Predicting risk of carbon leakage from perforated reservoirs

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Geologic Sequestration of Carbon

• Part of the carbon management plan for Canada
• Current plans to sequester 150Mt/yr of CO2 by 2050
  – The inputs to subsurface reservoirs are controlled and known
  – The outputs are not
    • Blowouts
    • Slow, gradual leakage
Carbon Leakage

• Leakage through natural geological pathways is negligible
  – GS candidate reservoirs have stored oil for millions of years

• Humans have damaged the reservoir integrity; Abandoned wells may now act as conduit for carbon leakage
  – Path of least resistance
  – CO2 buoyancy

Gasda et al. 2004
Carbon Leakage

- Abandoned oil wells are capped with mixed degrees of rigour
- Multiple leakage pathways along the well casing
  - Provides short-circuit between geologically disconnected aquifers/reservoirs

Celia et al. 2004
Carbon Leakage

- Most candidate reservoirs for large-scale sequestration are old oil reservoirs
  - Makes sense – we know they can hold fluid
  - Uh oh! - Riddled with abandoned wells

Bachu and Celia 2009.
Carbon Leakage

• Ideally, we would like to estimate the leakage rate
  – Some percentage of losses to atmosphere might be excusable
  – Might have impact on shallow GW quality
    • Increased pH – Leaching of contaminants
  – Must estimate risk to human, ecosystem health
• Unfortunately, there are multiple challenges to our ability to estimate leakage rates
  – *Imperfect knowledge* of system
    • Geologic system: properties, geometry, etc.
    • Abandoned well permeability, dependability, (location?)
  – Tremendous *number* of abandoned wells
  – Multiphase, *multiscale* physics non-trivial
    • Regional transport impacted by local well-scale physics
Estimating Carbon Leakage: Numerical Approaches

- There are a number of numerical models that can effectively simulate (most) of the important physics for one or two abandoned wells
  - TOUGH2, ECLIPSE, etc.
  - Computationally expensive
  - Sensitive to particulars

- Getting reasonable simulations for tens or hundreds of wells with a standard multiphysics model (for 1000s of realizations!) is out of the question

http://esd.lbl.gov/
Estimating Carbon Leakage:
Semi-Analytical Approaches

• Recent semi-analytical approaches have been used to estimate leakage rates from 100+ well systems (e.g., Nordbotten & Celia, 2006, 2009)
  — Highly simplified physics
  — Highly simplified geometry
  — Fast enough for uncertainty/risk assessment

• Currently being used by US EPA, Alberta Geol. Survey
Estimating Carbon Leakage:
Semi-Analytical Approaches

• Simplifies subsurface into parallel layered aquifer/aquitard system

• Critical limitation is inability to handle updip buoyant advection of carbon plumes
  – Essential component of CO₂ migration
  – Mechanism for *bypass* (potentially reducing leakage)
  – Mechanism for *accumulation* (potentially increasing leakage)
  – Ignoring this may be highly problematic
Estimating Carbon Leakage

- It is desirable to have a multiscale model that can include:
  - Geological geometric heterogeneity (~km^2)
  - Small scale (wellbore) heterogeneity (~cm^2)
  - Density effects
Waterloo CEE Research

• Dr. Gracie and I have been working on developing specialized models that can handle mixed scales of this problem
  – eXtended Finite Element Method (XFEM)
  – Gracie & Craig (2010), Craig & Gracie (2011)
• Still relies upon simplified physics (for now), but significantly reduces discretization costs
  – Abandoned wells handled through analytic “enrichments” rather than fine discretization
  – Multiple wells in one ‘grid block’
• Aimed at solving the big problem efficiently with more respect for the physics
Early XFEM Model

- Quasi-3D (fully 3D too expensive)
- Initially looking at system without density effects
  - Basically just a groundwater problem
  - Relevant to other water resources investigations

Gracie & Craig, 2010
XFEM Model

• Consider 100 m x 100 m aquifers separated by an aquitard. A single preferred leakage path exists between the aquifers.

Gracie & Craig, 2010
XFEM Model

• This is a tough problem! Regular FEM requires prohibitive discretization on a regular mesh...

Gracie & Craig, Finite Elements in Analysis and Design, 2010
Transient Leakage

Craig & Gracie, 2011.
XFEM Model

Head in Bottom Aquifer

Head in Top Aquifer
CMC Work

• We have just scratched the surface:
  – Demonstrated very poor performance of FEM
    • Bypassed these problems with XFEM
  – Methods that can handle multiple wells per element
    • Encouraging for reducing discretization costs
• Extension to multiphase w/ density effects (i.e., the real deal) part of current CMC research
  – Incorporation in Bayesian framework for dynamic monitoring of leakage
  – How to pass over the model information to be used in proper risk analysis
Questions?