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Abstract

Large amounts of CO2 would need to be injected underground to achieve a significant reduction of atmospheric emissions. The large areal extent expected for CO2 plumes makes it likely that caprock imperfections will be encountered, such as fault zones or fractures, which may allow some CO2 to escape from the primary storage reservoir. Leakage of CO2 could also occur along wellbores. Concerns with escape of CO2 from a primary geologic storage reservoir include (1) acidification of groundwater resources, (2) asphyxiation hazard when leaking CO2 is discharged at the land surface, (3) increase in atmospheric concentrations of CO2, and (4) damage from a high-energy, eruptive discharge (if such discharge is physically possible). In order to gain public acceptance for geologic storage as a viable technology for reducing atmospheric emissions of CO2, it is necessary to address these issues and demonstrate that CO2 can be injected and stored safely in geologic formations.

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ON LEAKAGE FROM GEOLOGIC STORAGE RESERVOIRS OF CO_2

Karsten Pruess

Lawrence Berkeley National Laboratory
Berkeley, CA 94720, U.S.A.
K_Pruess@lbl.gov

INTRODUCTION

Large amounts of CO_2 would need to be injected underground to achieve a significant reduction of atmospheric emissions. The large areal extent expected for CO_2 plumes makes it likely that caprock imperfections will be encountered, such as fault zones or fractures, which may allow some CO_2 to escape from the primary storage reservoir. Leakage of CO_2 could also occur along wellbores.

Concerns with escape of CO_2 from a primary geologic storage reservoir include (1) acidification of groundwater resources, (2) asphyxiation hazard when leaking CO_2 is discharged at the land surface, (3) increase in atmospheric concentrations of CO_2, and (4) damage from a high-energy, eruptive discharge (if such discharge is physically possible). In order to gain public acceptance for geologic storage as a viable technology for reducing atmospheric emissions of CO_2, it is necessary to address these issues and demonstrate that CO_2 can be injected and stored safely in geologic formations.

MECHANISMS AND ISSUES FOR LOSS OF CO_2 FROM STORAGE

The nature of CO_2 leakage behavior will depend on properties of the geologic formations, primarily their permeability structure, and on the thermodynamic and transport properties of CO_2 as well as other fluids with which it may interact in the subsurface. At typical temperature and pressure conditions in the shallow crust (depth < 5 km), CO_2 is less dense than water, and therefore is buoyant in most subsurface environments. In geologic formations that are suitable for CO_2 storage, CO_2 would normally be contained beneath a caprock of low absolute permeability with "significant" gas entry pressure. Upward migration of CO_2 will occur whenever appropriate (sub-)vertical permeability is available, and/or when the capillary entry pressure of the caprock is exceeded.

It is obvious that leakage from geologic storage reservoirs for CO_2 must not exceed a "small" fraction of total inventory, in order not to defeat the main objective of geologic sequestration, namely, to keep greenhouse gases out of the atmosphere. A general consensus appears to be building in the technical community that storage losses should not exceed 0.1 % of inventory per year in order to be acceptable (Pacala, 2003; Hepple and Benson, 2003; Ha-Duong and Keith, 2003).

Leakage along pre-existing wells that may be improperly plugged, or whose cements may corrode, constitutes perhaps the most likely scenario for loss of CO_2 from storage. Celia and co-workers have developed a stochastic approach to estimate leakage risk in an environment where the number of wells is too large, and their locations and flow properties too uncertain, to permit mechanistic modeling (Celia et al., 2005; Nordbotten et al., 2004). Celia et al. conceptualize wellbore flow as Darcian, which will be satisfactory for wells that provide relatively "small" flow pathways, but is not applicable to flow behavior in open-hole sections. Flow in a few open holes could contribute more to total CO_2 leakage than a multitude of slightly leaky wellbores, and approaches are needed to quantify and mitigate associated risks.

After a discharge of CO_2 is initiated it may be subject to "self-enhancement," due to the smaller density and greater mobility (smaller viscosity) of CO_2. Self-enhancement may also occur from geochemically and geomechanically coupled processes, when migrating CO_2 dissolves caprock minerals and causes movement along faults, increasing their permeability.

NUMERICAL SIMULATIONS

Here we briefly summarize results of numerical simulation studies for leakage and discharge scenarios that have demonstrated self-enhancement. All discharge scenarios we have investigated so far have shown self-limiting features as well.

CO2 Migration along a Fault

Fig. 1 shows a schematic model of a fault zone, along with simulation results for CO_2 discharge through this fault. The fault initially contains water in a normal geothermal gradient of 30 ˚C/km with a land surface temperature of 15 ˚C, in hydrostatic equilibrium. CO_2 discharge is initiated by injecting CO_2 at an overpressure of approximately 10 bar in a

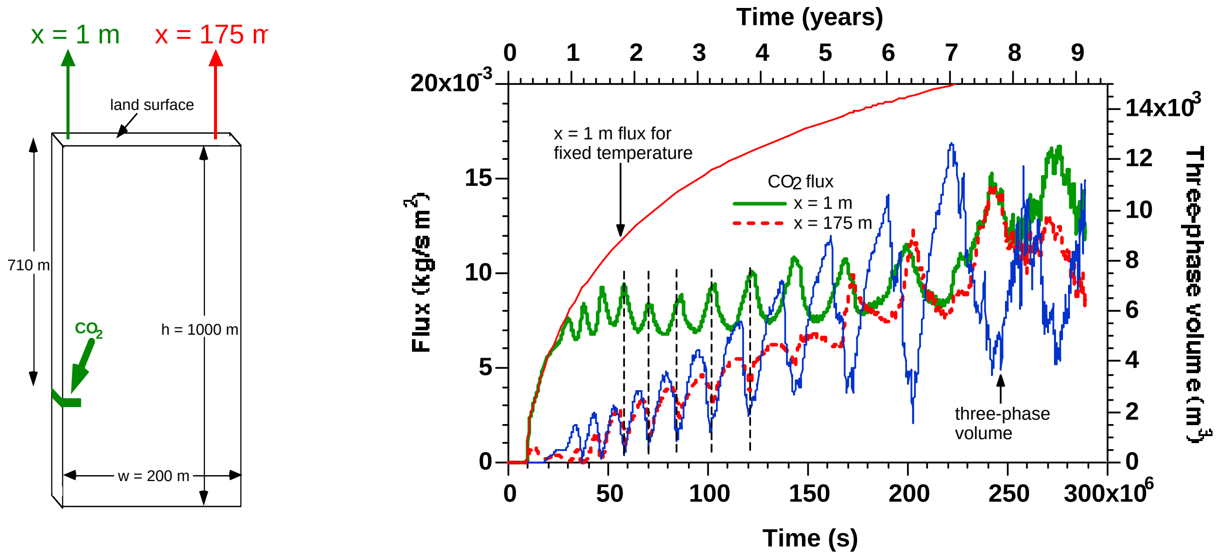

Figure 1. CO_2 leakage along a fault zone (from Pruess, 2005). A schematic model of a fault zone is shown on the left. The right panel gives temporal variation of CO_2 leakage fluxes at two different positions at the land surface. Total flow system volume with three-phase conditions is also shown.

portion of the fault at 710 m depth. The numerical simulation includes two- and three-phase flow of an aqueous phase and liquid and gaseous CO_2 phases in the fault, as well as conductive heat transfer with the wall rocks that are assumed impermeable (Pruess, 2005).

We find strong cooling due to the Joule-Thomson effect as rising CO_2 expands (Katz and Lee, 1990). Additional temperature decline occurs when liquid CO_2 boils into gas. The simulations show persistent flow cycling with increasing and decreasing leakage rates after a period of initial growth. No non-monotonic behavior is observed when flow system temperatures are held constant at their initial values. The cyclic behavior is explained in terms of varying fluid phase composition, due to heat transfer limitations, giving rise to an interplay between self-enhancing and self-limiting features.

Discharge of Water/CO_2 Mixture from a Well

We present preliminary simulation results for the discharge of CO_2-laden water from a well. A wellbore of 20 cm diameter extending to 250 m depth is subjected to inflow of water with 3.5 % CO_2 by weight (Fig. 2), which is slightly below the CO_2 solubility limit for prevailing temperature and pressure conditions at 250 m depth. The well discharges to atmospheric conditions of (T, P) = (15 ˚C, 1.013 bar). As rising fluid encounters lower pressures, CO_2 exsolves and two-phase conditions develop. In order to model two-phase flow in the wellbore, we incorporated the "drift flux" model of Zuber and Findlay (1965) into our TOUGH2 simulator (Pruess, 2004). Fig. 2 shows the simulated discharge behavior for a constant aqueous phase injection rate of 0.2 kg/s at the base of the well. In

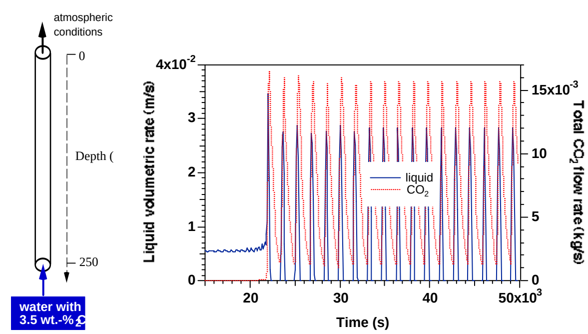

Figure 2. Discharge of a water-CO_2 mixture from a well. The wellbore model is shown on the left, while the right panel shows simulated discharge rates from the well.

our simulation the water initially in the well is CO_2-free, and discharge rate is constant for an initial time period, until CO_2 exsolution effects come into play. Subsequently the discharge goes through regular cyclic variations with a period of approximately 1600 s, i.e., the well behaves as a geyser. The geysering is due to an interplay between different flow velocities for gas and liquid, and associated changes in the average density of the two-phase mixture as CO_2 gas exsolves. Discharge is enhanced by CO_2 gas coming out of solution, but the preferential upflow of CO_2 also depletes the fluid of gas. This produces alternate cycles of self-enhancement and self-limitation.

In natural systems CO_2 venting usually occurs in a diffuse manner, but there are "cold" geysers that are driven by the energy released when high-pressure CO_2 expands, such as the Crystal Geyser in Utah (Shipton et al., 2004).

"PNEUMATIC" ERUPTION?

The mechanical energy of compression accumulated in a CO_2 storage reservoir is very large, equivalent to approximately 1 megatonne of TNT for storing the CO_2 generated by a coal fired plant of 1,000 MW electric power capacity over a period of 30 years (Pruess, 2006). If just a small fraction of this energy could be discharged in localized fashion over a short period of time, this would generate very serious consequences. In the volcanological literature, the possibility of a "pneumatic" eruption has been suggested (Giggenbach et al., 1991; Browne and Lawless, 2001; Benson et al., 2002). In contrast to the well known hydrothermal or "phreatic" eruptions, which are powered by the thermal energy stored in an accumulation of hot water, pneumatic eruptions are presumed to be driven solely by the mechanical energy stored in an accumulation of non-condensible gas, without substantial contributions from thermal energy. Pneumatic eruptions remain hypothetical at this time, but substantial CO_2 release events have been reported from CO_2-enhanced oil recovery projects, where CO_2 breakthrough occurred at production wells (Skinner, 2003). All of the CO_2 discharge scenarios we have investigated so far have shown self-limiting features that prevented an eruptive release.

Eruptive discharge of CO_2 from geologic storage, if it is at all physically possible, may be a "low probability–large consequence" type of event. Although such events may not qualify as "high risk" in formal risk analysis, experience has shown that the public is extremely reluctant to accept technologies that have a potential for accidents with large consequences, even if the probability of such accidents may be exceedingly low. A thorough evaluation of the possibility of high-energy discharges would be useful for demonstrating the technical feasibility of storing CO_2 in geologic reservoirs, and achieving public acceptance of the technology.

CONCLUDING REMARKS

CO_2 leakage from man-made storage reservoirs can occur through a variety of mechanisms. A credible analysis of associated risks must be based on a sound understanding of the underlying physical and chemical processes, and on an adequate characterization of potential leakage pathways. Naturally leaky CO_2 reservoirs provide ideal settings for studying the behavior of CO_2 in the subsurface over the large space and time scales required for CO_2 storage. Studies of natural CO_2 discharges in the Colorado Plateau region have documented extensive mineral deposition, yet many CO_2 vents and springs do not self-seal, and persist for thousands of years (Evans et al., 2004). These observations are consistent with recent findings from reactive chemical transport modeling (Gherardi et al., 2005).

Studies of the physics and chemistry of CO_2 leakage behavior to date have been quite limited. Popular news media have made reference to the lethal CO_2 bursts at Lakes Monoun (Sigurdsson et al., 1987) and Nyos (Tazieff, 1991) to suggest that geologic storage of CO_2 may be dangerous. The mechanisms that released major CO_2 accumulations at these lakes cannot be replicated in subsurface storage reservoirs; yet concerns raised by these eruptions may seriously impede public acceptance of geologic storage of CO_2. Focused research efforts are needed to provide a rational basis for assessing risks associated with geologic storage of CO_2, and to gain assurance that a high-energy, eruptive discharge is not possible.

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