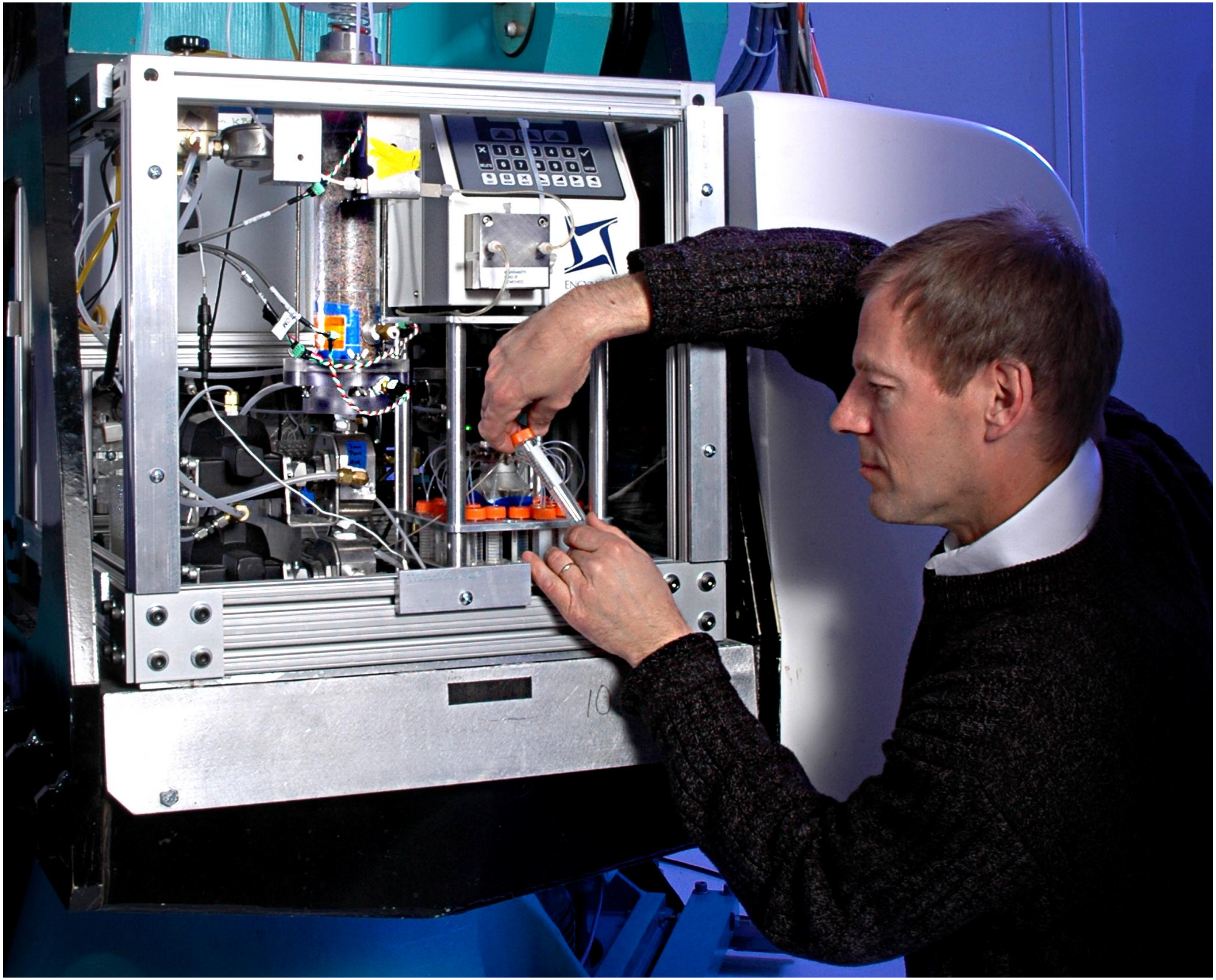
a) b) c) d)

Fraction Collector Designed to withstand High Accelerations

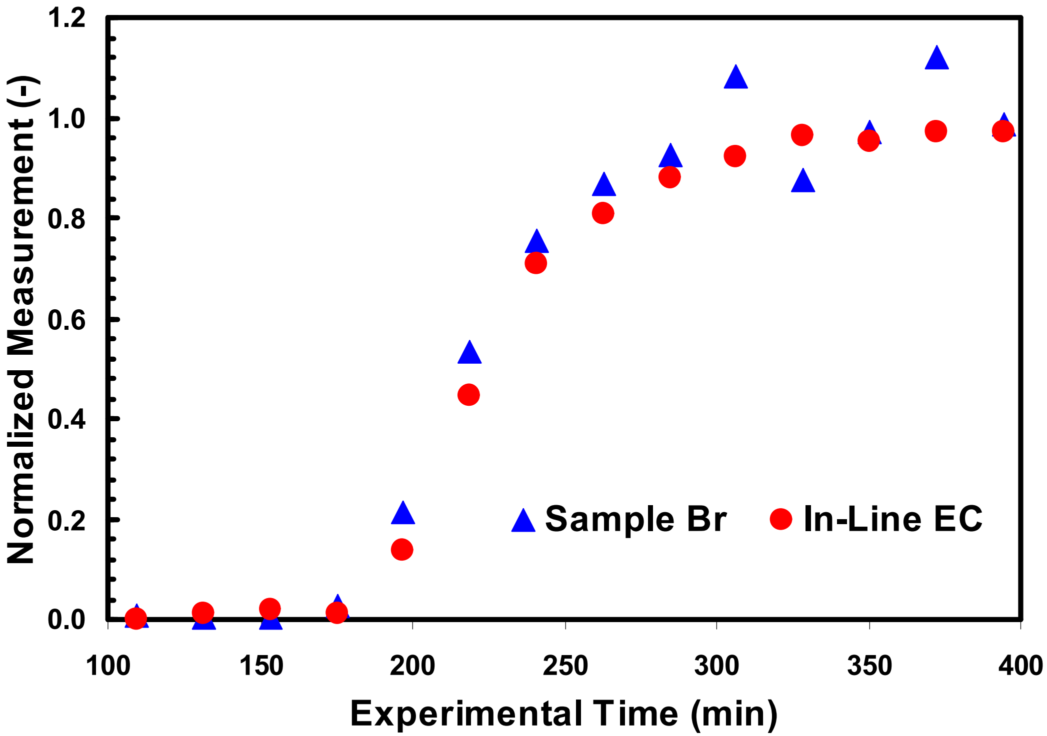




Column Experiments



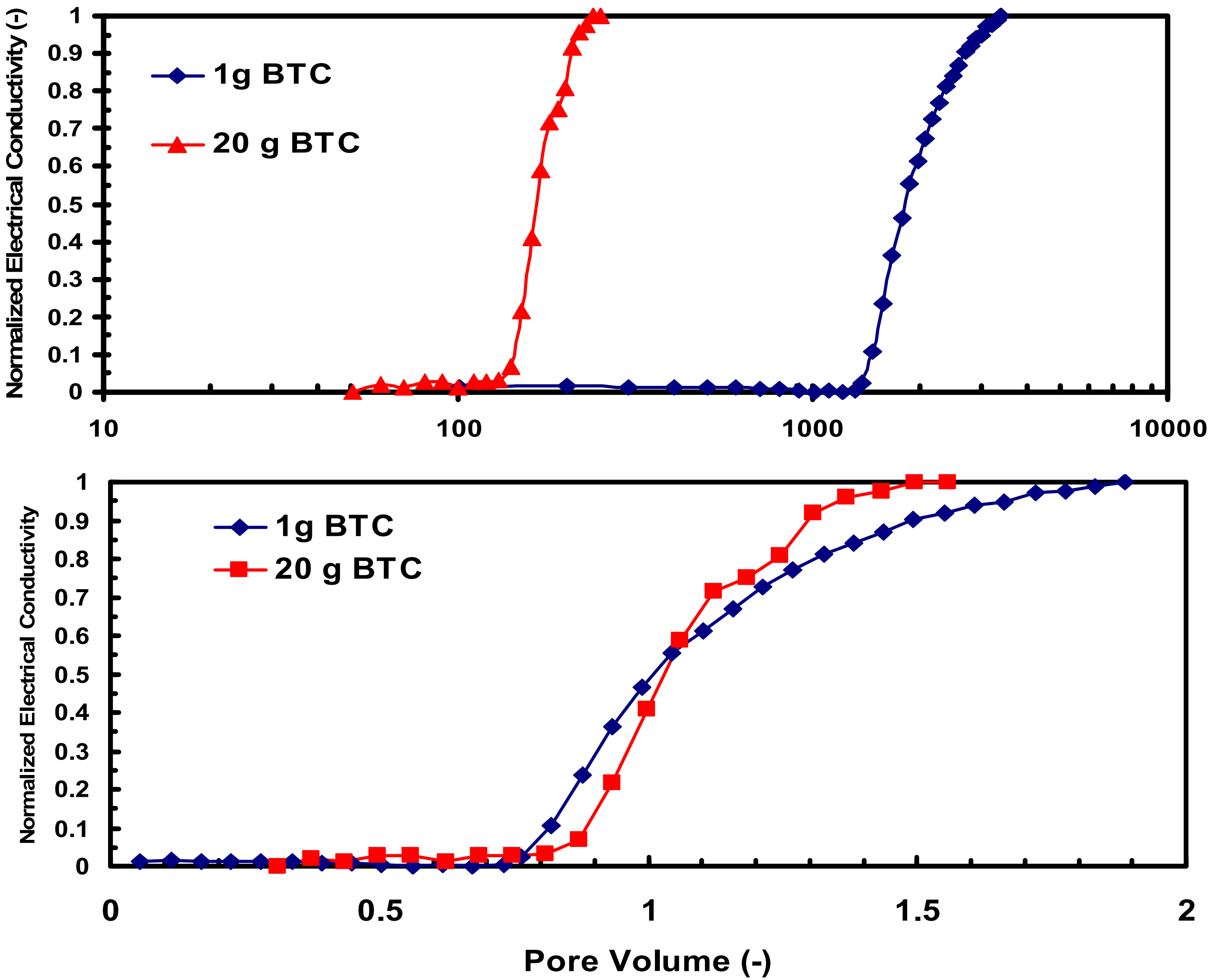
Column Experiments



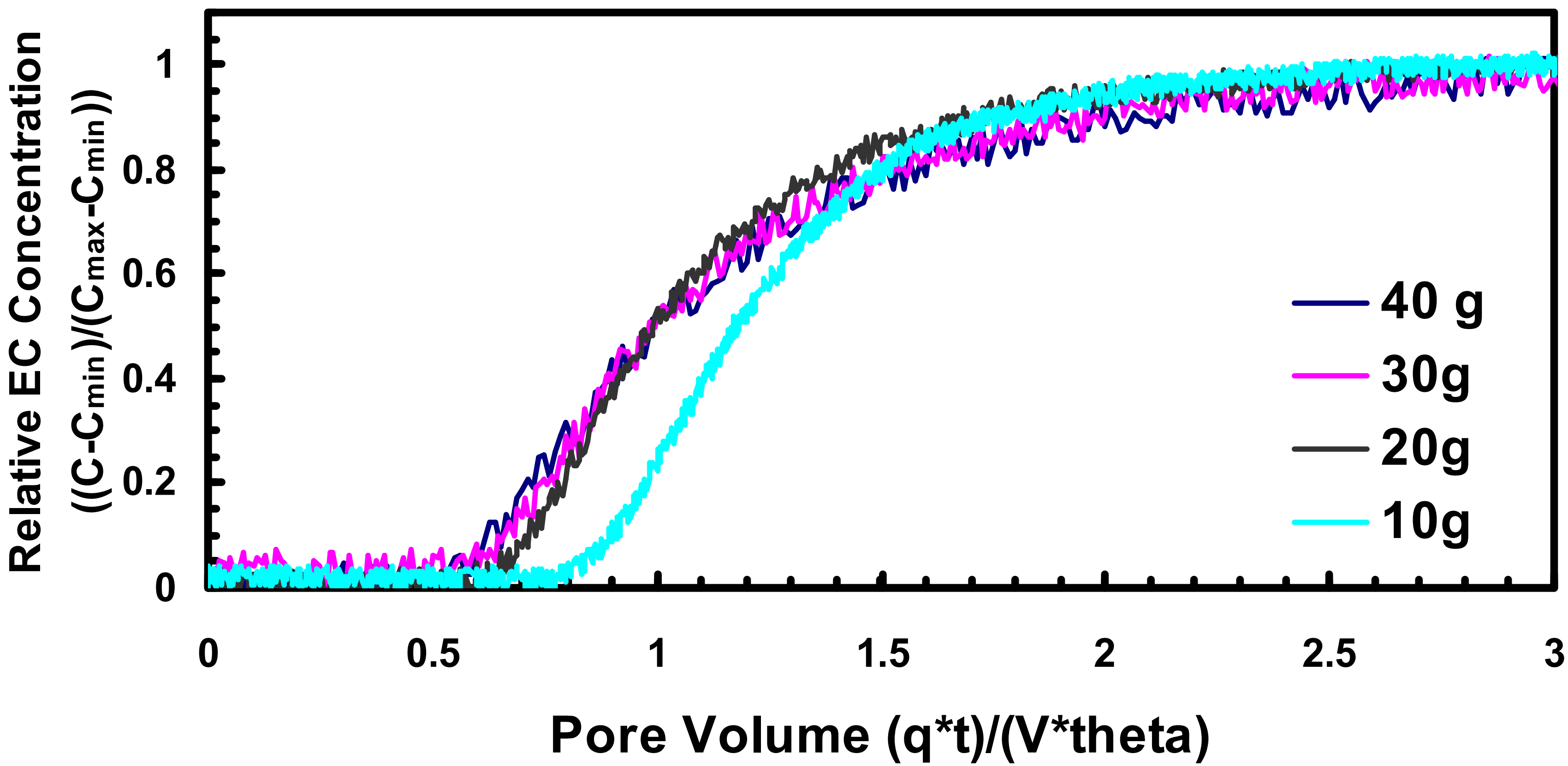
	Analysis of Normalized Br effluent sample concentrations	Analysis of Normalized in-line electrical conductivity measurements
Regressed velocity ($cm\ min^{-1}$)	0.140	0.135
Regressed dispersion ($cm^2\ min^{-1}$)	0.0437	0.0517

Idaho National Laboratory

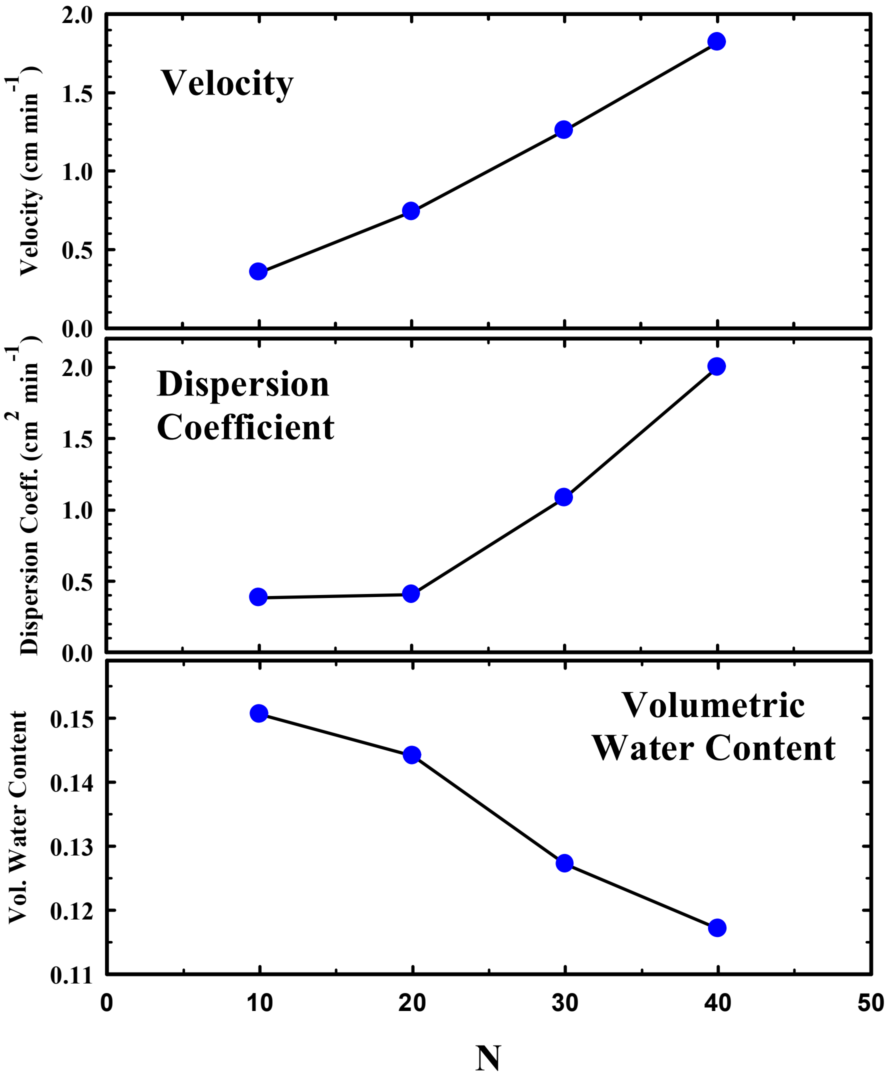
Comparison of 20-g and 1-g Experiments

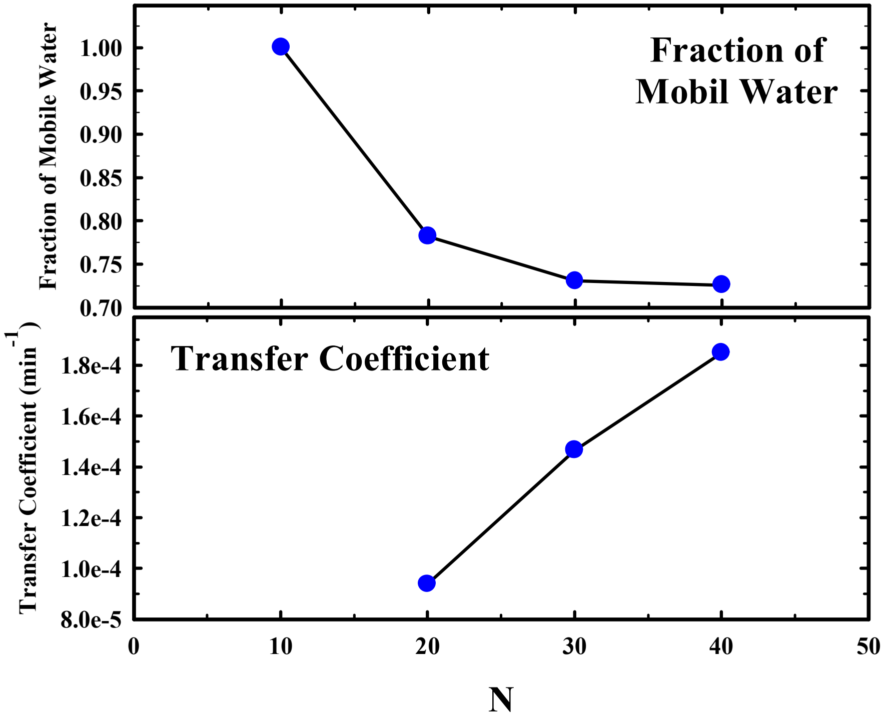


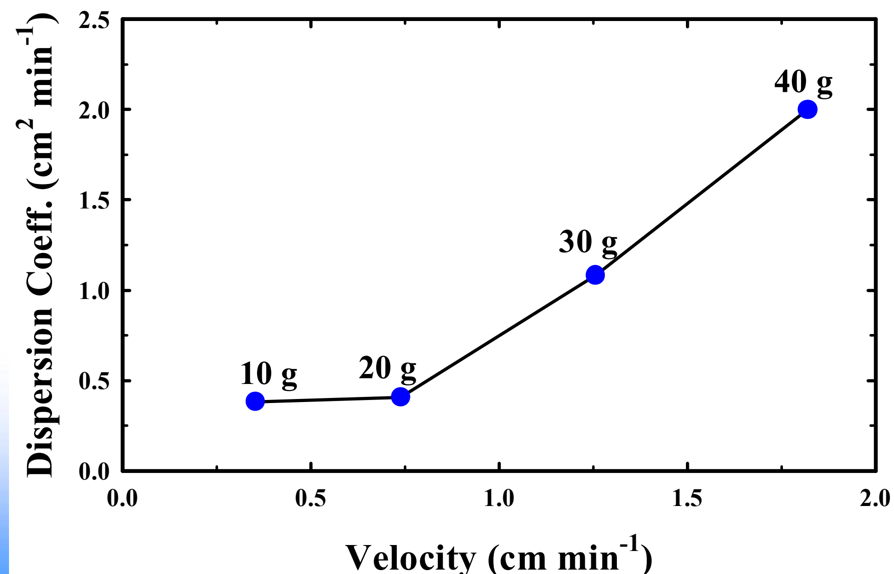
Column Experiments



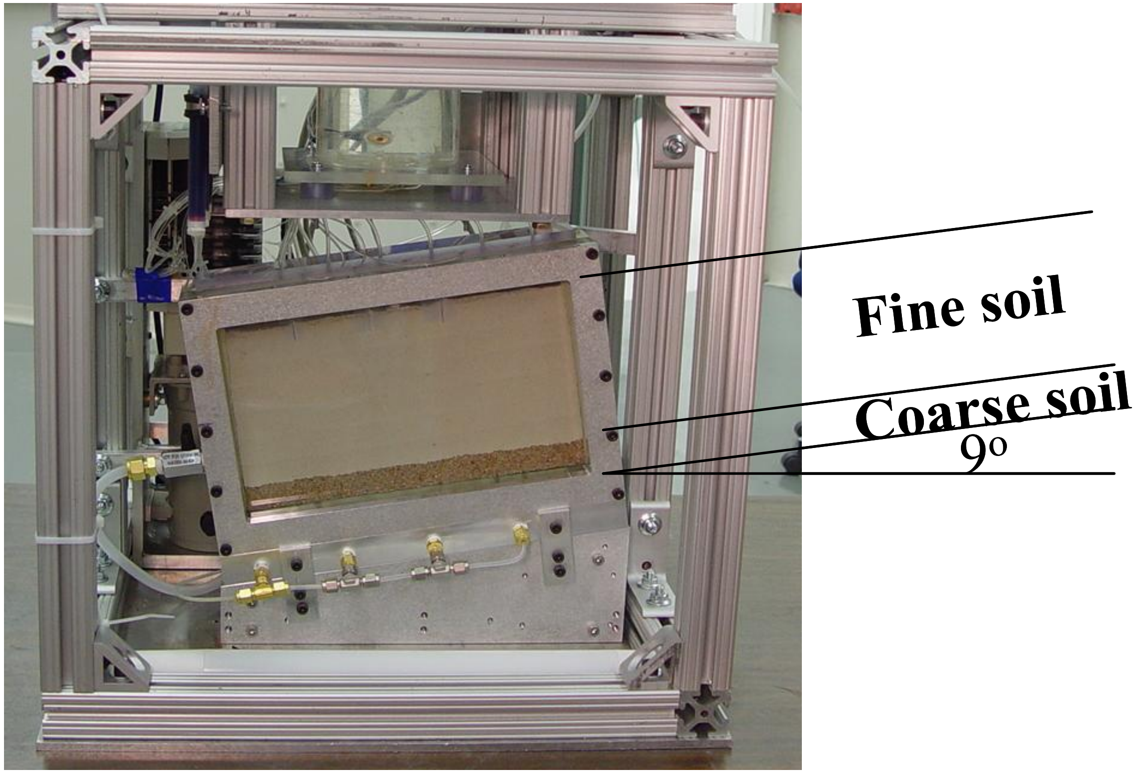
Idaho National Laboratory

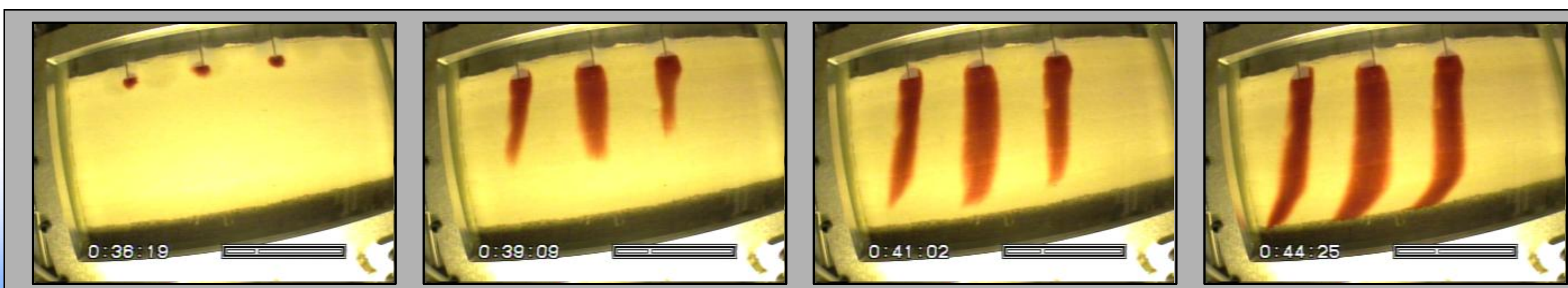

Velocity
Velocity (cm min^-1)
Dispersion Coefficient
Dispersion Coeff. (cm^2 min^-1)
Volumetric Water Content
Vol. Water Content
N


Fraction of Mobil Water
Fraction of Mobile Water
Transfer Coefficient
Transfer Coefficient (min^-1)
N


10 g
20 g
30 g
40 g
Dispersion Coeff. (cm^2 min^-1)
Velocity (cm min^-1)

Capillary Barrier Studies





Summary

- Developed theoretical background that serves as a basis for improved design, interpretation, and simulation of experiments
  - fluid potential,
  - pressure, pressure head, & hydraulic head in centrifugal field,
  - specific discharge,
  - Coriolis effects,
- Advanced techniques needed to conduct in-flight sampling and monitoring on the geocentrifuge,
  - Improved moisture probes,
  - fraction collector for geocentrifuge,
  - general experimental setups for geocentrifuge
- Conducted experiments that demonstrate that the geocentrifuge technique is a viable experimental method for the study of subsurface processes where gravitational acceleration is important

Summary

Key Advantages of Geocentrifuge Approach:

- Decrease time required to complete an experiment compared to 1g experiments.
- Obtain spatial scaling real-world problems according to the acceleration.
- Study a wider range of conditions than is capable under 1g acceleration.

Coriolis Effects