Detection of Underground Nuclear Explosions: Improving Estimates of Subsurface Radionuclide Transport Using Experimental Xe Diffusion Data and Numerical Methods

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Background

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) includes provisions for signatory countries to monitor for signs of clandestine nuclear testing. If enough remote evidence exists to suggest an underground nuclear explosion (UNE) has taken place, an on-site inspection and sampling of trace radionuclide gases may take place.

Among these radionuclide gases of interest are several different Xe isotopes. Because of their relatively rapid decay, the window of opportunity for detection of these gases at the surface is limited. Numerical models that simulate multi-phase gas transport in fractured bedrock can be useful in predicting surface gas arrival times.

We conduct this research using a twofold approach that combines laboratory gas experimentation and numerical modeling to verify and refine these simplifying assumptions in our current models of gas transport. Using a gas diffusion cell, we are able to measure air pressure transmission through fractured tuff core samples while also measuring Xe gas breakthrough measured using a mass spectrometer. We can thus create synthetic barometric fluctuations akin to those observed in field tests and measure the associated gas flow through the fracture and matrix pore space for varying degrees of fluid saturation. Our numerical approaches also include the ability to simulate the reaction equilibrium kinetics of dissolution/volatilization in order to identify when the assumption of instantaneous equilibrium is reasonable. These efforts will aid us in our application of such models to larger, field-scale tests and improve our ability to predict gas breakthrough times.

Research Goals

- Develop a better estimate of Xe gas diffusion rates in variably-saturated fractured rock
- Determine the validity of simplifying assumptions:

  Equilibrium conditions of gas dissolution/volatilization (instantaneous or kinetic Henry's Law partitioning)

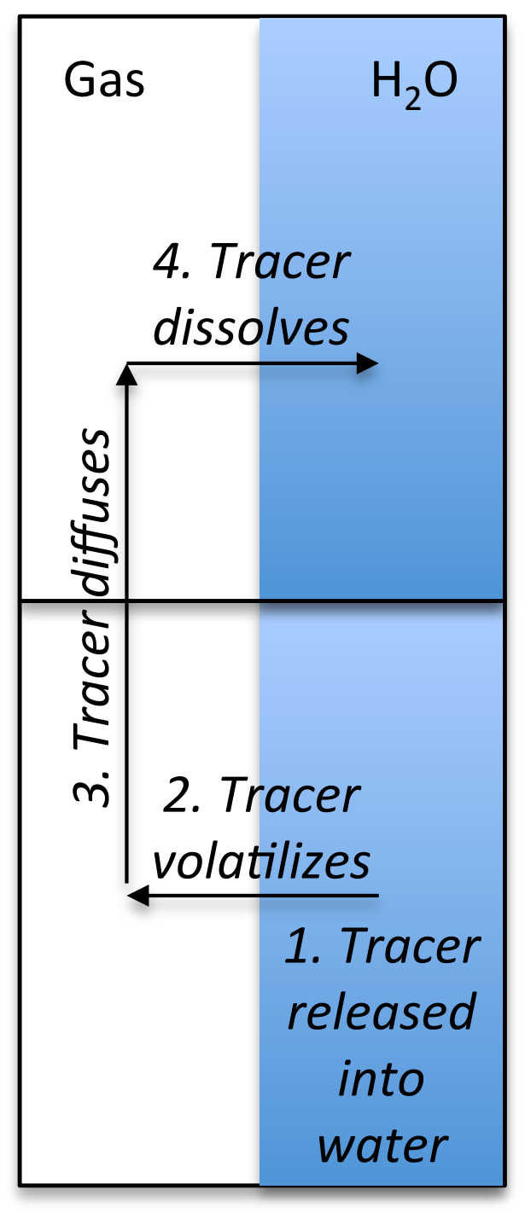

Figure 1. Conceptual diagram of gas tracer dissolution/volatilization.

Experimental Methods

Experimental data was collected from diffusion experiments on fractured tuff cores. The core was contained in a sealed chamber with pressure transducers affixed to both sides to measure pressure through the core. A bladder and second chamber were attached to allow for pressure fluctuation. A mass spectrometer allowed for measurement of Xe tracer concentrations. The research performed so far established the effect of saturation on the core with both sides under the same barometric pressure.

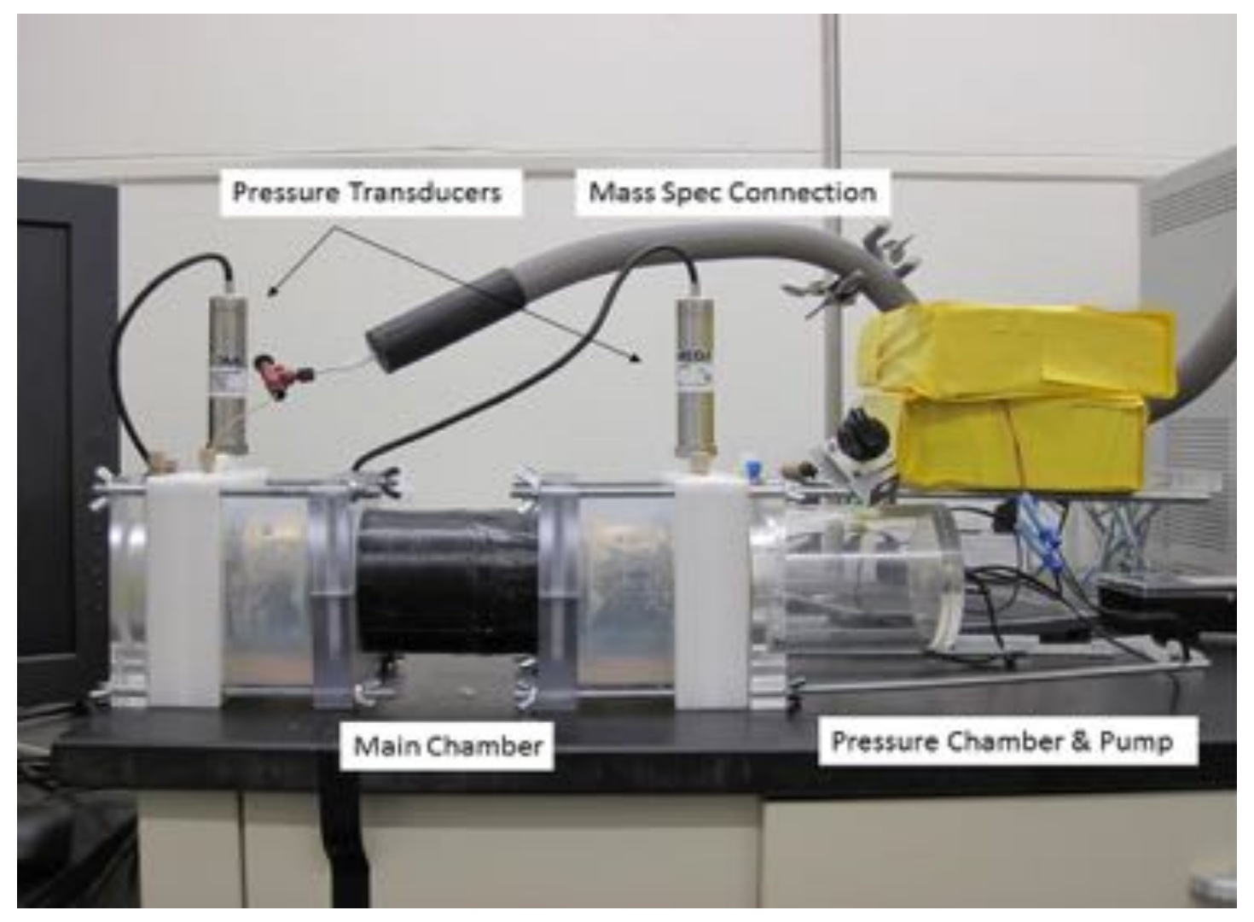

Figure 2. Full testing chamber

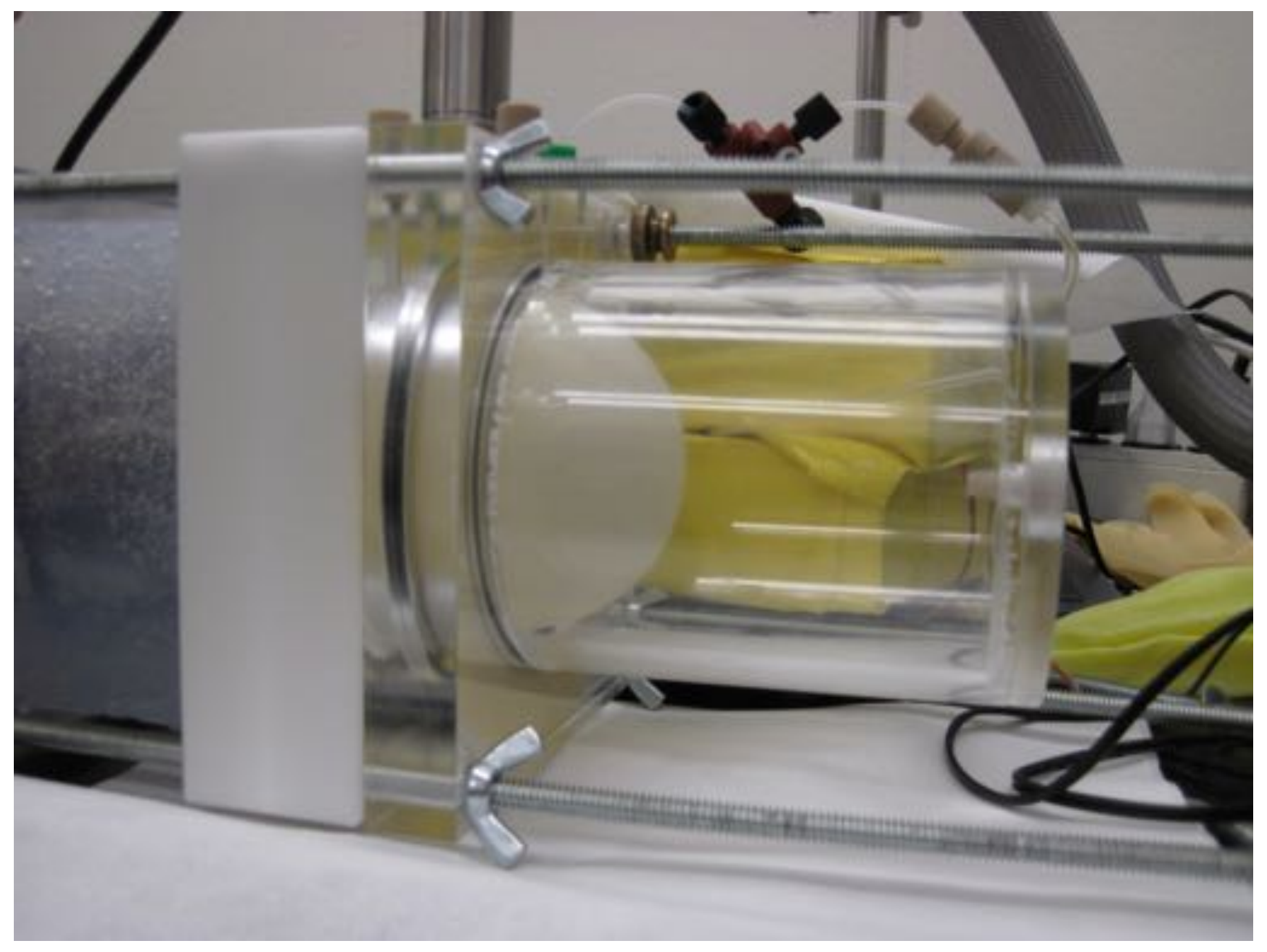

Figure 3. Low pressure created in pressure chamber, lowering pressure of the main chamber.

Sampling was completed using a flow control valve to reduce effects of sampling. Vacuum was also prevented. 50 mL Xenon was injected and allowed to diffuse until maximum concentration was reached and concentration started dropping.

Some Notes:

- Full saturation can take multiple days.
- Quick breakthrough could be from residual xenon back-diffusing.
- Core saturation reduces available pore space for gas transport.
- Low saturation affects outer pores first, prevents gas from diffusing and thusly forces gas into fracture rather than allowing into pore space.

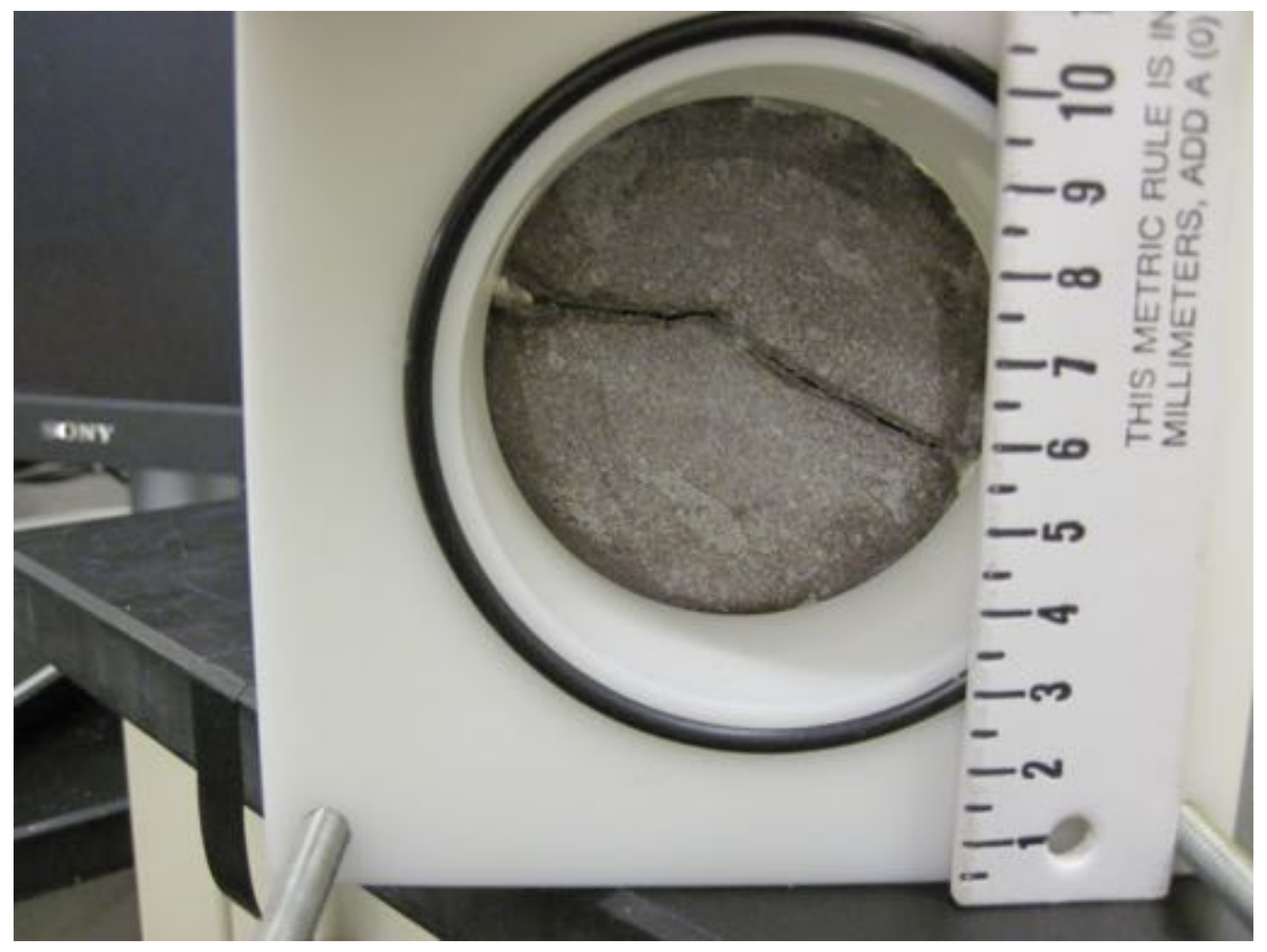

Figure 4. Fractured tuff core sample.

Numerical Methods

- Transient 2D CV modeling in *FEHM*
- Assumes instantaneous dissolution/volatilization equilibrium
- Domain approximates core dimensions and fracture aperture (1 mm)
- Boundary Conditions:
  - **Flow:** Closed system (no-flow boundaries)
  - **Transport:** Constant tracer concentration B.C. on bottom
- Fracture aperture $(\delta_f) = 1\,mm$
- Matrix porosity $(\phi) = 25\%$
- Degree of saturation $(\theta) = 29\%$
- Henry's Law coefficient $(K_h) = 0.1048$
- In the absence of a pressure gradient, all Xe transport is purely diffusive.

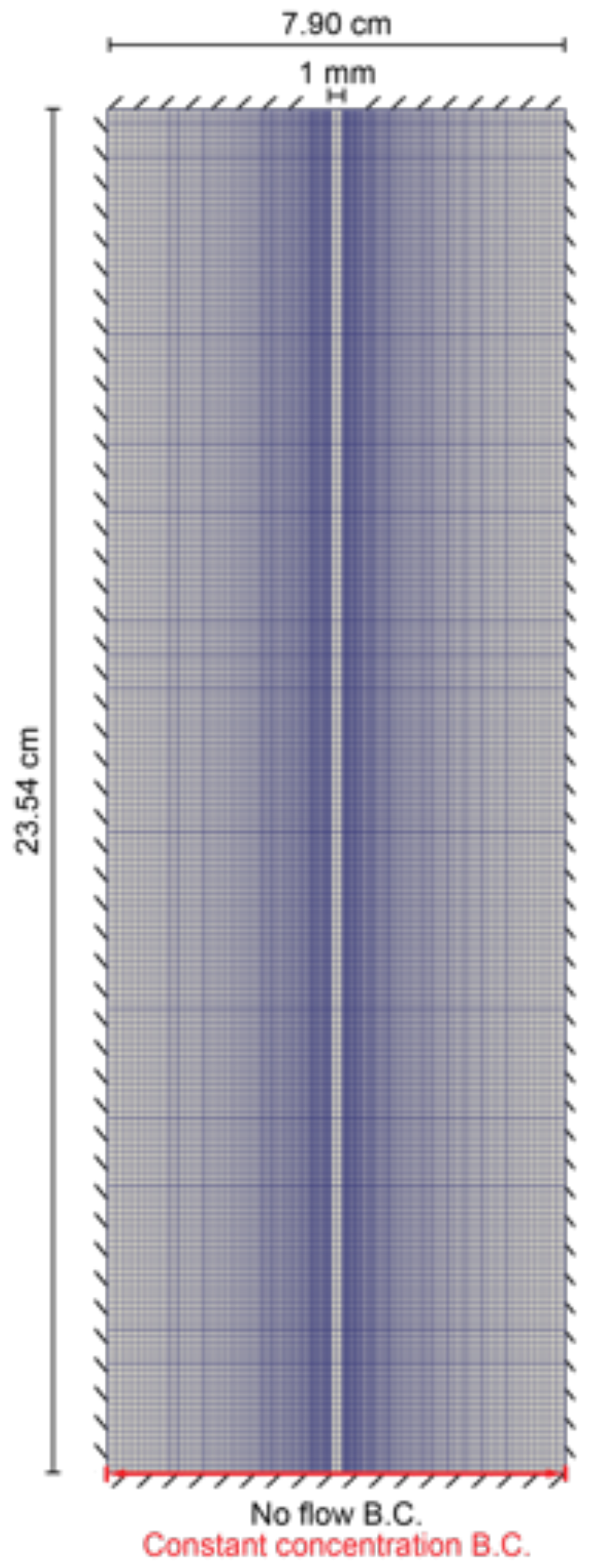

Figure 5. Two-dimensional schematic diagram of grid with boundary conditions used in FEHM to represent fractured tuff core.

Results

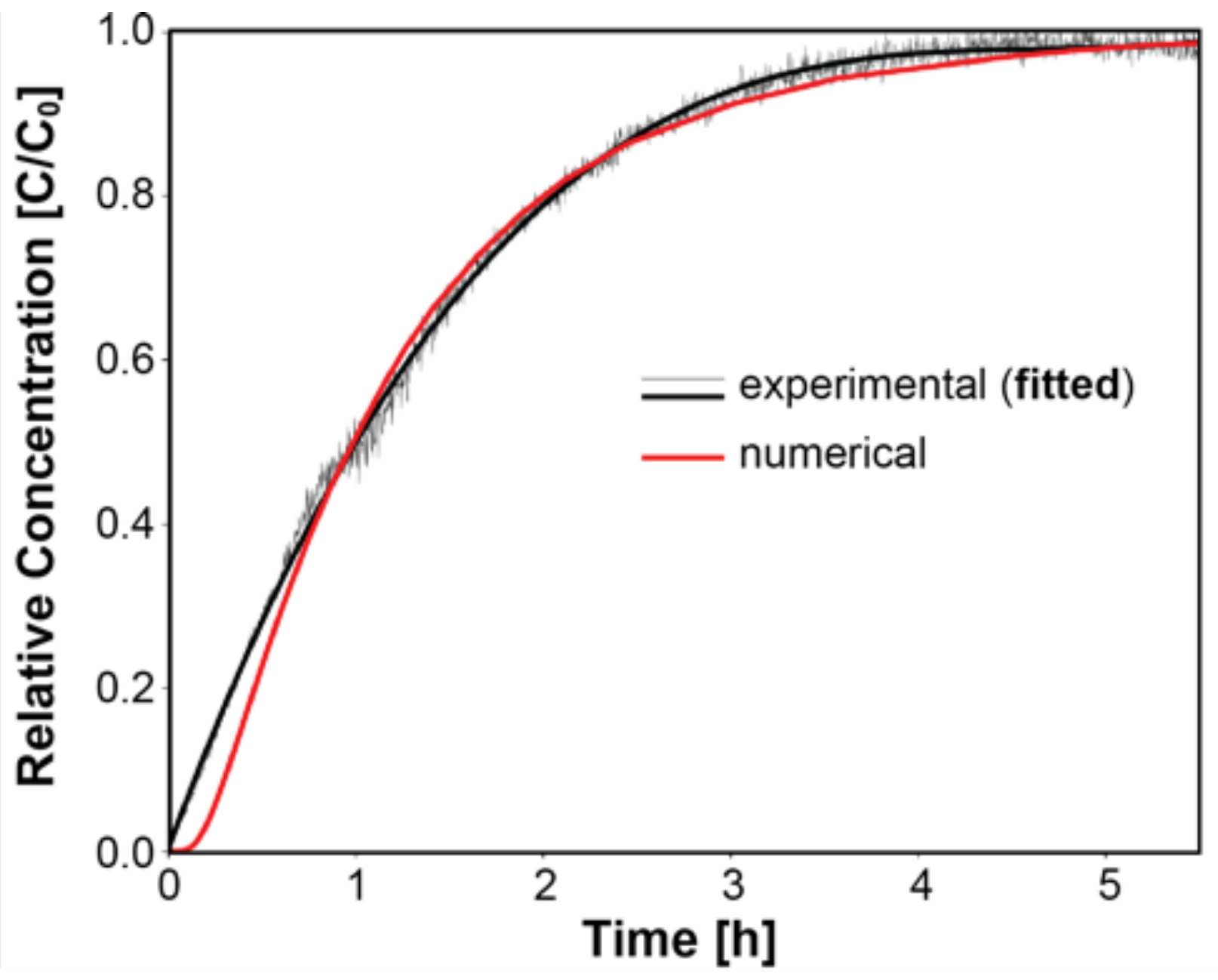

Figure 6. Numerical tracer breakthrough superimposed on experimental data. Note the early-time discrepancy (likely attributed to residual tracer present in core sample between experiments).

Despite early-time discrepancies (likely due to residual tracer between experiments), it seems instantaneous equilibrium for gas dissolution/volatilization is appropriate for the given conditions and spatiotemporal scales.

We found a gas tracer diffusion coefficient of ~6.4 × 10^{-6} m^2s^{-1} to fit the experimental data well.

Conclusions & Future Work

We have a better estimate of matrix diffusion of Xe_{132} in fractured rock.

The instantaneous gas equilibrium partitioning assumption appears valid. When advective conditions are considered, gas diffusion should become comparatively less important.

Future work should include transient pressure variations to simulate barometric pumping.