Helium and other noble gases exist in high concentrations in hydrocarbon reservoirs, as by-products of radioactive decay of naturally occurring uranium and thorium. Helium is a very small molecule, and all noble gases are chemically inert (they do not sorb to the formation like methane does). These properties make He an ideal gas to sample during hydrocarbon production to obtain more information regarding...

• early detection of reservoir and well completion flow regimes, and
• understanding of transport and delivery mechanisms inside the reservoir.

We combine approximate solutions, semi-analytical solutions, and numerical models to predict flow of noble gases from the reservoir to horizontal wells completed using hydraulic fracturing.

Naturally occurring tracers may only be brought to the borehole through advection (since they have a uniform initial concentration), driven by pressure gradients. Different species may have their own effective permeabilities, porosities, and compressibilities — helium being the most favorable, because it is a small inert molecule.

Multiporosity Flow Model

We take the classical double porosity flow model of Warren and Root [1963] (W-R), and extend it using the multiporosity approach of Haggerty and Gorelick [1995]. The dimensionless governing equation for fracture flow (subscript \(f\)) can be written as

\[
\frac{\partial \phi_f}{\partial t} = \frac{1}{\sqrt{\lambda_f}} \frac{\partial}{\partial y} \left( \sqrt{\lambda_f} \frac{\partial \phi_f}{\partial y} \right)
\]

where \(\phi_f\) is the dimensionless change in pressure, \(\phi_f = \frac{p_f - p_w}{p_m - p_w}\), \(\lambda_f\) is a ratio of fracture to matrix total storage capacity (\(c_f\) is compressibility and \(\phi_f\) is porosity), \(t_0 = \frac{t}{H (2 \sqrt{\lambda_f} / \mu)}\) is dimensionless time, \(\mu\) is viscosity, \(c_f\) is wellbore radius, and \(\lambda_f\) is a probability distribution function. The dimensionless matrix flow equation (subscript \(m\)) for pseudo-steady interporosity flow is

\[
\frac{\partial \phi_m}{\partial t} = \rho \frac{\partial \phi_m}{\partial t} = \sqrt{\lambda_f} \frac{\partial}{\partial y} \left( \sqrt{\lambda_f} \frac{\partial \phi_m}{\partial y} \right)
\]

where \(\lambda_f = k_f/(k_f c_f)\) is a interporosity flow coefficient. Using the Laplace transform to solve the matrix and fracture governing equations, we get

\[
\omega \phi_m (s) + \frac{s}{\lambda_f} \phi_m (s) = \left( \frac{s}{\lambda_f} + \frac{\partial}{\partial y} \right) \phi_m (s) = V \phi_m (s)
\]

where \(s\) is the Laplace parameter and an overbar indicates a Laplace-transformed variable. The solution is computed using a numerical inverse Laplace transform. The \(\rho\) and \(\lambda_f\) coefficients can be chosen in different manners to obtain different types of solutions.

The multiporosity model is sufficiently flexible to represent flow in several different classically considered cases as degenerate or special cases. Using a flow model with a great deal of flexibility allows the modeler more options during the parameter estimation portion of the analysis. Pseudo-steady-state double porosity W-R flow can be simulated using a matrix-governing equation with just a single term in (2) \((N = 1)\). Triple porosity or further extensions are handled in an analogous manner \((N = 2, \text{ etc.})\).

Radial Well Test Solutions

The W-R pressure solutions for pseudo-steady double porosity interporosity flow are shown for a range of permeability and storage coefficient ratios. Solutions which assume radial symmetry are associated with the fracture/matrix geometry shown in the diagram below.

The well is open to a man-made fracture, which is planar and centered on the production well. A multi-stage fractured well consists of several parallel fractures.

Bayesian Analysis

As a first step in the Bayesian analysis, empirical Arps model \(q = q_0 (1 + D_0 t)^{-m}\) is fitted to daily gas production data (see left figure). The parameter’s posterior distributions are shown as histograms in the right figure, with the bi-variate posterior distributions of parameters on the off-diagonals (showing clear correlation between parameters in this simple model).

We are working to extend the Bayesian approach using the newly developed diffusion-based models and soon-to-be-collected natural tracer data. The posterior probability distributions from one analysis are used as priors for additional analysis, to show the effects additional information has on parameter estimation and identifiability.

Bayesian Analysis

These physically based flow solutions and the widely used Arps models can be fit to shut-in or production data from wells to improve estimates of reservoir and fractures parameters and total reserves. We use the Markov chain Monte Carlo sampler DREAM [see Braak and Vrugt, 2008] to perform Bayesian analysis.