Migration of Noble Gas Tracer of Underground Nuclear Testing

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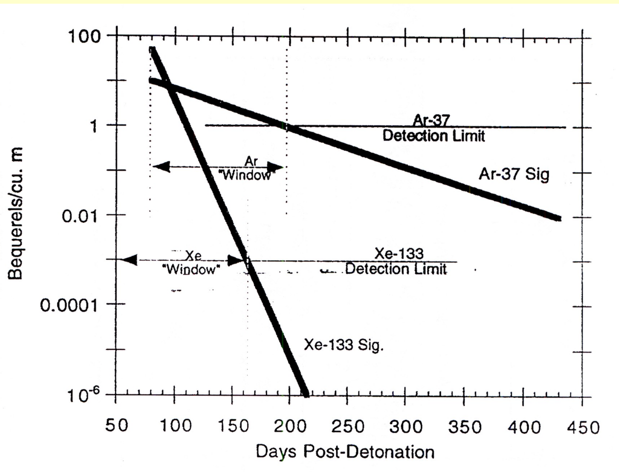
Introduction

Cyclical changes in barometric pressure can draw gas upward out of the soil into the atmosphere. In fractured permeable medium, the resulting transport process may be of orders of magnitude more significant than molecular diffusion [1]. Clandestine underground nuclear tests produces radionuclides at depth of several hundred meters, which migrate to the surface induced by this atmospheric pumping. A deep understanding of the transport mechanism is needful to state the estimated time of arrival for on-site inspectors of the Comprehensive Test Ban Treaty Organisation (CTBTO).

DPM for Xenon

Nuclide	Atomic Mass	NN	Abun %	Spin	Half Life	DM	DT	Decay Energy (MeV)
^{131m}Xe	130.9042 (+ 0.164 MeV)	77	Syn	11/2-	11.84d	IT		0.164
^{133}Xe	132.9059	79	Syn	3/2+	5.24d	β_-	^{133}Cs	0.427
^{133m}Xe	(+ 0.233 Mev)	79	Syn	11/2-	2.19d	IT		0.233
^{135}Xe	134.91	81	Syn	3/2+	9.14h	β_-	^{135}Cs	1.151

The atmospheric activity concentration of ^{133}Xe is well below the detection limit. Therefor only non-natural sources like nuclear power plants or nuclear weapons contribute to a countable amount.

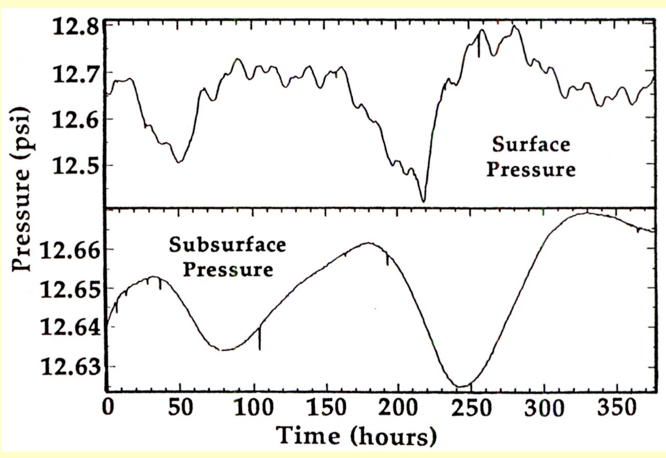


^{133}Xe is preferred for the detection of nuclear explosions for two reasons:

- they are not produced naturally in significant quantities so that natural back-ground levels are exceedingly low
- their short half-lives of 5.2 days can be used to infer the recentness of an event

Atmospheric Pumping

Weather patterns causes cyclical variations in the barometric pressures having differential amplitudes of 10-30 millibars over periods of a few days. These cyclical motions can draw radioactive gases upwards produced by an underground nuclear explosion. A typical comparison between surface pressure and downhole pressure is shown right [2].



Enhanced Thermal Conduction Process

Kurzweg [3] examined analytically the hydrodynamics of enhanced longitudinal heat transfer through a sinusoidally oscillating viscous fluid in an array of parallel-plate channels with conducting sidewalls. This process underlies the Double-Porosity Model. It has the effect of increasing the conducting heat transfer in the axial direction by a factor of 10^4 and higher.

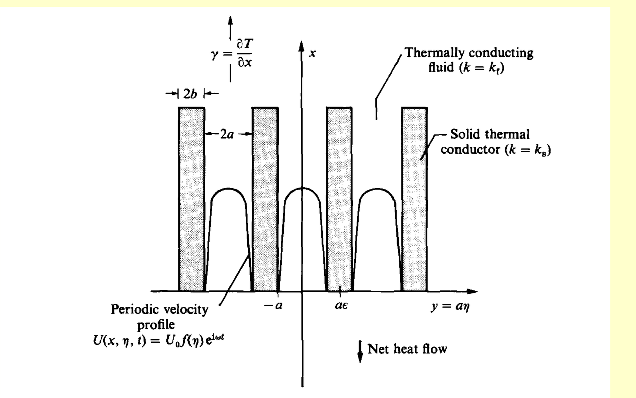


FIGURE 1. Geometry of the parallel-channel flow configuration under investigation.

The ends of the channel terminate in large reservoirs which are maintained at constant but different temperatures. This problem is analogous to the contaminant -diffusion problem under oscillatory conditions. Neglecting end effects and assuming laminar-flow conditions, the axial-velocity profile existing in the central channel is represented by the real part of:

$$U(\eta,t) = U_0 f(\eta)\exp(\mathrm{i}\omega t) = U_0\frac{\mathrm{i}\lambda}{\alpha^2}\left[1-\frac{\cosh\sqrt{\mathrm{i}}\alpha\eta}{\cosh\sqrt{\mathrm{i}}\alpha}\right]\exp(\mathrm{i}\omega t)$$

The corresponding differential equations are given by:

$$\frac{\partial T}{\partial t} + U_0 F(\eta)\exp(\mathrm{i}\omega t)\frac{\partial T}{\partial x} = \kappa_f\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$
$$\frac{\partial T}{\partial t} = \kappa_s\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$

U_0 : Representative axial velocity
κ_f, κ_s : Thermal diffusivities of fluid and solid
η : non-dimensional coordinate normal to the flow direction (y/a)

The time-averaged axial temperature gradient has the constant value γ, one can try a locally valid solution of the form:

$$T(x,\eta,t) = \gamma[x + ag(\eta)\exp(\mathrm{i}\omega t)]$$

An effective avaraged thermal diffusivity can then be defined by the equality:

$$-\kappa_e\gamma = \frac{\omega}{2\pi}\int_0^{2\pi/\omega}\mathrm{d}t\int_0^1 [T(x,\eta,t)]_R\,[U_0 f(\eta)\exp\mathrm{i}\omega t]_R\,\mathrm{d}\eta$$

Double-Porosity Model (DPM)

Conceptual Model

A schematic diagramm is given below [2],[4]. Fractures of halfwidth δ_f are surrounded by a porous matrix material having porosity and permeability

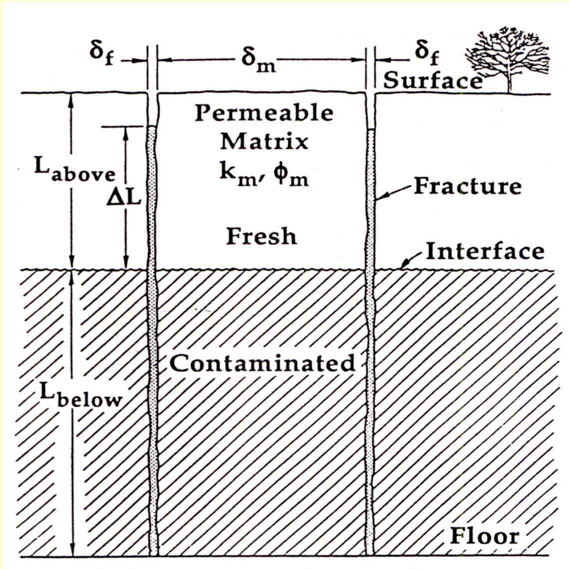


Fig. 1. Schematic of a double-porosity medium. During a period of falling barometer, contaminated gas from fractures and matrix blocks below the interface expands upward through the fractures. Only the relatively small fracture volume above the interface serves as a buffer volume.

Governing Equation

The pressure response of the fractured porous medium is controlled by the following pair of coupled equations [5]:

$$\frac{\partial p}{\partial t} = \alpha_f\frac{\partial^2 p}{\partial x^2} + \frac{\phi_m\alpha_m}{\delta_f}\frac{\partial p}{\partial y} \qquad \text{Fracture}$$
$$\frac{\partial p}{\partial t} = \alpha_f\frac{\partial^2 p}{\partial x^2} + 2\frac{\phi_m\alpha_m}{\delta_f}\frac{\partial p}{\partial y} \qquad \text{Matrix}$$

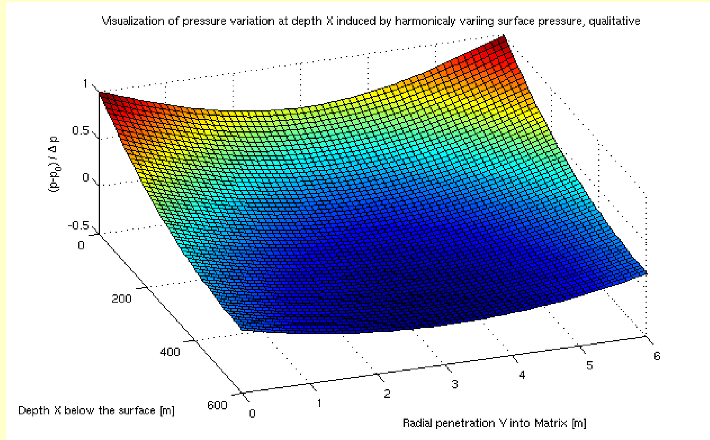
The parameters α_f and α_m are the so-called pneumatic diffusivities, which control the speed of pressure waves along the fracture and within the porous matrix. These are defined as follows:

$$\alpha_f = \frac{(\delta_f)^2}{12}\frac{p_0}{\mu} \qquad \alpha_m = \frac{k_m p_0}{\mu\phi_m}$$

δ_f : Fracture width; k_m : Matrix permeability
ϕ_m : Matrix porosity; μ : air viscosity

for laminar flow along a fracture of width δ_f and Darcian flow within the matrix blocks. These equations apply to isothermal flow of an ideal gas in the absence of inertial and turbulence effects.

Sinusoidal Pressure Response of a Fractured Porous Medium

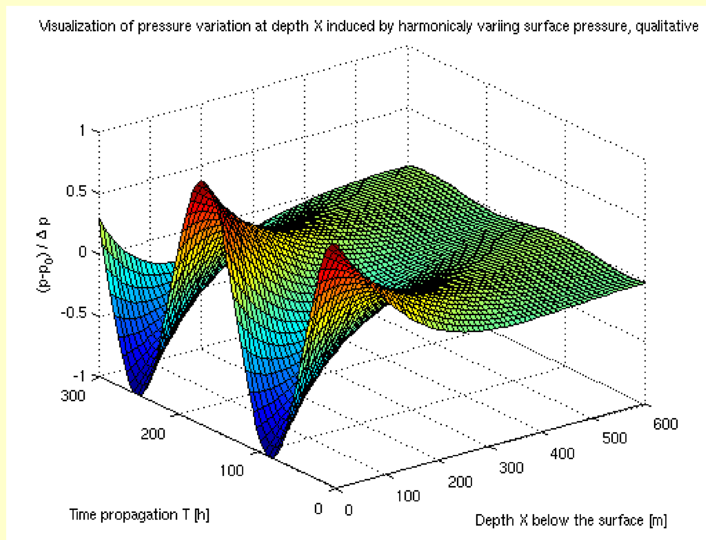


Using standard separation of variables techniques the exact solution to the previously mentioned pair of coupled equations is the real part of:

$$\frac{p-p_0}{\Delta p} = \frac{\cosh\lambda_{fm}\sqrt{\mathrm{i}}\left(1-\frac{x}{L}\right)}{\cosh\lambda_{fm}\sqrt{\mathrm{i}}}\,\frac{\cosh\lambda_m\sqrt{\mathrm{i}}\left(1-\frac{2y}{\delta_m}\right)}{\cosh\lambda_m\sqrt{\mathrm{i}}}\exp(\mathrm{i}\omega t)$$

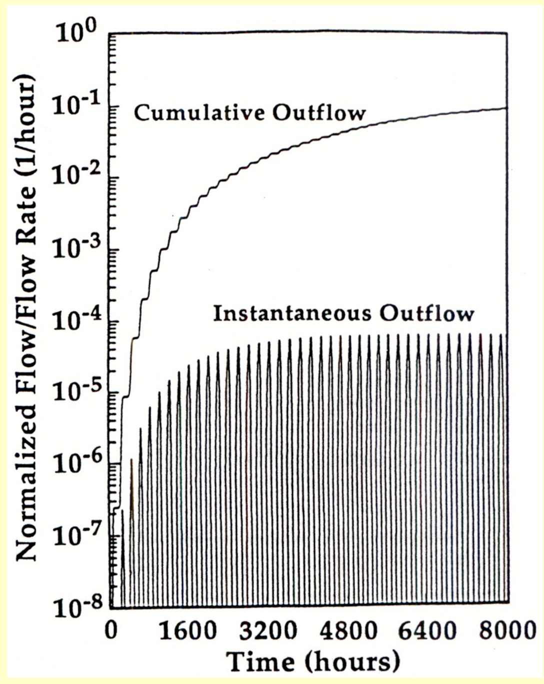
$$\lambda_m = \frac{\delta_m}{2}\sqrt{\frac{\omega}{\alpha_m}}$$
$$\lambda_f = L\sqrt{\frac{\omega}{\alpha_f}}$$
$$\lambda_{fm} = \lambda_f\sqrt{1+\frac{\phi_m\delta_m}{\delta_f}\frac{\tanh\lambda_m\sqrt{\mathrm{i}}}{\lambda_m\sqrt{\mathrm{i}}}}$$

in which are dimensionless Fourier numbers associated with the matrix alone, the fracture alone and the composite fractured matrix, respectively.



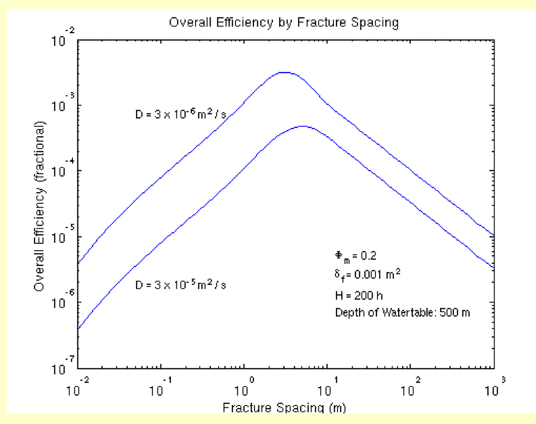
Filtering Regime and Quasi-Steady Contaminant Transport

A typical numerical simulation of the pumping effect is shown below [2]:



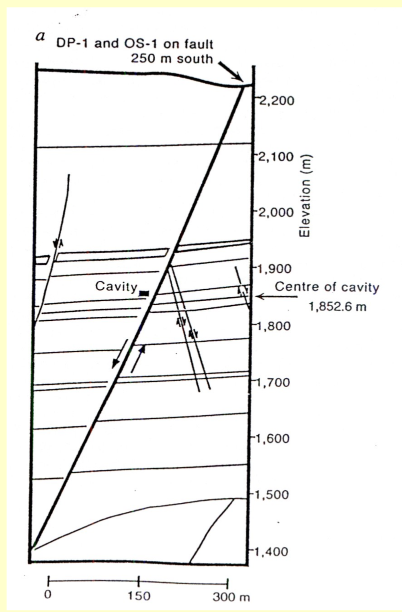
In the early time filtering regime, the outflow of contaminant is retarded. The underlying mechanism loses its effectiveness beyond the first few cycles of pumping

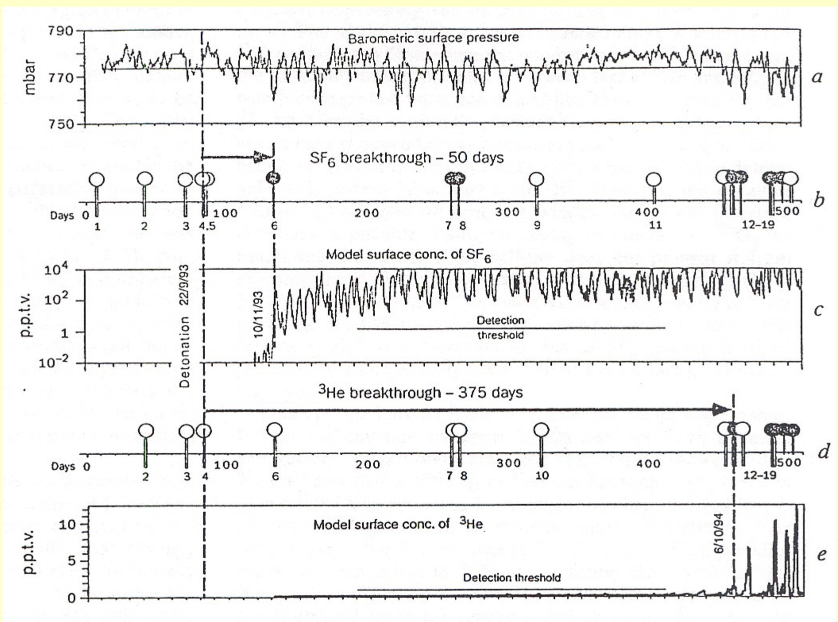
Overall Transport Efficiency

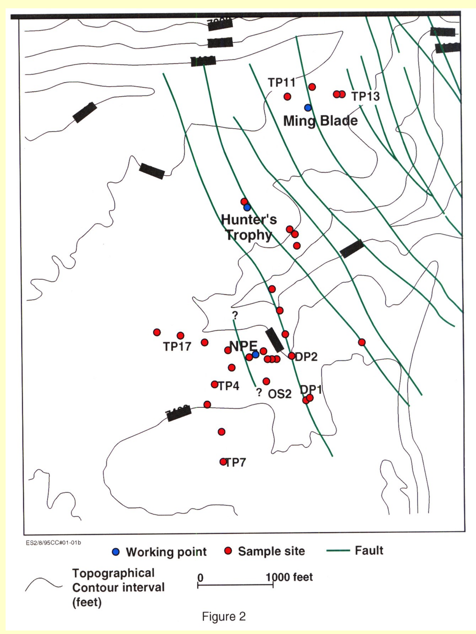


An increase in the molecular diffusivity reduces the overall transport efficiency by one order of magnitude.

Application







The Non-Proliferation-Experiment

On 22 Sept 1993 a simulated 1kt nuclear explosion was produced by the detonation of 1.3 mio kg of chemical explosives in a mined cavity sited at a depth of 400 m in the bedded tuff of Rainier Mesa at the Nevada Test Site. Two gas tracers with different diffusivities were released. The less diffusive tracer (SF_6, D = 9.1 x 10^{-6} m^2/s,) was detected on a nearby geologic fault 50 days after detonation. The more diffusive tracer (^{3}He, D = 7.6x$10^{-5}$$m^2$/s) was detected 375 days after release. [1], [5]

Our Project

- Development of a gas migration model based on the Double-Porosity Model for ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe
- Determine shift of ratio for ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe
- Estimate time of arrival for different geologic and stratigrafic structure as given for the Nevada Test Site (Nevada) and the Novaya Zemlya Test Site (Novaya Zemlya)

The *Carl Friedrich von Weizsäcker Centre for Science and Peace Research* is an interdisciplinary centre of the *University of Hamburg*

The *Carl Friedrich von Weizsäcker Centre for Science and Peace Research* is funded by the *German Foundation for Peace Research.*

We are members of the network of *Independent Group of Scientific Experts on detection of clandestine nuclear-weapon-usable materials production (iGSE).*

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