Investigation of Pore-Scale Processes that Affect Soil Vapor Extraction

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EM Need and Problem Addressed

- Dense nonaqueous phase liquid (DNAPL) contamination in the vadose zone is a significant problem at Department of Energy sites

  - Chlorinated hydrocarbons identified at over 60% of DOE Facilities (Riley & Zachara, DOE Report, 1992)

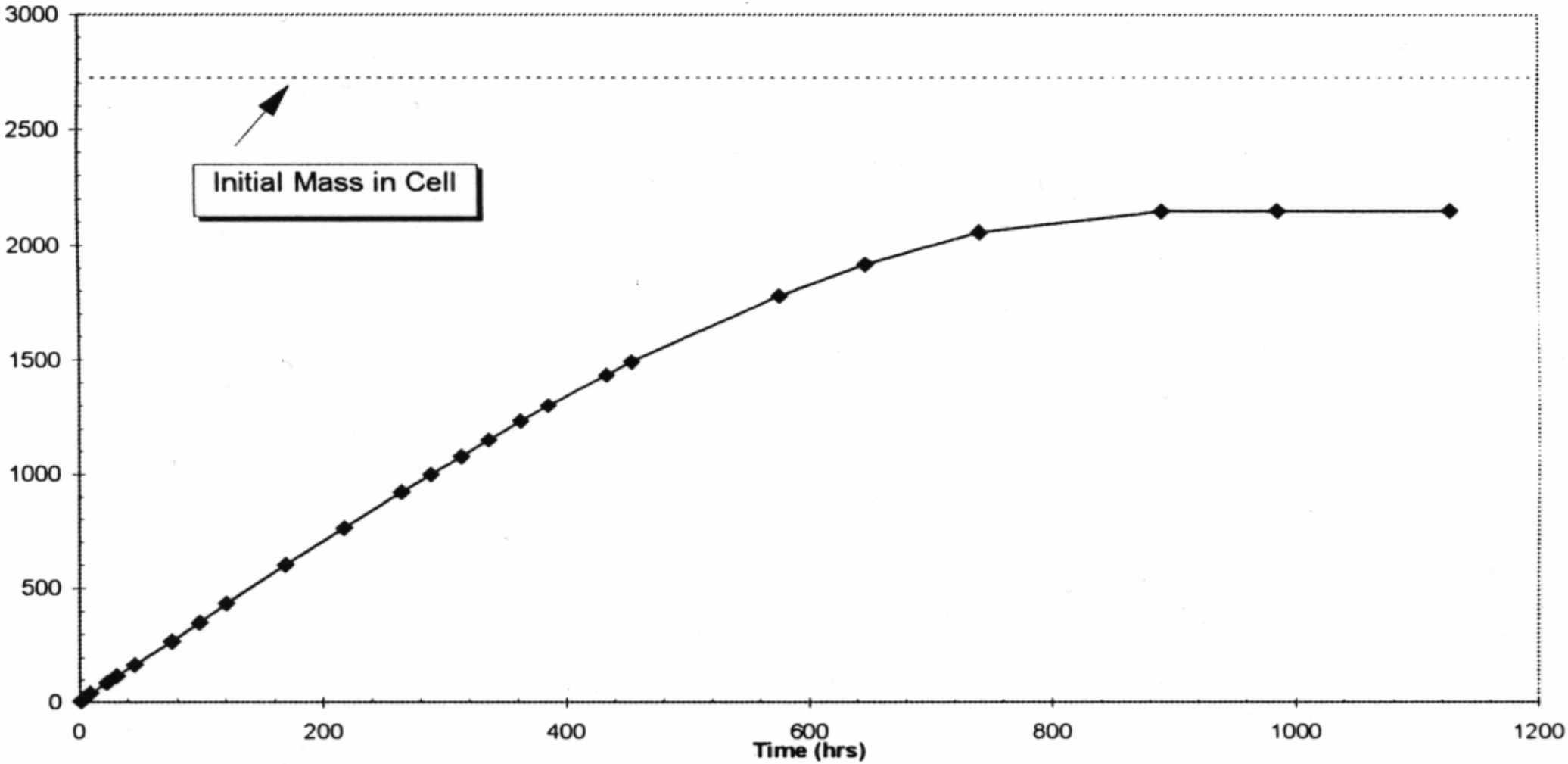
  - Approximately 360,000 to 580,000 liters (1.3 to 2 x 10^6 lbs.) of carbon tetrachloride discharged to the vadose zone in the 200-West area at Hanford (Yonge et al.,1996)

  - Approximately 2 x 10^6 lbs. of chlorinated solvents (PCE & TCE) released in M area at the Savannah River Site (Hodges & Falta, 1996)

EM Need and Problem Addressed

- Soil vapor extraction (SVE) is commonly used to remediate DNAPLs from the vadose zone

- **In most cases, a period of high recovery has been followed by a sustained period of low recovery. This behavior has been attributed to multiple processes including slow interphase mass transfer, retarded vapor phase transport, and diffusion from unswept zones of low permeability**.



Sand Box Experiments using Hanford Soils (Yonge, et al. 1996)

Research Objectives

- The processes that control SVE vary at the pore scale and with time
  - For example, if dry vapor is pulled into the ground during SVE, the soil matrix may "dry out" along the vapor phase flow path, resulting in changes to the mass transfer mechanisms which control SVE. This is especially important in arid environments like Hanford, where SVE is being used to remove carbon tetrachloride from the vadose zone.

Research Objectives

- Research proposed here aims to determine the pore-scale processes which limit the removal of DNAPL components in heterogeneous porous media during SVE. The specific objectives of this research are to:

(1) determine the effect of unswept zones on DNAPL removal during SVE

(2) determine the effect of retarded vapor phase transport on DNAPL removal during SVE

(3) determine the effect of interphase mass transfer on DNAPL removal during SVE, all as a function of changing moisture and DNAPL content.

Methods

- Batch and Column Studies of Vapor-Phase Sorption

  -Investigate the impact of relative humidity upon vapor phase retardation and slow desorption

- Magnetic Resonance Imaging (MRI)

  -Observe and quantify the location and size of individual pores containing DNAPL, water, and vapor in flow through columns filled with model and natural sediments

  -MRI is unique because it is non-destructive, allowing three-dimensional images to be taken of the phases within actual pores as a function of space and time

Methods

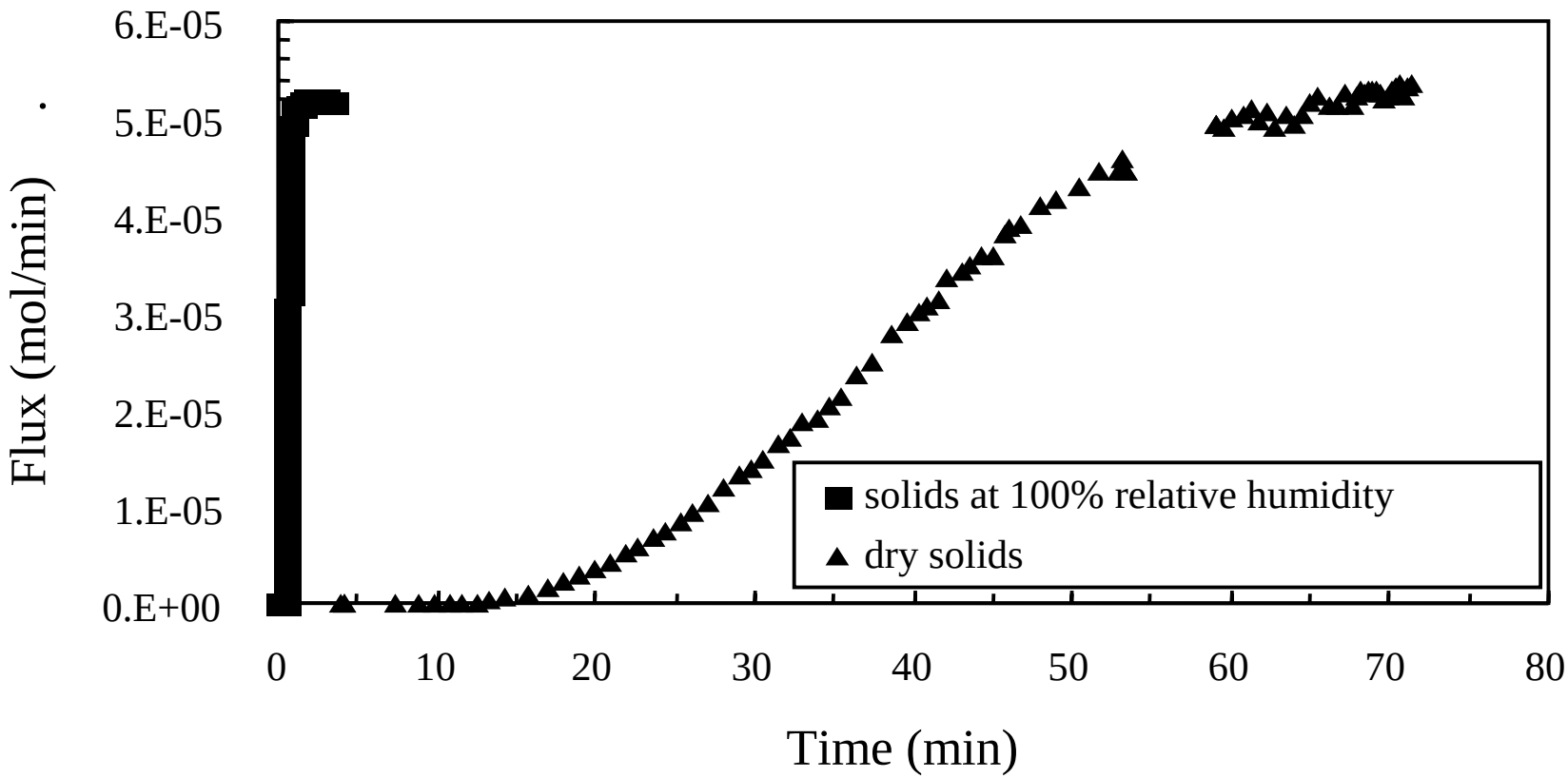
- Numerical Modeling

  -Develop spatially and temporally dependent constitutive relations which describe the transient distribution of phases inside a column experiment

  -Constitutive relations will be incorporated into a site-scale transport model to evaluate how the different processes affect SVE performance in practical applications.

Preliminary Results

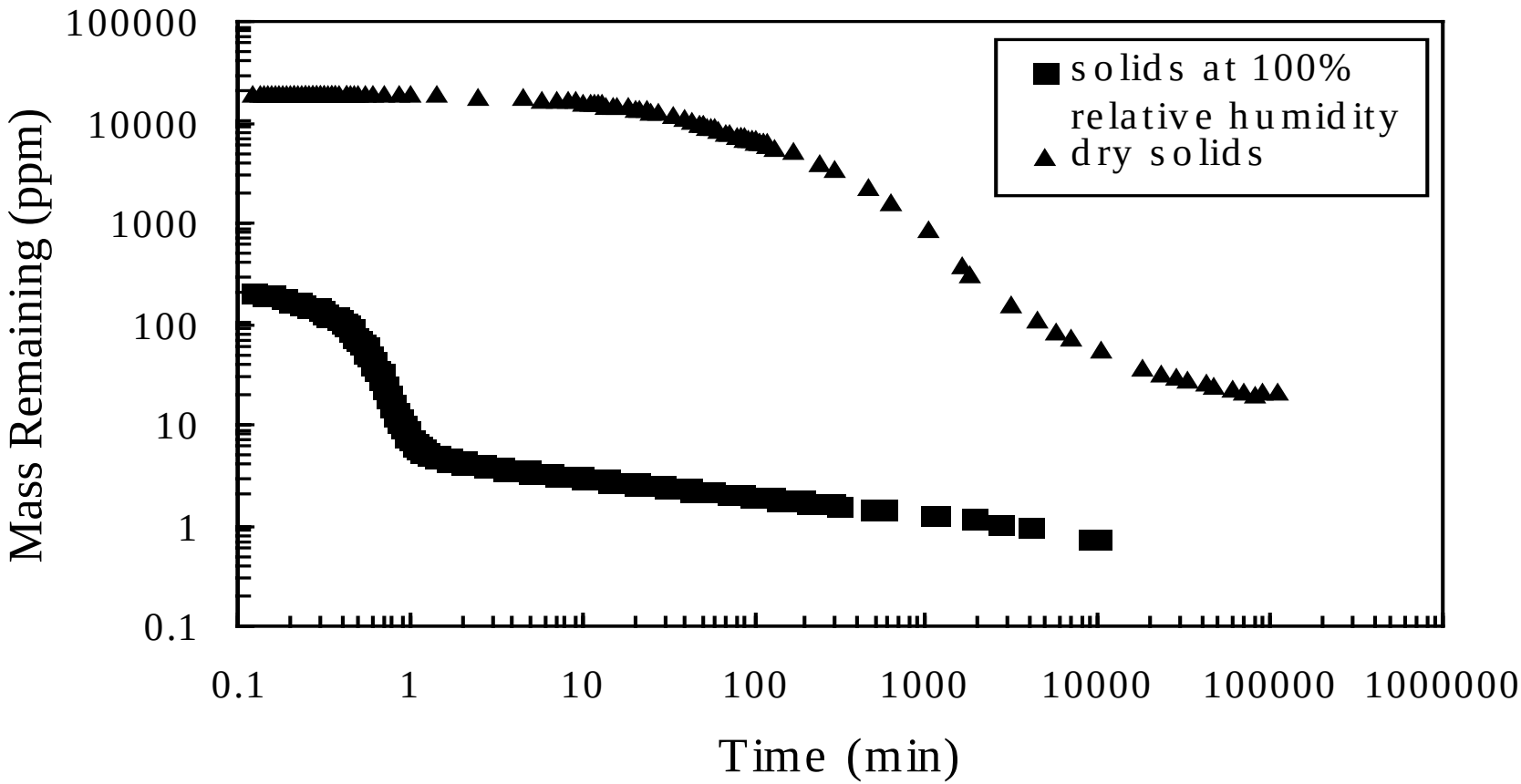
Batch and Column Studies of Vapor-Phase Sorption



Vapor phase TCE breakthrough profiles for a column filled with Livermore sand fraction at 100% relative humidity and a column filled with Livermore sand fraction near 0% relative humidity.

Preliminary Results

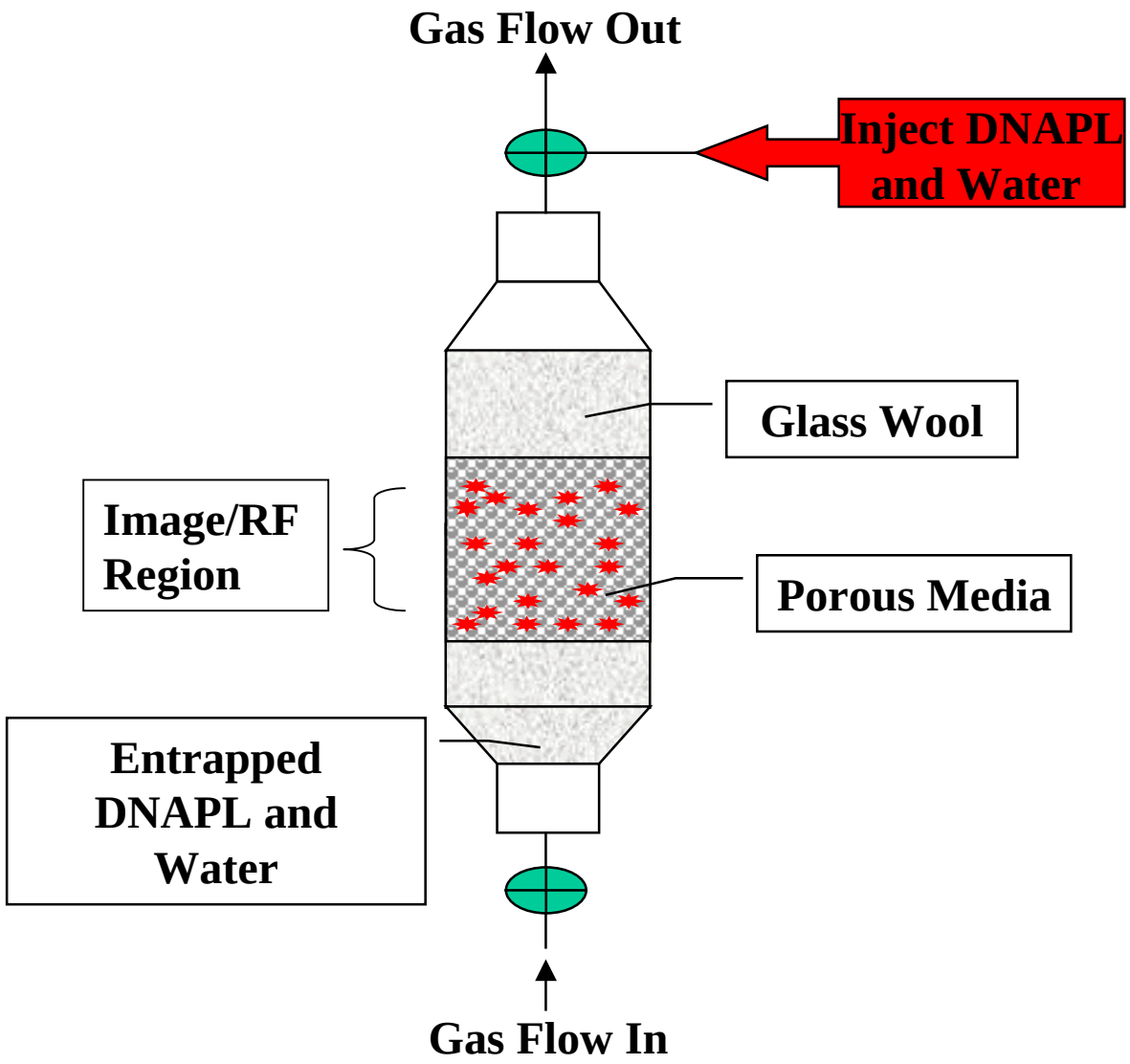
Batch and Column Studies of Vapor-Phase Sorption



Vapor phase TCE desorption profiles from a Livermore sand fraction at 100% relative humidity an from a Livermore sand fraction near 0% relative humidity

MRI Experiments

Experimental
Column Setup

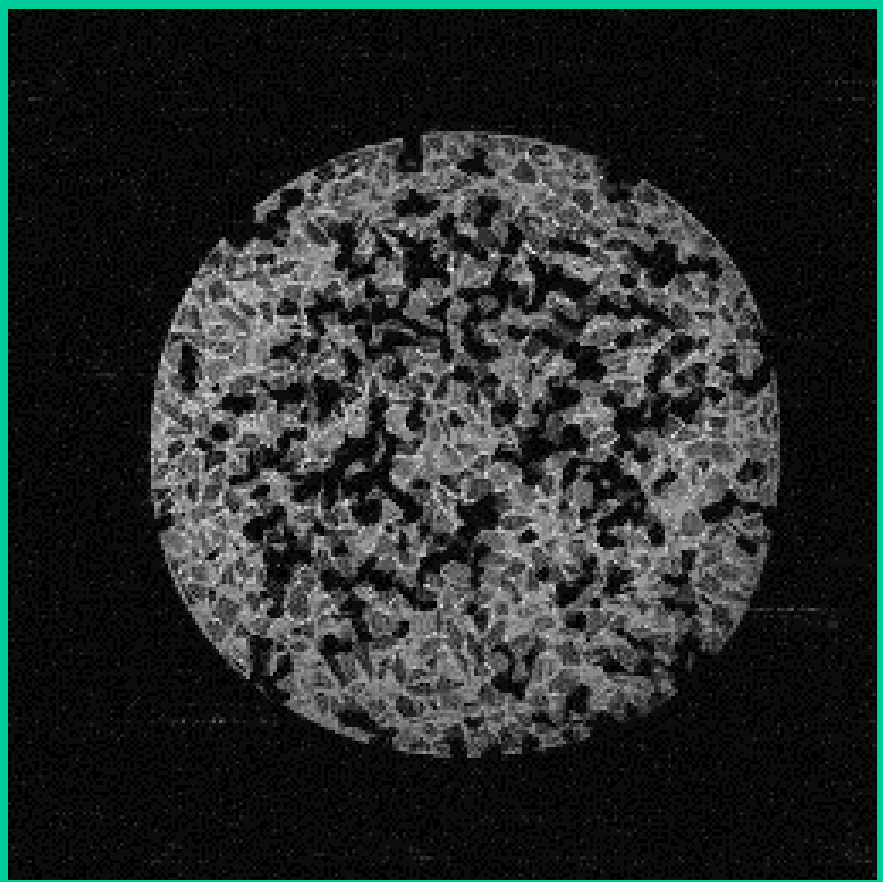


Magnetic Resonance Imaging

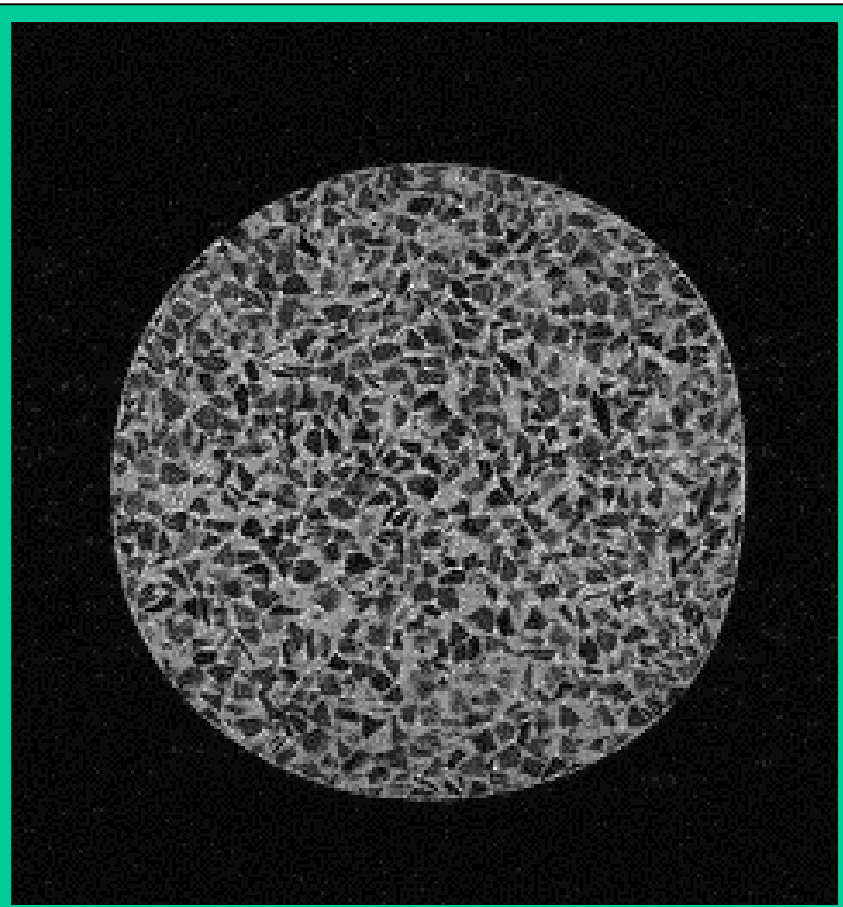
- MRI - a noninvasive tool to take ‘pictures’ of column interior
- 3D Images at pore scale resolution (voxels~60 μm^3)
- H^+ imaging
- Excite nuclear spins in RF region
- Signal intensity based on proton density - more protons, stronger signal
  - water: white
  - silica gel: gray
  - organic: black
- Subtract images at successive dissolution times from image at time zero to obtain change in mass in pore space

Initial Results From Magnetic Resonance Imaging

Cross-section image of TCE, silica gel, and water in flow-through column



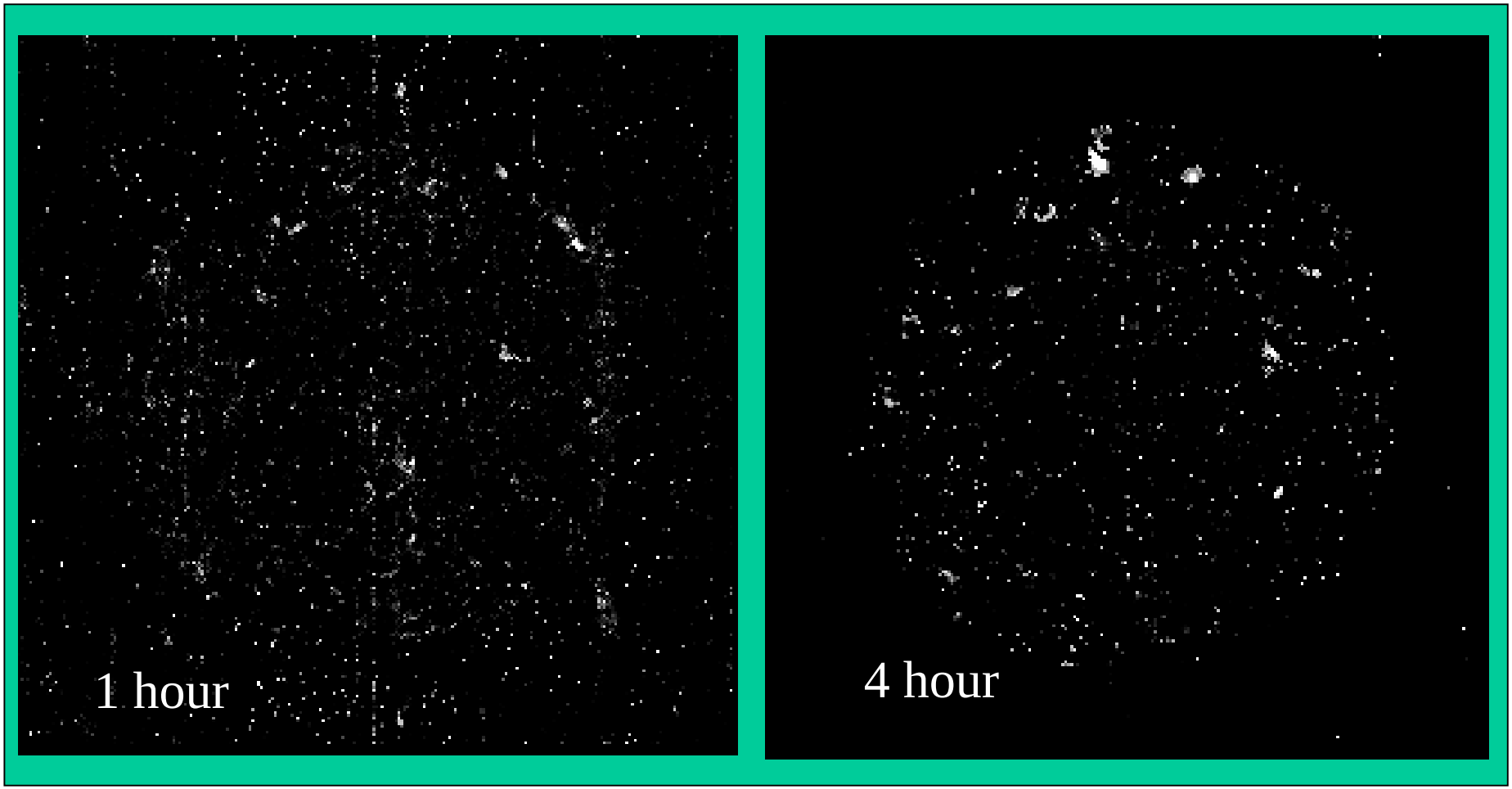
Residual Saturation of TCE

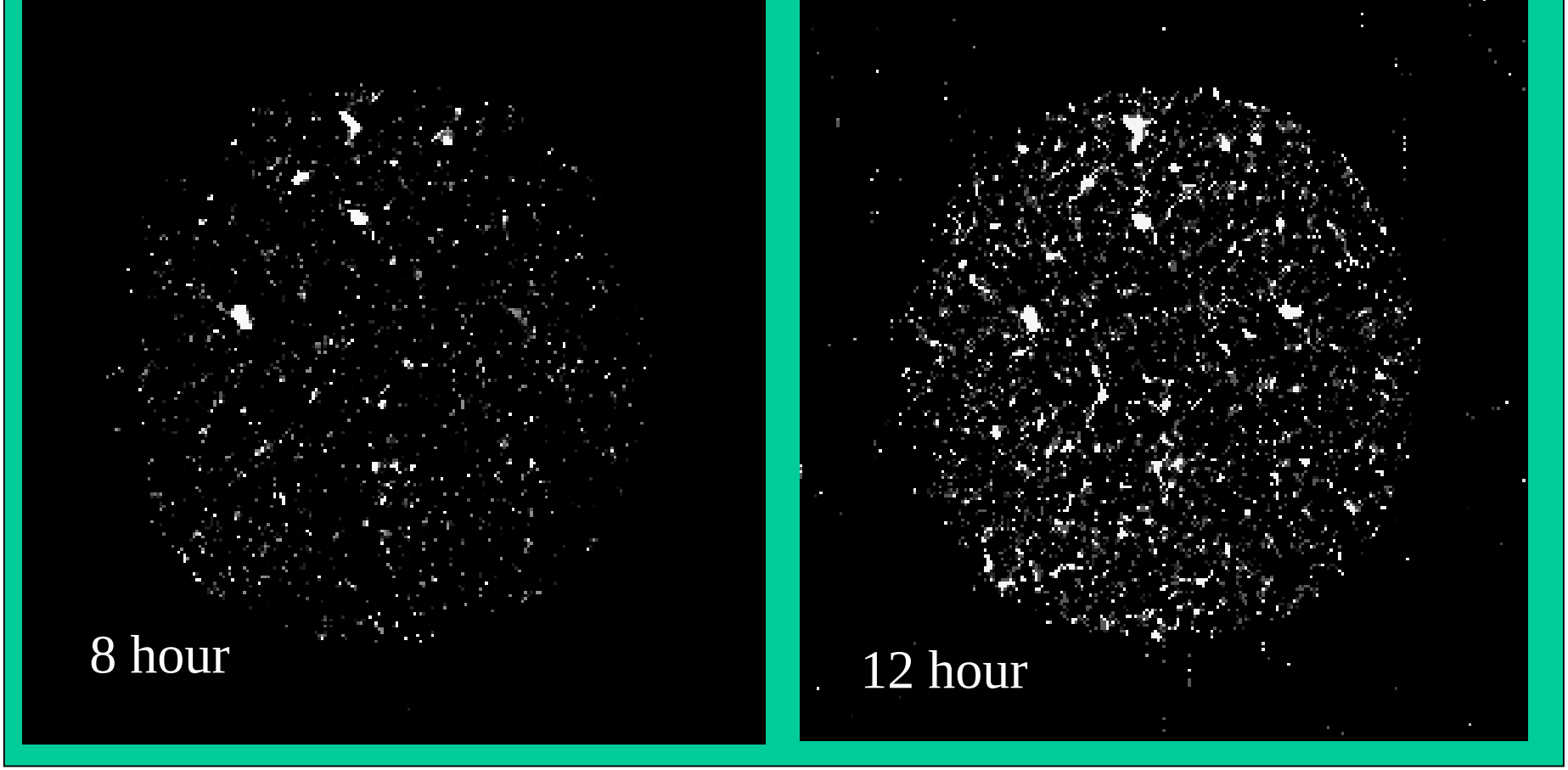


After TCE Dissolution

Initial Results From Magnetic Resonance Imaging

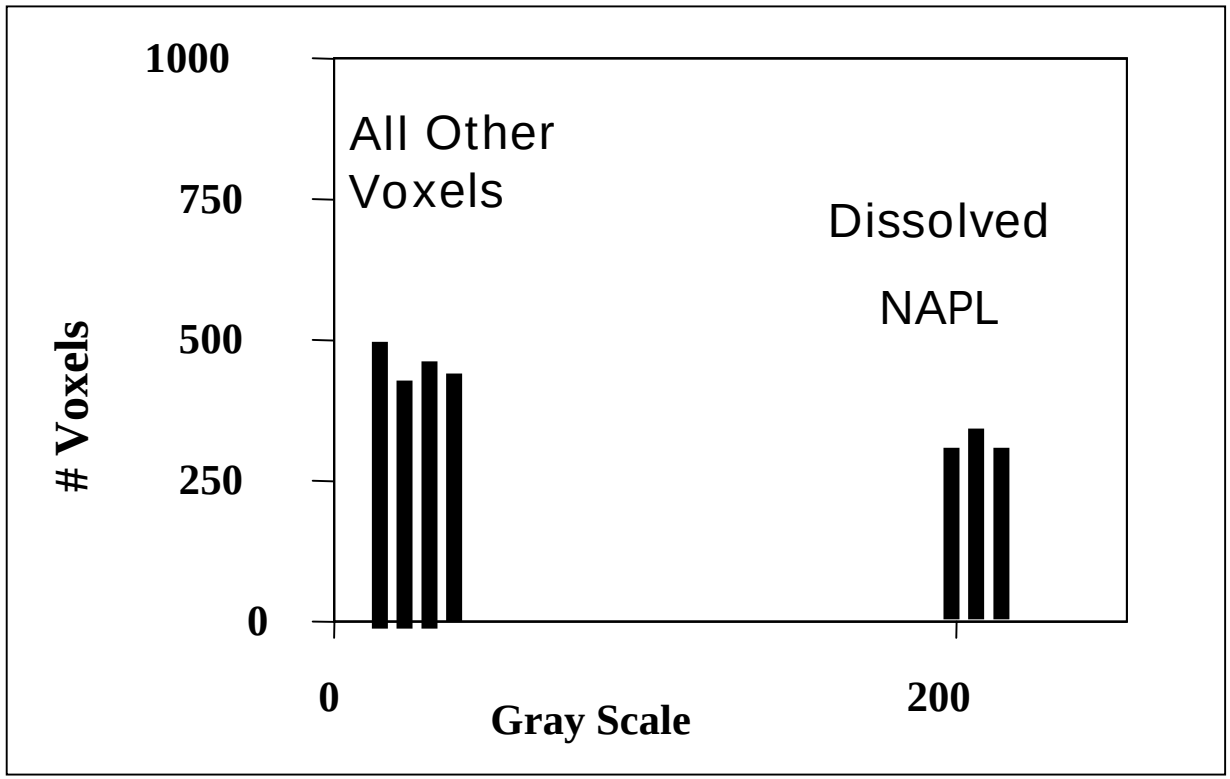
Images obtained by subtracting image at time t from image at time zero.




8 hour
12 hour

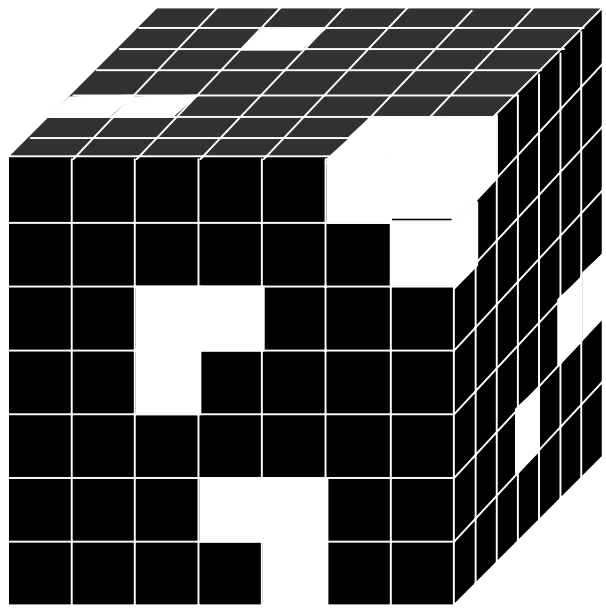
Analysis of MRI Results

- MRI images contain 16 million voxels that span 256 gray scales
- A histogram of an subtracted MRI image shows large gray scale values are associated with DNAPL blobs that have dissolved and small gray scale values are associated with everything else



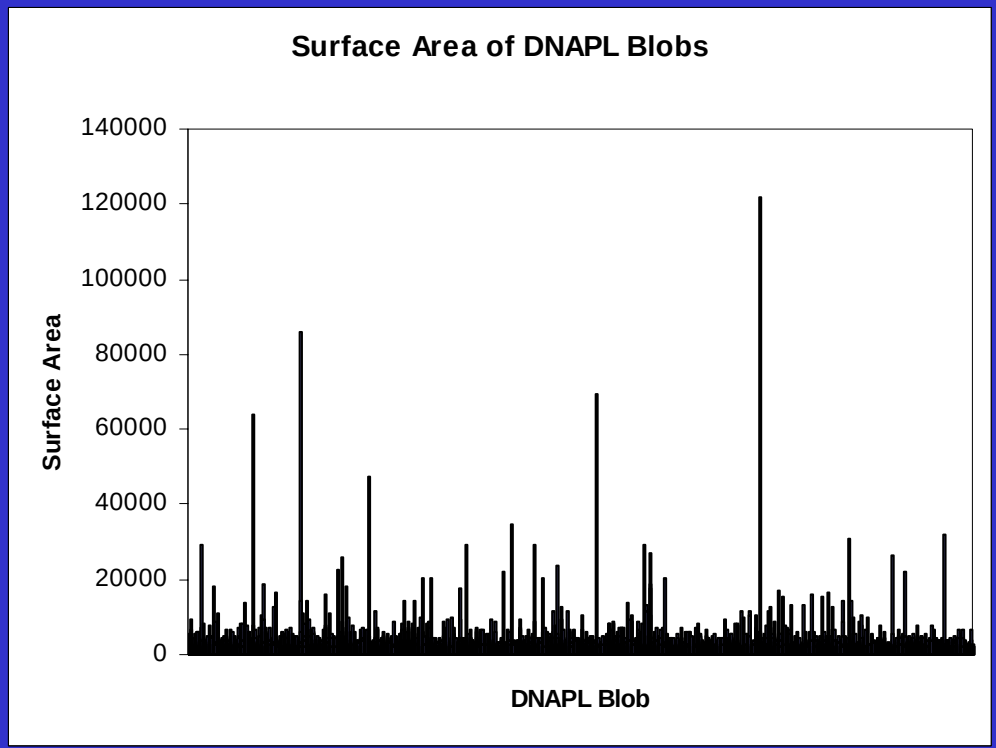
Analysis of MRI Results

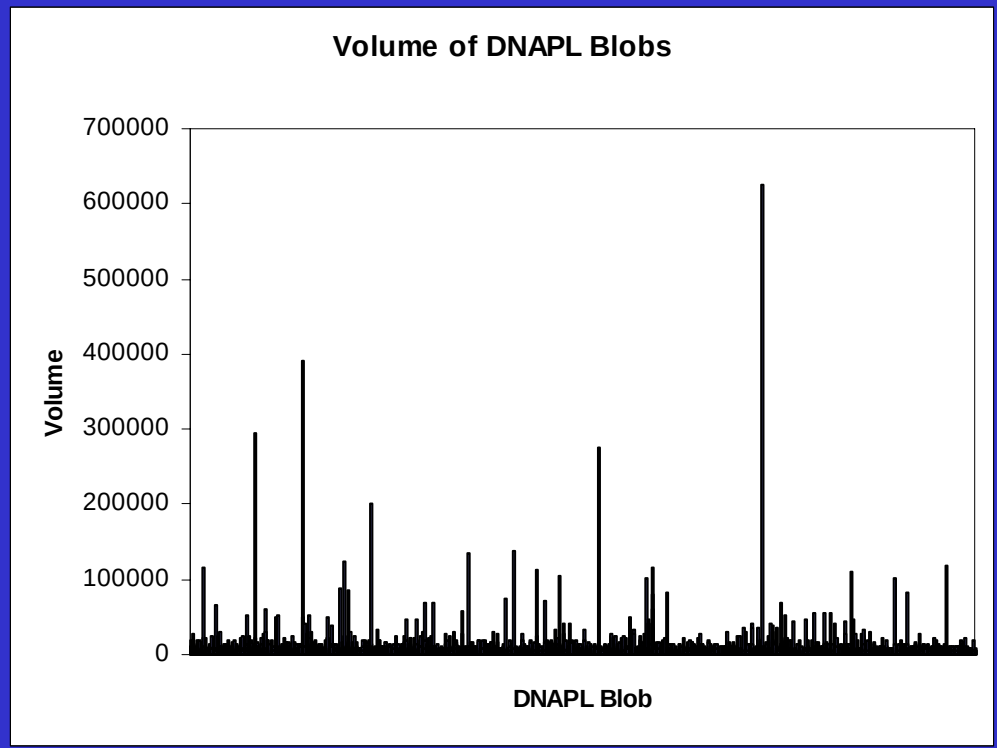
- A computer code was developed that:
  - identifies all individual DNAPL blobs by locating clusters of voxels that are above a threshold value
  - Calculates the surface area and volume of all individual DNAPL blobs by nearest neighbor arguments



Analysis of MRI Results:

Frequency Distribution Analysis of 12 Hour Subtract Image





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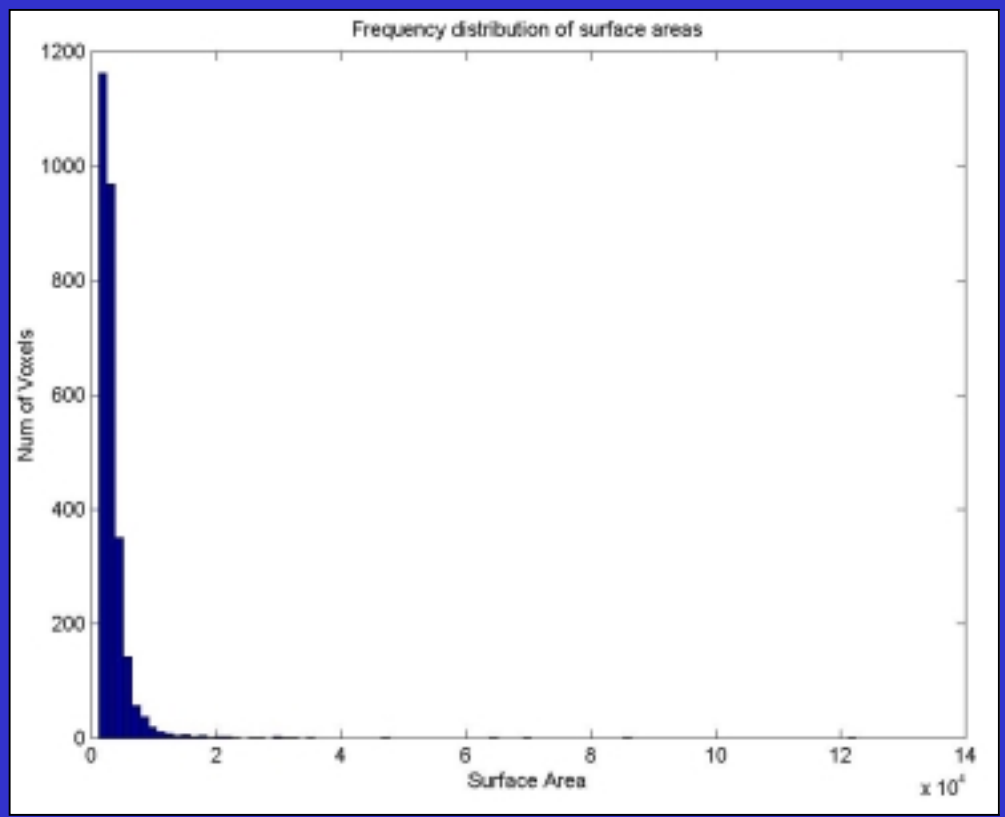

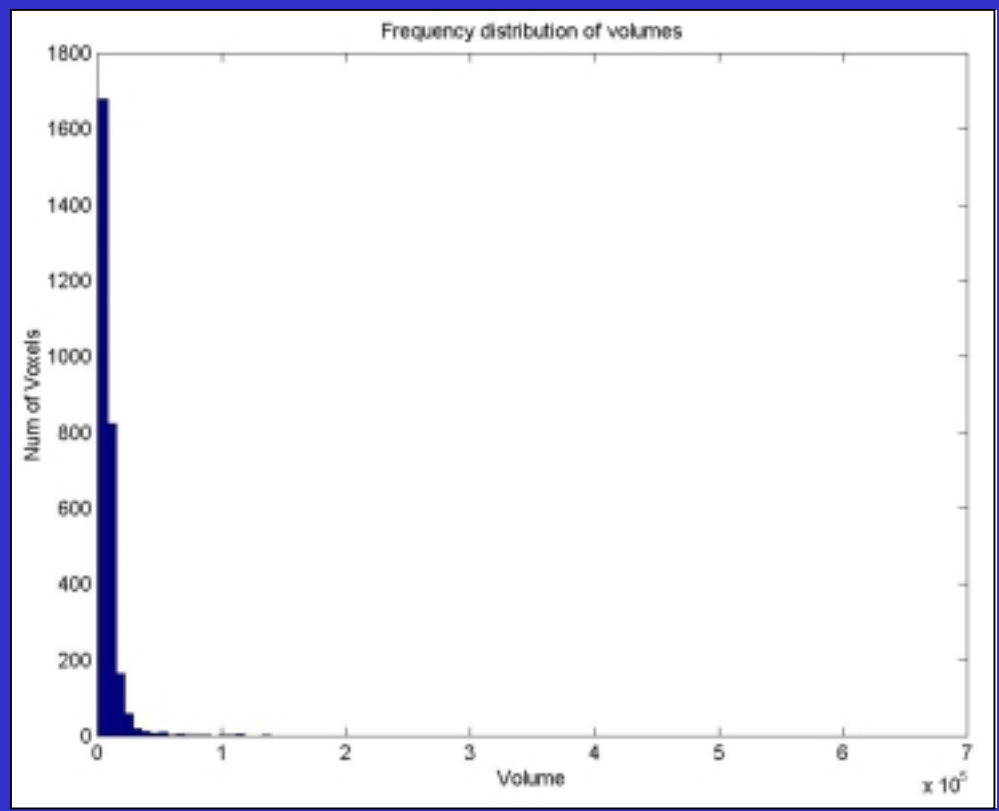

Future Work

- Evaluate surrogate DNAPLs containing fluorine
  - Improve image resolution and allow differentiation of air & DNAPL
- Continue to refine 3D image analysis algorithm to evaluate spatial and temporal variability
- Measure SVE efficiency at different water & DNAPL saturations
- Begin mathematical model development

Benefits to DOE

- Improved understanding of pore-scale processes
- Improved engineering models of long-term performance of SVE systems
- Improved assessment of uncertainty of long-term DNAPL removal
- Establishment of realistic treatment goals and better assessment of long-term risk